The Specialist Committee on High Speed Craft

Final Report and Recommendations to the 26th ITTC

1. INTRODUCTION

1.1 Membership

The 25th ITTC appointed the Specialist Committee High Speed Craft with the following membership.

- Yoshiho Ikeda, (Japan), Chair, Osaka Prefecture University.
- Giles Thomas (Australia), Secretary, Australian Maritime College.
- Gregory Grigoropoulos, (Greece), National Technical University of Athens.
- De Bo Huang, (China), Harbin Engineering University.
- Dominic Hudson, (UK), University of Southampton.
- Kourosh Koushan, (Norway), MARINTEK.
- Gordana Semijalac, (Croatia), Brodarski Institute.
- Andrey Sverchkov, (Russia), Krylov Shipbuilding Research Institute.
- Osman Turan, (UK), University of Glasgow & Strathclyde.

1.2 Meetings

Four Committee meetings were held as follows:

- Brodarski Institute, Zagreb, Croatia, May 2009.
- National Technical University of Athens, Athens, Greece, October 2009.
- Australian Maritime College, Tasmania, Australia, May 2010.
- Osaka Prefecture University, Osaka, Japan, December 2010.

1.3 Recommendations of the 25th ITTC

The following is the specific guidance provided by the 25th ITTC on the work to be undertaken by this committee.

1. Review and identify numerical and experimental developments for the prediction and behaviour of high-speed craft, especially multi-hull vessels, addressing seakeeping, powering, manoeuvring, far field waves and wash, air resistance and stability.

2. Identify validation data for new designs appropriate for benchmarking purposes. Include relevant data about the ship geometry and loading condition, allowing the validation of numerical techniques in realistic conditions including some or all of the major challenges: large domains, complex bathymetry and unsteady effects.

3. Review, identify any requirements for changes and, if approved by the Advisory Council, update ITTC Recommended Procedures applicable to high-speed craft.

4. Update the ITTC Symbols List for high-speed craft, especially with respect to waterjet propulsion, taking into account ISO 31 “The Principles of Notation” and making the symbols

consistent in the procedures for high-speed craft.

2. REVIEW OF STATE-OF-THE-ART

Prior to the formation of this current specialist committee, the last ITTC committees with a high speed craft focus reported to the 22nd ITTC in 1999. For that ITTC there were two high speed craft specialist committees: Safety of High Speed Marine Vehicles and the Model Testing of High Speed Marine Vehicles. In the intervening years many developments in the field of high speed craft have been covered by the work of the standing ITTC committees.

Following consultation with the Advisory Council the review of state-of-the-art has been limited to developments presented in the public domain for the years 2005 to 2010. Whilst the main focus of the review is on multihull vessels, some significant work is included for monohulls and novel craft.

2.1 Seakeeping

Numerical Methods. For semi-displacement craft the numerical methods available for the prediction of vessel motions are similar to those used for 'conventional' ships in their mathematical basis. That is, potential flow techniques may be adopted and these may be either two-dimensional (strip theory) or three-dimensional (panel, or boundary-element) methods. The details of the mathematical models and numerical approaches are thus well documented elsewhere (ITTC 2005, 2008). The accuracy achieved with application of such techniques varies depending on craft configuration, geometry and speed.

With regards to two-dimensional methods, which do not usually account for any three-dimensional effects including those associated with forward speed, there is a development specific to high speed craft where the free surface boundary condition includes the effects of speed. This was initially developed by Zhao and Faltinsen (1991) and is variously referred to as a '2.5D method', '2D+t', 'high speed strip theory', etc. It is documented with examples in Faltinsen (2005). This method is capable of representing the interaction effects between the hulls of a multi-hull vessel travelling at high forward speed. Other applications of a similar method to semi-displacement hull forms include those of Holloway and Davis (2006), where an extensive discussion of the development of the theory is presented along with predictions for two mono-hulls and comparisons to experimental measurements. It is shown in both Faltinsen (2005) and Holloway and Davis (2006) that the 2.5D method provides a practical method for predicting the motions of semi-displacement vessels with a significant improvement in accuracy over conventional strip theories and faster computational times than full three-dimensional calculations. This finding is in agreement with earlier work on these methods (see for example, Takagi et al., 1995 and Duan et al., 2001).

When using a more conventional two-dimensional (strip theory) approach, where forward speed effects associated with the free surface are not included, for catamaran vessels it is possible to perform the calculation using both demi-hulls, or ignoring the effects of one demi-hull on the other. The former approach tends to overestimate the interaction effects between the two hulls at high forward speed, although may work well at low speeds. At moderate to high forward speeds better results are obtained through neglecting the interaction effects between the hulls (Thomas et al., 2009).

Arribas and Fernandez (2006), however, demonstrate good accuracy between numerical predications and experimental data using a more conventional strip theory, by augmenting the basic potential flow theory to include approximations for viscous lift and drag forces.

An interesting development of the linear strip theory approaches is the nonlinear strip theory of Tiao (2010). This applies a third order Volterra model to the strip theory to derive nonlinear expressions for the pressure over the hull of a high speed patrol craft. These pressures are used to predict the motions of the craft. Tiao (2010) applies statistical techniques to the responses of the vessel in order to compare results with experimental measurements. This comparison indicates good agreement.

Three-dimensional potential flow methods, particularly those utilising a translating, pulsating source Green's function are capable of predicting motions of semi-displacement craft reasonably accurately – and in particular representing correctly the interaction of flow between the hulls of a multi-hull vessel as speed increases. This is demonstrated by Inoue and Kamruzzaman (2008) for a variety of multi-hull vessels through comparison with experimental data. An application of such a method in predicting motion sickness onboard a high speed catamaran ferry form of wave-piercing design is given in Fang and Chan (2007), which also includes comparisons to experimental data. In line with earlier findings (e.g. Bailey et al, 1999), these papers indicate a translating, pulsating source method is capable of predicting catamaran motions reasonably accurately, however the pitch response around resonance tends to be over-estimated. Three-dimensional methods incorporating non-linear effects – usually to the Froude-Krylov and restoring terms may also be applied to high speed craft (e.g. Ballard et al, 2001).

An alternative three-dimensional potential flow approach to the prediction of ship motions is the use of Rankine sources where the free surface is represented by panels, together with the hull surface. This approach avoids some of the numerical difficulties associated with the evaluation of the forward speed Green's function, whilst also being more readily extended to non-linear predictions if a time domain formulation is used. Difficulties may arise, however, at the intersection of the body and free-surfaces. An example of the application of such a method to the prediction of high speed craft motions is in Sclavounos et al. (2003) who investigated both calm water resistance and response in waves with and without the effects of a motion control surface. No comparisons to experimental data are included in this work, however. Comparisons between predictions using a Rankine source method, Green's function approaches (with and without the forward speed Green's function), conventional strip theory and experimental data are provided in Bruzzone et al. (2001) and also Cappelletti et al. (2003). These papers indicate that both the Rankine source and the forward speed Green's function methods capture forward speed effects well, in contrast to the conventional strip theory and the Green's function method without forward speed. In some circumstances – most notably the prediction of peak pitch RAOs – the Rankine source method offers an improvement over the forward speed Green's function approach.

Predicting the motions of planing, rather than semi-displacement, craft remains a challenge but progress has been made in recent years. Garme (2005) demonstrates improvements to a potential flow strip theory technique, through particular attention to the calculation of pressure close to the transom stern. Comparisons to experimental and full-scale data indicate improvement to the strip theories usually adopted for planing craft, essentially based on the work of Zarnick (1978). A recent example of such a strip theory, applied to a rigid-inflatable planing boat is that of Lewis et al. (2007) who demonstrate reasonable agreement when compared to experimental data, even though the craft is outside the range of parameters tested by Zarnick (1978) and more usually associated with the application of such a method.

Progress is being made in the simulation of high speed vessel responses using Reynold's Averaged Navier-Stokes (RANS) methods, although computational times remain too long for practical applications. Two alternative approaches have been reported in Caponnetto et al. (2003), both using the commercial flow solver COMET. The first of these approaches re-meshes at each time step and the second retains the same mesh but moves it at each time step. In a comparison with experiments both appear promising with the re-meshing strategy offering an improvement.

Experimental Results. Experimental data on the motions of high speed craft are extremely valuable, both in their own right for design purposes and for validation of numerical methods. Experimental data includes both model-scale and full-scale investigations

Full-scale measurements are particularly valuable, since any questions over scaling – and the scaling process - are removed. Davis and Watson (2005) describe the derivation of response amplitude operators for an 86m wave-piercing catamaran using measurements made during a delivery voyage. Fukunaga et al. (2008) measured ship motions in six degree of freedoms of a full scale wave-piercing catamaran for several months to identify the effect of the ride control system on pitch and roll motions.

For planing craft, Morch and Hermundstad (2005) describe in detail the acquisition of full scale pressure measurements in waves. These data are relatively rarely available in the public domain. In another study of planing craft, Blount and Schleicher (2006) report experimental data for accelerations measured onboard a hard chine craft. Schleicher (2006) further discusses the use of acceleration data for planing craft and the statistical treatment of such data necessary when the vessel's responses are highly non-linear.

More extensive data is available for model-scale experiments. In addition to those papers mentioned when discussing developments in theoretical methods, there have been many useful reports over the years. Measurements of catamaran motions were undertaken by Molland et al. (2001) for Froude numbers of 0.2, 0.5 and 0.8 in head seas and 0.65 in head and oblique waves (heading angles of 120 and 150 degrees. These measurements covered a systematic variation of hull forms based on both the NPL series and the Series 64. Data are also presented for added resistance, one of the few public domain reports of this quantity for semi-displacement multi-hull craft. More recently Thomas et al. (2009) undertook measurements on a catamaran travelling at Froude numbers of 0.203, 0.406 and 0.508 at a heading angle of 160 degrees to the waves for a similar hull form derived from the NPL Series. Although neither of these sets of measurements conforms to ITTC requirements for benchmark studies they nonetheless provide a useful resource for both designers and those developing numerical prediction tools. The measurements of Katayama (2007) of roll damping of multi-hull vessels are also of benefit to developers of numerical prediction methods. The description of a prediction method for roll damping (Katayama, 2008) is of particular value.

Investigations into planing craft at model scale include Chiu et al. (2007) and Chiu et al. (2009), who measured pressures, as well as Katayama and Ikeda (2005) who developed a new experimental test method for planing craft. There are relatively few recent model tests on systematic variations in planing craft hullforms in waves, this makes the work of Kowalyshyn and Metcalf (2006) particularly valuable. Taunton et al. (2011) measured heave, pitch and acceleration responses of a more limited series of four hard-chine planing hulls in waves with a view to investigating the effects of such motions on the crew.

Townsend et al. (2009) investigated the performance of rigid inflatable boats through experimental testing that included the effects of the pressure in the inflatable tube on the measured heave and pitch responses. Regular and irregular wave testing was performed and the effects of slamming considered.

Operability. A key parameter in the design of high speed craft is often the operability of the craft in realistic sea-states. This is clearly governed by the seakeeping response of the vessel which may be evaluated using one of the theoretical techniques discussed, or derived from specific model tests, or full-scale data. The criteria to use to judge operability may be based on the likely susceptibility of passengers to motion sickness through an assessment of motion sickness incidence (MSI) – in a manner comparable to that used for displacement vessels. Alternatively for craft not designed for passenger transportation other measures may be more appropriate. For planing craft the effect of shock impacts on the long term health of the crew or the motion-induced fatigue of the crew may be the limiting factor in the operation of the craft.

In all cases the operability criteria may be applied in a design optimisation and combined with measures of hull resistance, service economics and safety. Examples of such combined approaches for high speed craft are those of Turan et al. (2003), Dudson and Rambech (2003) and Ikeda et al. (2003.

Although the use of motion sickness incidence (MSI) as evaluated by the classic method of O'Hanlon and McCauley (1974) persists in naval architecture, more recent advances in the understanding of motion sickness and its dependence on motion amplitude, frequency and duration suggest that a MSI derived from a motion sickness dose value (MSDV) is more appropriate (see, for example, Lawther and Griffin, 1988). These recent advances are included in the relevant ISO standard (ISO 2631, 2003) and this is now generally recommended for use. Fang and Chan (2007) is an example of the application of this standard to the calculation of motion sickness onboard a wave-piercing catamaran.

For high speed planing craft the same ISO standard (ISO 2631, 2003) also includes measures of Vibration Dose Value (VDV) that may be appropriate to the evaluation of crew fatigue, together with measures suitable for the evaluation of spinal injury. This latter uses Part 5 of the ISO standard to calculate a 'daily equivalent static compressive dose value' for the lumbar spine region. These methods are starting to be applied to the design of high speed craft (see, for example, Peterson et al. (2004) and Taunton and Hudson (2009)).

A similar approach to that of Schleicher (2006) to the response statistics of planing craft motions is taken by Allen et al. (2008) in the context of investigating exposure to vibration onboard small high speed planing craft. Other work looking into the effects of motions on crew effectiveness includes McMorris et al. (2009), who looked at the effects of different seat types on crew performance using physiological measurements, as well as Nieuwenhuis (2006) who measured the influence of the helmsman on the motions of a rigid inflatable boat at full scale. This latter effect is extremely important, yet rarely investigated.

2.2 Resistance

Numerical Techniques. Computational Fluid Dynamics (CFD) has made great progress in recent years, with many workshops and conferences promoting its development, e.g. Naval Hydrodynamics Symposia and FAST Conferences. Various codes of both potential and viscous CFD have been developed and applied in many aspects in high speed craft. Some of these can accommodate complex ship forms and conditions, e.g. unsteady RANS code, simulations of resistance of high speed ships using water jets and the use of level set method to treat highly distorted water surfaces (breaking waves & overturning bow waves). Complex appendage grid generation methods allow an efficient treatment, and dynamic grids are used to cope with structured- or unstructured-grid-expressed body motions.

Some of the codes have been reported to achieve as little as 3 to 10% discrepancies when compared with experimental test results, showing good predictions for resistance, sinkage and trim for monohull and multihull high speed craft. However comparisons for certain hullforms give predicted resistances with considerable discrepancies from model test results. Whilst some codes can provide a very good simulation of the free surface (breaking waves, spilling breakers, turnover phenomenon, wave pattern and wave profile, using viscous codes, particularly grid generation, is time-consuming.

Researchers have indicated that there are still several issues requiring consideration, e.g. choice of turbulence models; V&V problems in reaching the asymptotic range, oscillatory convergence; unrealistic order of convergence; monotonic divergence; issues with complex geometries (appendages); necessary conditions to reach grid convergence (unequal refinement in different coordinate directions) and severe grid dependency of the pressure resistance.

Much of the resistance research work has focused on numerical predictions using CFD techniques. For example Brizzolara et al. (2005) investigated the hullform optimisation of a fast trimaran ferry with the help of CFD tools, coupled with modules for automatic geometry generation and differential evolution algorithms to converge on the best solution. The wave making resistance was evaluated by means of a free surface potential flow panel method and the accuracy was validated over a large speed range against model experimental results. Then the numerical model was used in a more complex optimisation to obtain the best multi-hull configuration for low wave-making resistance. Li et al. (2005) used the commercial CFD code CFX to calculate the flow field around a trimaran and the viscous forces acting on the hulls. Four different turbulent models were used and steady and transient simulations were compared. The results showed considerable discrepancies with resistance tests in the high speed range, and the viscous force calculated using a proposed semi-empirical formula suitable for monohulls appeared different from that calculated using the CFD methods.

Mizine et al. (2009) discuss the hydrodynamic flow interference effects between the main and side hulls of trimaran ships. The hydrodynamic research and model testing of the large trimaran ship - Heavy Air Lift Support Ship (HALSS) showed a large change in resistance (70%) due to a moderate (15% from length of center hull) shift in the longitudinal side hull position. CFD calculations were performed with various computational codes and compared to test data. Dudson et al. (2005) present the hydrodynamic optimisation of the central hull of a 290m pentamaran to maximise the speed of the vessel with a pre-determined machinery package. The optimisation of the hullform was performed by combining the parametric CAD program FRIENDSHIP-Modeler with the CFD code SHIPFLOW via the generic optimisation tool FRIENDSHIP-Optimiser. A series of resistance tests was conducted to verify the accuracy of the CFD calculations and to prove the validity of the optimisation. Colicchio et al. (2005) carried out a comprehensive numerical study on semi displacement mono-hulls and catamarans. They extended the study to the trimaran configuration and conducted a series of model experiments for validation purposes.

Several other numerical methods have received attention in recent years including slender ship theory, improved Dawson method and 3-D Green's function. Degiuli et al. (2005) conduct an investigation into the resistance components in calm water of trimaran with symmetric outriggers. Calculations were completed for ten different trimaran configurations of the Wigley series and for a Wigley monohull using linear wave theory and Michell approximation. The total resistance and resistance components were then determined through an extensive experimental programme. The calculations using linear wave theory and Michell approximation showed poor agreement with wave pattern resistance. However the results provided a better understanding of the hydrodynamic content of the resistance components and the influence of the trimaran configuration on them.

Han et al. (2007) investigated the calculation of wave resistance of trimarans and pentamarans based on the linear new slender-ship theory and the Kochin function. The coefficient of trimaran's wave-making resistance was calculated and the numerical results agreed well with that of model tests showing that the new slender ship wave resistance theory is applicable to the calculation of a high-speed multihull's wave resistance. Zhang et al.（2006） calculated, under the linear condition, the surface wave and bottom pressure caused by a high speed slender ship based on shallow water wave theory. They then successfully measured and analysed the wave and pressure field induced by a towed ship model with the surface wave and bottom pressure measuring system they developed. Wang et al. (2009） investigated the effect of the side hull positions on trimaran wave making resistance using linear wave resistance theory for the wave resistance, and proposed a method to optimise the side hull position according to the main hull wave pattern. The same technique was used by Li et al.（2007） for a Wigley trimaran model, with configurations of side hulls at 3 transverse and 5 longitudinal locations. The results were compared with those from model tests. In addition the form factor (1+k) was found by Prohaska's method and the relationship between the form factor and the sidehull positions discussed.

Li et al. (2005) employed the 3-D Green function satisfying linear free surface and body surface boundary condition to analyse the wave making resistance and wave profile of a multihull ship. The comparison of wave profile induced by a moving time domain point source with those by a Havelock source appears satisfactory.

Chen J. P. et al. (2006) developed an improved Dawson-method-based code for predicting the wavemaking resistance of catamarans and trimarans, taking into consideration the transom stern problem. The numerical results agreed quite well with the experimental results and its application to the optimisation of trimaran side hull configuration was exploited.

Experimental Investigations. Conducting high quality experiments of high speed craft is still challenging. Some of the commonly used test techniques and assumptions might not be directly applicable to some high speed craft, such as the correlation line and form factor (1+k).

Hadler et al. (2007) present the results of resistance, heave and trim measurements made with a systematic series of 5 models in which the transom area ratio was varied from 10% to 100% of the maximum section. The hulls, which used elliptical sections to minimise the wetted surface, had a length-to-beam ratio of 12, the same design water plane and bow shape. They were tested at the same length-volume ratio over a speed range from Fr = 0.2 to 1.1. The speed was also determined when the flow separated at the transom and the results compared with other published results. The tests showed that stern form has a marked impact on the calm water resistance of high speed slender hull forms over the whole speed range but most particularly at Fr below 0.85. Test results for a catamaran configuration with different demihull spacings, including resistance, heave and trim are presented for five models by Hadler et al. (2009).

Friedhoff et al. (2007) conducted an experimental investigation into the performance of a small planning craft in a shallow water basin, aiming at better understanding hull-propeller interaction and scale effects. Special attention was paid to the shallow water effect, with the transition from displacement to planning state. Furthermore, model self-propulsion tests were performed to study the influence of inclined propeller shafts and to validate the extrapolation procedure. Extending this work, Friedhoff et al. (2009) tested two geometrically similar models of different scales. The results showed that even at very small blockage ratios, planing craft experience shallow water effects. The dynamic trim, resistance and wave patterns differed significantly from open water data.

Developing a Deep-V catamaran series, Mantouvalos et al. (2009) conducted physical model tests to assess their performance. They also report the Artificial Neural Network (ANN) based regression equations for the determination of the wave resistance coefficient, form factor and wetted surface area. Dong et al.（2008） investigated a 140 tonne high speed wave piercing, with model tests of resistance and seakeeping performance.

Control Surfaces. Control surfaces are used extensively on high speed craft to obtain optimum running trim and reduce vessel motions in waves. Fridman et al. (2007) discuss the practical applications and theoretical results associated with interceptors installed on high speed craft. They provided historical reference on the development of this technology in Russia and world-wide and provided examples of existing and envisaged high-speed ships utilising interceptors. They made use of the method of matched asymptotic expansions (MAE method) as a theoretical approach to the description of hydrodynamics of interceptors. Applications of the MAE method to the flow problems involving planing and supercavitating surfaces were illustrated in both two and three dimensions. Their discussion of the results covered the influence of interceptor geometry and dimensions (e.g. relative width), flow boundaries and their location with respect to the device, span-wise extent of the interceptor.

Wilson et al. (2007) investigated by experimental tests and computations the effect of a stern flap on the propulsion performance of a slender, high-speed ship model tested at self-propelled conditions using four waterjets. They provided results for the changes of measured jet-powered tow force and for the self-propelled RPM changes, with and without a stern flap, with several flap angles at different vehicle speeds. Computed predictions for the effective drag and for the hull trim angle and heave are in reasonable agreement with the test results. It is shown that a stern flap can reduce the effective model waterjet self-propelled resistance by up to 4%, and the estimated propulsion power by over 5%, due to the improvement of interaction of flap-induced and waterjet-inflow-induced hull pressures.

A comprehensive series of model tests, to improve the hydrodynamic characteristics of an asymmetric catamaran hull form was conducted by Misirlis et al. (2009). The tests compared alternative configurations with add-on devices and three demi-hull separations. The add-on devices were: trim tabs at 0, 5 and 10 degrees, interceptors and hydrofoils. All configurations showed considerable improvement in the performance of the model which benefited from the correction of the running trim.

Resistance Reduction Methods. Techniques for the reduction of drag of high speed craft have focused on the use of air injection and air cavity techniques. Fakhraee et al. (2007) used two models to investigate drag reduction by the application of air film and air injection. One model was a simple catamaran and the other was a catamaran with air cavity injection under its bottom. It was shown that while the air injection equipment adds appendage drag to the barge hull, the bottom air flow results in a net drag reduction of between 12.5 and 23%. Sverchkov (2005) presented results of research into a planing catamaran with asymmetric demihulls using the artificial cavity concept. A comparison of model test resistance data from two design options was shown, with traditional smooth hull lines and with air cavities on the bottom. Experimental results demonstrated that artificial cavities enable the reduction of catamaran resistance by about 20% with only minor power losses for the air supply. Dong et al. (2007) systematically studied, with four conventional high-speed craft and three bottom hollowed craft (B.H.) models, applying air injection, the influence of the hull form, craft speed, methods of air injection and air flow rate on the drag reduction rate. The total resistance reduction rate of conventional hulls reached 10% to 25%. While that of the bottom-hollowed craft could reach 50% and is better in keeping a stable layer, whereas its resistance will increase without air injection.

2.3 Powering and Performance Prediction

The prediction of the full scale performance of high speed craft continues to receive attention from researchers using a variety of numerical and experimental techniques.

Numerical Methods. When predicting the performance of high speed planing hulls, Savitsky et al. (2007) suggest the inclusion of whisker spray drag, which can be up to 15% of the total drag, and the aerodynamic drag in the performance. Furthermore, they conclude that the equilibrium trim angle identified in the prediction program using the modified Savitsky's method is, for non-prismatic hulls, related to the trim angle of the ¼ buttock line, when measured at the forward edge of the mean wetted length.

Park et al. (2007) used commercial CFD code FLUENT and self-propulsion model tests to analyse the stern flow of twin-skeg ships. They concluded that of propulsive efficiency of these ships may be improved if the axial velocities in the skeg tunnel are high, the flow lines along the stern bulb are straightforward, and there is flow balance between the inner and outer side of the stern skeg to ensure straightforward streamlines along the stern overhang.

Bhushan et al. (2009) presented numerical results, among others, for the powering characteristics of fully appended Athena hull form. The computations using rough-wall conditions compare well with the full-scale data extrapolated from model–scale measurements using the ITTC ship-model correlation line including a correlation allowance.

Scherer et al. (2010) used commercial CFD codes (ANSYS Fluent, ANSYS CFX and STAR CCM+) to enhance the performance prediction capabilities for planing boats with the inclusion of appendages, propellers, tabs/interceptors and their interactions. They provide experimental evidence for some of their results.

Model tests. Katayama et al. (2007b) proposed an estimation method of running performance for high-speed planing craft with outboard engine. The method is based on experimental data for resistance and propeller open water in conjunction with engine performance curves and model and full-scale results for the self-propulsion factors. They also estimated the hydrodynamic forces on the lower hull of the outboard engine. The method was evaluated by full scale tests.

Radojcic and Bowles (2010) investigated the propulsive performance of high-speed monohulls in shallow water. They concluded that (a) the hump speed (vessel speed at which maximum trim occurs) is less in shallower water, (b) the propulsion power significantly increases in the critical region as water depth decreases, and (c) propeller shaft speed (n) at a given vessel speed increases as water depth decreases (indicating a reduction in efficiency).

Min et al. (2009) carried out extensive model tests with contra-rotating propellers (CRP) and discuss some tips for their design and their full-scale performance prediction on the basis of experimental results.

Full Scale Trials. Morabito and Snodgrass (2010) discuss the contribution of carefully conducted full-scale trials combined with towing tank tests on existing and concept designs of motor yachts and demonstrate the implementation of the proposed methods in the design of the Viking 82.

2.4 Manoeuvring

Numerical Methods. On the basis of the experimental results derived by Katayama et al. (2001), the same authors (2002) developed a computer program to simulate transverse porpoising. The numerical results are in fairly good agreement with the experimental ones. In addition, using the simulation program, the effects of the location of the centre of gravity on transverse porpoising were investigated. The numerical results, confirmed by experiments, suggest that, reduction of transverse porpoising can be achieved by moving the centre of gravity forward or upward. Although transverse porpoising is a coupling motion among roll, pitch and heave motion, it is concluded that only the roll and the heave motions play important roles in the occurrence of the transverse porpoising.

Sutulo and Soares (2005) note that some observations of the manoeuvring motion of fast displacement catamarans indicated that dynamic changes in the ship's attitude in vertical planes (sinkage, trim and heel) observed during manoeuvres at high-speed can affect the hydrodynamic forces on the horizontal plane and the dynamic properties of these vessels. However, all manoeuvring simulations for catamarans used to be based on simplified 3DOF mathematical models. The authors used regression models for all six components of the hull forces accounting for the influence of the attitude alteration effects previously developed on the basis of Computerized Planar Motion Carriage captive-model tests. Basing on these regressions, a relatively complete 6DOF manoeuvring mathematical model was developed for a particular river-going catamaran equipped with steerable water-jets. Certain components of the hydrodynamic force, which could not be determined from the captive-model tests, were estimated by means of the slender-body theory, the cross-flow drag concept and other semi-empiric approaches. Standard manoeuvres were simulated using both the 6DOF and 3DOF mathematical models. The comparison of the numerical results with available full-scale data leads to the indication that the 6DOF modelling is superior at higher speed.

Ayaz et al. (2006) proposed a coupled non-linear 6-DOF model with frequency dependent coefficients, incorporating memory effects and random waves, aiming at improving the estimation of ship motion in astern seas. The authors used a new axes system that allows straightforward combination between seakeeping and manoeuvring, whilst accounting for extreme motions. In order to enhance further the numerical model and obtain useful information on motion coupling, extensive captive and free running model tests were carried out. Good agreement with the experimental results was achieved. These studies provide convincing evidence of the capability of the developed numerical model to predict the dangerous conditions that a ship could encounter in extreme astern seas. As a result, it could offer new insights towards establishing relationships linking ship behaviour to design, environmental and operational parameters. Validation of the numerical model on the basis of benchmark tests commissioned by ITTC's Specialist Group on Stability demonstrated qualitative, yet not fully satisfactory agreement between numerical and experimental results in line with other predictive tools. Anyway, the inclusion of frequency dependent coefficients definitely affects the accuracy of the predictions. Armaoglu et al. (2006) extended the previous method to semi-displacement ships travelling in astern seas, taking into account high-amplitude motions. They focused on the vertical dynamic forces which should not be neglected at the higher speed range. On the basis of fully captive model experiments they created a database of dynamic forces acting on the ship depending on the running attitude and speed of the ship and they used it to investigate their effect on numerical simulations. They performed semi-captive model tests in regular following waves in 3DOF to validate the numerical results, and they discussed the effect of speed on transverse stability.

Javanmardi et al. (2008) studied the effect of three longitudinal positions of outriggers in the manoeuvring behaviour of a trimaran. They used the code NUMELS [NUmerical Marine Eng. Lab. Sharif], which was developed for simulating three-dimensional, time-dependent two-phases, viscous flow coupled with rigid body motion. The numerical results for a set of test cases were in good agreement with experimental data. On the basis of the numerical results they concluded that the longitudinal positions of the outriggers greatly affects the manoeuvrability of trimarans.

Bhushan et al. (2009) carried out model- and full-scale URANS simulations of DTMB 5415 hull form for manoeuvring. The study demonstrated the versatility of a two-point, multilayer wall function in computing model- and full-scale ship flows with wall roughness and pressure gradient effects. The wall-function model is validated for smooth flat-plate flows at Reynolds numbers up to 109, and it is applied to the fully appended DTMB 5415 hull form for the manoeuvring simulation. The manoeuvring calculation shows slightly more efficient rudder action, lower heading angle overshoots and lower roll damping for full-scale than shown by the model scale.

Model Tests. Ikeda et al. (2000), investigated experimentally the characteristics of hydrodynamic derivatives in manoeuvring equations for a very high-speed planing hull, at speeds in the Fr=2.0 to 6.0 range. The hydrodynamic forces acting on a small model were measured by an oblique towing test, a PMM test, and a newly developed PMM test, in which roll, pitch and heave motions are measured under free condition. Measured data show that the derivatives significantly depend on running attitudes at high speed. This fact suggests that effects of motion modes other than the horizontal motions should be taken into account in the mathematical model of manoeuvring motion for planing hulls. On the basis of the measured hydrodynamic forces, course keeping qualities, turning performances and stability qualities of such hulls at high speed are discussed.

Katayama et al. (2000) developed a partly captured PMM model test method, to measure unstable motions of a planing craft induced by periodic manoeuvring motion. The experimental results for a planing craft at Fr=2.0 demonstrate that a violent motion, encompassing large rolling, heaving and pitching coupling motion occurs when the frequency of motion given by PMM coincides with the rolling natural frequency, and with the half of the heaving and pitching natural frequency of the craft. The rolling motion has the same frequency as the forced motion given by PMM, while the heaving and pitching motions have twice the frequency of the forced motion. In order to clarify the cause of the violent motion, the hydrodynamic forces acting on the hull in periodic manoeuvring motions were measured by PMM tests for a captured model and obliquely towing tests. The experimental results showed that the rolling displacement of the craft generates hydrodynamic heaving force and pitching moment at high speed. A non-linear time-domain simulation of the motions using the measured hydrodynamic forces was carried out. The simulated motions were in fairly good agreement with the experimental ones.

Katayama et al. (2001) carried out an experimental investigation into the transverse porpoising instability of a planing craft in drifting motion at high advance speeds in calm water. Some types of transverse porpoising were observed when the motions in oblique towing tests under heave, pitch and roll free condition were measured. In order to clarify the influence of hydrodynamic forces on the transverse porpoising, captive model tests in oblique towing condition were performed by systematic variation of the trim and drift angles, the, towing speed and the draft. On the basis of the measured hydrodynamic forces, the restoring forces and moments of heave, roll and pitch were calculated. The results showed that the heave and pitch coupling restoring coefficients between have opposite signs to each other (∠FZ/∠θ>0, ∠My/∠z<0). The same holds true for the heave and roll coupling restoring coefficients (∠Fz/∠φ>0, ∠Mx/∠z<0) at large drift angles. The results suggest that transverse porpoising may be a self-excited phenomenon in a coupling motion among roll, pitch and heave.

Sutulo and Soares (2004) developed an approach to synthesising D-optimized experimental designs for an arbitrary number of factors. They tested it on a third-order polynomial regression model with 5 to 8 factors concluding that genetic algorithms are superior over exhaustive and quasi-random searches for the internal optimisation procedure. Captive-model tests with a catamaran model with varying Froude number, drift angle, rate of yaw, sinkage, trim, and heel are presented as an example of the practical synthesis of the experimental design. The linear regression model constructed is a third-order, 5-factor polynomial with respect to all factors except for Froude number which influence the polynomial's regression coefficients, represented as a truncated Fourier series with a linear term added.

Yasukawa et al. (2005a) investigated the influence of outrigger position of a high speed trimaran on manoeuvrability. The trimaran was composed of a centre hull with L/B=8.0 and B/T=3.57 where L, B and T denote the length, breadth and draft respectively, and the outriggers with l/L=0.375, where l denotes the outrigger length. The captive model tests were conducted at Fr=0.35 in the towing tank of the Hiroshima University to capture the hydrodynamic force characteristics of the trimaran with three different outrigger positions. Using this data they carried out manoeuvring simulations and they found that, by shifting the outrigger position aft the lateral resistance at the stern part increases. Consequently, the tactical diameter also increases and the course-keeping ability is improved.

Yasukawa et al. (2005b) investigated the positive effect of skegs on the course-keeping ability of ships. They tested a scaled model of a high-speed, water-jet propelled monohull at 40 kn, with remarkable course-keeping instability without skegs. For this hull form they designed skegs with AS/(LT)=1/50, where AS is the total skeg area, L the ship length and T the draft. Then, they carried out captive resistance and circular motion tests to capture the hydrodynamic force characteristics for the ship with and without skegs. Based on the experimental data, manoeuvring simulations such as 15/15 zig-zag maneuver and 30 deg turning were made to investigate the effectiveness of the skegs. On the basis of the simulations, they concluded that skegs with AS/(LT)=1/33 are needed to improve the course-keeping ability of the hull form. Furthermore, they confirmed by oblique towing tests at various speeds, that the skegs are effective in a wide speed range from slow to high near 40 kn.

Following Katayama and Fujimoto (2008), a variety of peculiar instability phenomena, such as cork-screw, pure transverse stability loss, dipping and directional instability, were observed on high-speed planing craft, at very high forward speeds, where most of the hull is raised above the water surface, even in calm water. To reveal the mechanism of unstable phenomena, it is very important to keep safety for the craft. The authors focused on the directional instability of outboard-engine type super high-speed planing craft. Two existing scaled models were tested and one of them caused the directional instability at super high forward speed. In an earlier paper, Katayama et al. (2006) presented preliminary investigations on the possibility that the loss of transverse stability and the characteristics of manoeuvring hydrodynamic forces can cause an unstable manoeuvring motion. They estimated the speed range where this transverse instability occurs for two craft and measured the manoeuvring hydrodynamic forces. In addition, by numerical simulation of the manoeuvring characteristics of both craft, where the unstable manoeuvring motion was also simulated, they found out that the two models indicate quite different manoeuvring characteristics.

St. Pierre et al. (2007) carried out numerical analysis and extensive model tests to investigate the manoeuvring characteristics and the controllability of foil-assisted, high-speed hull forms. They concluded that the current controllability criteria and specifically the dynamic stability issues are not well defined within the state-of-the-art criteria for high-speed craft and they should be updated.

Manoeuvrability of Planing Craft. Running attitude consisting of draft, trim angle and heel angle of a high-speed craft commonly changes during its manoeuvring motion. Therefore, a new or modified estimation method taking into account some of the effect of the change of running attitude is required to express adequately manoeuvrability of planing craft. Kimoto et al. (2004), Katayama et al. (2005a & 2005b) investigated experimentally the effect of manoeuvring motions on running attitude and the effect of a change of running attitude on manoeuvring hydrodynamic forces. The results demonstrated that some manoeuvring motions affect its running attitude and the effect of the change of running attitude on the manoeuvring derivatives is significant. Thus, this effect should be taken into account during the evaluation of the manoeuvrability of planing craft. Kimoto et al. (2006) and Katayama et al. (2006) developed a manoeuvring motion simulation method using measured manoeuvring derivatives, and Katayama et al. (2009) applied it to evaluate the manoeuvrability of a high-speed trimaran.

Katayama and Ikeda (2005c) proposed some methods to assess the performance of high-speed planing craft, which is affected by the hydrodynamic forces caused by high forward speed. The methods use the experimental data of the hydrodynamic forces acting on a captured model for various attitudes, mainly in pitch and heave and sometimes in roll and yaw, at high forward speed in steady state. The measured data, moreover, can also be used to assess the possibility of occurrences of dynamic motions due to instability and ship motion in wave. The analysis procedures for some of such motions are also explained.

Oura and Ikeda (2007) studied the serious problems faced sometimes by a high-speed catamaran ferry during manoeuvring in harbors, at low speed in strong winds, because of its large above water structure. In order to clarify this situation, force measurements and drift speed measurements were carried out using a scaled model of a wave-piercing catamaran in a towing tank with a wind generator and they estimated its performance at steady sailing on a straight direction and the station-keeping behavior at zero speed in wind, using the experimental data.

Muhammad and Maimun (2008) presented a method to improve the manoeuvring performance of a planing hull (patrol vessel) in calm water. The method involves the use of spray-strakes attached to the hull of the vessel. The investigations for turning circle and zig-zag manoeuvres were carried out using a time domain simulation program. The hydrodynamic derivatives of the simulation program for surging, swaying and yawing motions of the planing hull with and without spray-strake were obtained through captive model tests in the towing tank using a Planar Motion Mechanism (PMM). The results indicate that the turning circle tactical diameter of the hull with three spray-strakes at half-length, fitted from amidships to the stem (3SS-Fwd) is reduced by about 3% compared to the bare hull. To assess the manoeuvring performance of a planing vessel fitted with spray-strake in design, the lift and drag principle was used to develop the mathematical model of a spray strake. The method developed involves the setting-up a 3-DOF mathematical model (surge, sway and yaw) in a module of Mathematical Modeling Group (MMG). The following main parameters of spray-strake that influence the manoeuvring quality were identified: the location of strake (xSS), the breadth of strake (bSS) and the projected of strake area (ASS). The accuracy of the equation was confirmed with turning circle and zig-zag maneuver tests.

Mizine et al. (2010) presented an innovative 181 m long High-Speed Trimaran Trailership design sailing at 30 kn. In the conclusions they state that its manoeuvrability was improved by placing the side hulls forward of the center hull transom to achieve turning radius requirements, and in placing side hulls differently for directional stability.

Full Scale Trials. Dand et al. (2008) carried out full-scale trials of the RNLI inflatable lifeboats for speeds in the 20 to 25 kn range to investigate ventilation on turns and speed loss on reciprocal maneuver. They concluded that ventilation on reciprocal turns is caused by the long sponson overhangs aft reducing the water level local to the propeller as the turn develops. Furthermore, speed loss on reciprocal turns can be of the order of 80%.

2.5 Loads

Numerical Techniques. A two-dimensional time-domain strip-theory method is presented by Holloway & Davis (2006). It is based on the transient Green function solution for strips of the water perpendicular to the direction of motion which are fixed in space. The method is used to compute longitudinal bending moments for an 86 m high speed catamaran and the results correlated against full scale measurements (Davis et al. 2005). Good agreement between the computed and full-scale data is found in both bow quartering and head seas at high Froude number.

A method for predicting wave loads of multihull vessels is proposed by Ogawa (2008). It is an extension of Newman's Unified Theory to catamarans and trimarans. The method is validated against existing model test data for catamarans (Kashiwagi 1993) and trimarans (Yashukawa 2005) and preliminary predictions for the vertical bending moment of the main hull of a trimaran, at Fr = 0.35 in head seas, are presented. the vertical bending moment increase for longer wave lengths ($\lambda/L > 1.0$) and decrease for shorter wave lengths ($\lambda/L < 1.0$). The effect of the arrangement of side hulls on the wave loads are examined and it is found that as the side hulls are shifted aft, the vertical bending moment increase for longer wave lengths ($\lambda/L > 1.0$) and decrease for shorter wave lengths ($\lambda/L < 1.0$).

Ge et al. (2005) present a numerical model for calculating the global response and impact experienced by a high-speed catamaran accounting for forward speed and global hydroelasticity. The strip theory by Salvesen et al. (1970) is generalised to calculate the linear hydrodynamic loads on the rigid segments and a 6-degree-of-freedom structural model is used to model the flexible test catamaran. The slamming on the flat horizontal wetdeck is assumed to be two-dimensional and is incorporated in the theoretical model using a Von Karman approach. The total dynamic system is solved in the time domain by a modal-based method. Numerical predictions of vertical shear forces and bending moments are successfully compared with the experimental data of Okland (2002).

A method for estimating the transverse bending moment and horizontal torsional moment of SWATHs is presented by Lin et al. (2007a). It is based on regressional analysis of model experiments conducted at the China Ship Research Centre and the David Taylor Model Basin. The method correlates closely to the model test results for vessel displacements over 3000 tonnes.

Sikora & Klontz (2005) document the generation of several seaway load prediction algorithms for catamarans, trimarans, and surface effect ships, based on available model and full-scale test data. These global load algorithms are quickly computed, making them suitable for preliminary or concept design studies.

Non-linear time-domain simulations of ship motions and load effects are carried out on a high-speed pentamaran by Wu and Moan (2006). In this hydroelastic method the global hull deformation is approximated by an aggregate of flexible modes, and the wave-induced ship responses are obtained by modal superposition. The simulated responses are validated against model tests with satisfactory results. The structural dynamic effects, mainly whipping, are shown to increase the classification society design load values by 30% to 50%.

Lin et al. (2007b) present a numerical simulation method for predicting the motions and wet deck slamming loads of a high-speed catamaran. Large Amplitude Motions Program (LAMP) uses a time-domain potential flow panel code as a framework to solve the three-dimensional wave-body hydrodynamics and rigid-body dynamics problems. Slamming pressures are captured by coupling a semi-empirical wedge entry model (Ge et al. (2005)). Comparisons with model experiments for a catamaran show LAMP correlates quite well with the overall magnitude and phasing of the wetdeck pressure responses.

Fang and Chen (2008) developed a three-dimensional source-distribution method, using a pulsating source potential incorporating a panel method. Through investigating wave loads experienced by trimarans it is concluded that moving the side hulls forward will generally reduce wave loads on the main hull and cross deck.

A non-linear time-domain method is presented by Shan and Wenyang (2009) to calculate the motions and wave loads of high-speed ships. The extended 2.5D theory is used to evaluate the nonlinear fluid radiation and diffraction forces, which account for both the effects of the change of the wetted surface and the ship's forward speed. Numerical results are favourably compared with model test data for a high-speed monohull.

Experiments. Lavroff et al. (2007, 2010) report on hydroelastic segmented model tests which were undertaken in head seas to investigate the parameters affecting the whipping vibratory response of high-speed catamaran vessels subject to slamming. The first longitudinal modal frequencies measured on full-scale catamaran vessels were used as a basis for predicting the flexural response frequency of the hydroelastic segmented model. As documented in Davis et al. (2009), the hydroelastic segmented model allowed the measurement of bending moments in regular wave towing tank tests. Since the centrebow and forward portion of the wet deck was constructed as a separate segment from the two demihulls, slam loads could also be determined. Slams of up to 2200 tonnes peak force (full scale equivalent) were found to occur when the wet deck arches between the main hulls and centre bow fill. This hydroelastic segmented catamaran model was also tested in irregular head seas, for a variety of significant wave heights and modal periods (Thomas et al. 2009). The slam events were identified in the test data and analysed with respect to kinematic parameters. Differences in slam characteristics were found for the two model speeds tested; slams at the slower speed generally occurred further forward on the hull, prior to the wave crest and with a bow down pitch angle.

Experimental work using hydroelastic monohull models has been conducted by Dessi and Mariani (2009), Ogawa et al. (2007) and Okaet al. (2007). To validate their slamming prediction model, Dessi & Mariani (2009) constructed a 6 segment model of a fast ferry using the backbone-modeling technique. The vertical bending behavior of the ship was reproduced by making the elastic backbone out of 20 elements of constant length but variable transverse section. The hull was divided into six segments, each one connected to the elastic beam with a vertical steel leg. Several tests in regular waves were performed using the 1:30 scale model at Fr = 0, 0.43 and 0.58.

To measure wave loads, Ogawa et al. (2007) conducted a series of seakeeping tests using an elastic model of a high-speed vessel. A backbone, whose rigidity was similar to the real ship, was attached inside the model which was divided into 4 parts. Measurements in head seas showed that the sagging moment increased as model speed and wave height increased, becoming about two times of the hogging moment due to bow slamming. The same hydroelastic model was utilised by Oka et al. (2007) in irregular wave experiments.

Full Scale Measurements. Full-scale measurements of wave loads and vessel response are extremely valuable. However since they are expensive to conduct and usually confidential to the ship builder or owner, results for high-speed multihulls are very limited in the published literature.

Thomas et al. 2005 reports on full-scale measurements of slam events on a 98m Incat catamaran to investigate its slamming behaviour in a variety of sea conditions. The full scale results are then used to determine the influence of the presence of slam events on fatigue life. In addition the effects of significant wave height, slam occurrence rates, slam peak stresses, whipping behaviour on fatigue life are examined. The fatigue life is found to reduce significantly with the presence of slam events. For two large high-speed catamarans, full-scale measurements of slam events were conducted, as well as anchor drop tests whilst the vessels were stationary in calm water, by Thomas et al. (2008). This allowed the characteristics of transient whipping vibration to be identified, including damping.

Amin et al. (2009) present a new technique to predict sea loads for high-speed wave piercing catamarans based on finite element modelling and sea trials data. The sea trials data was for a 98 meter Incat vessel. Comparing the results shows that the FE RMS strains are in good agreement with trials RMS strains. A method for using wavelet analysis to identify slamming and whipping in full scale records is outlined by Davis et al. (2009).

Fu et al. (2009) report on an Office of Naval Research (ONR) sponsored project to obtain full-scale qualitative and quantitative wave slamming and ship motion data on the X-craft, an 80 m high-speed catamaran. The authors propose that slam and near slam events appear to be caused by a grouping of two or more waves. The most severe slam occurred while the ship was moving at the highest forward speed.

Kivimaa and Rantanen (2007) developed a new monitoring system and used it to monitor global hull beam loadings of fast monohull SuperSeaCat4. The monitoring system consisted of sensors linked using distributed digital network technology for data collection and integration. Sample results from the measurements, which were performed in the Gulf of Finland, are presented.

Full-scale trials were performed by Rosen et al. (2007) to evaluate the structural design of the Visby Class corvette. A method which enables the detailed experimental evaluation of the hydrodynamic loads on high-speed craft hull structures is presented. Experimentally derived panel loads are shown to be distinctly higher than the minimum requirements according to classification rules.

Wave Impact and Slamming. Since slam impacts generally result in the largest wave loads experienced by high speed craft significant work, both numerically and experimentally, has been undertaken in this area.

Stenius et al. (2006) used the explicit FE code LS-DYNA to model the fluid–structure interaction for two-dimensional rigid wedges impacting on a calm water surface. Hydroelastic effects on the panel response were systematically studied for different impact velocities, boundary conditions and structural mass (Stenius et al. 2007). It is concluded that hydroelastic effects can result in a significant reduction of the structural response for certain combinations of panel deadrise, impact velocity and boundary conditions. Cao & Wu (2007) also used LS-DYNA to study the slamming of trimaran cross structure. A 2-D finite element model was built and the slamming pressure of the trimaran at different velocities was calculated. The results showed that the air captured by the hulls acts as a buffer cushion and greatly reduces the slamming pressure.

Smoothed Particle Hydrodynamics (SPH) is a relatively new mesh-free Lagrangian computational method suited to modeling fluids with a freely deforming surface. It has been used by Oger et al. (2006), Viviani et al. (2008), Veen and Gourlay (2009) and Shahraki et al. (2011) to evaluate slamming loads on two-dimensional wedge forms impacting with a free surface. Results from all the studies show reasonable agreement with previous experimental studies. Preliminary work by Shahraki et al. (2011) has shown the potential of SPH to model the slamming of multihulls. It is proposed that SPH presents significant advantages over other CFD approaches since it has the inherent capacity to capture free surfaces, sprays and complex kinematics.

Hudson et al. (2007) used a viscous two-dimensional CFD analysis to compute wedge impacts. The results presented demonstrate that such a CFD approach predicts the magnitude and time history of the pressure distribution accurately when compared to available experimental data. This in turn leads to an accurate prediction of the wedge speed as it enters the water. Further work on the slamming impact of planning monohulls is provided by Kumar et al. (2008). They present a free-surface RANSE computation to account for the response of the boat to incident waves, vertical acceleration and hydrodynamic impact. The method is validated against towing tank experiments; but the authors conclude that more validation studies especially impact load validation in waves, for which experimental data are not widely available, should be carried out.

In the case of a wave-piercing catamaran with a centrebow, wet deck slamming occurs when the arches between the demihulls and centrebow fill. Davis and Whelan (2007) and Davis et al. (2007) present a computational model, drop test results and full-scale data concerning such an event. The basis of the computational method is the variation of added mass as the hulls enter the water. Residual air is entrained at the top of the arch due to bubble formation by turbulent mixing and this modifies the effect of the water added mass on the hull. The computational model therefore introduces a soft connection between the water added mass associated with the slam and the hull. Comparison with 2-D model drop tests led the authors to conclude that the added mass computation is adequate for slam modelling in global motions and loads calculations since it gives a good representation of the maximum total forces on the section and their duration.

Whilst all of the aforementioned methods are for 2-D entry only, Faltinsen and Chezhian (2005) present a numerical method for predicting water entry loads on three-dimensional bodies. The problem is solved as an initial value problem using the boundary element method. The Green second identity is used to represent the velocity potential as a distribution of Rankine sources and dipoles over the body surface and free surface. The problem is stepped up in time using the information from the boundary conditions. The kinematic free-surface condition is used to determine the intersection between the body surface and free surface at each time step. Drop tests were carried out using three dimensional monohull shapes to validate the numerical simulation; agreement between theory and experiments is good.

2.6 Propulsion

Waterjets. Design tools and procedures were investigated and reported in several papers. Brewton et al. (2006) present an investigation of the capability of a RANS code, FLUENT, as a design analysis tool for multi-stage waterjets. The study included two assemblies, one with just the rotor, shaft and casing; the other with the rotor and stator. Results were compared with experimental data. Heder (2007) describe how the influence of different factors was computed as a part of the development process of a very large waterjet. The result showed that the axial deflections of the hull and the shaft have a significant influence on the tip clearance. The bending deflections were found to have only a small influence. Methods of compensating for the tip clearance in the installation are presented. Lavis et al. (2007) describe the development and validation of a compact waterjet propulsion system. The development was conducted in four discrete phases: studies of pump-type options for compact units; advanced CFD to design the preferred pump type; the performance/cavitation testing of the pump and the testing in a towing tank of a self-propelled model to determine the critical interaction effects between the hull and the waterjet inlet. Bulten et al. (2007b) present the development of an axial-flow type pump. The performance was determined both experimentally and numerically. Agreement between both methods is good for the pump head and efficiency. Comparison of the axial pump with the mixed-flow pump showed a significant reduction of the size of the installation and/or an improvement of the cavitation margins. Zangeneh et al. (2008) present a methodology for designing waterjet pumps to meet multi-objective design criteria. The method combines a 3D inviscid inverse design method with multi-objective genetic algorithm to design pumps. A generic pump stage is used to demonstrate the methodology.

Several experimental studies have also been reported. Mavluidov et al. (2005) present the method for measuring the thrust and shaft torque against the inflow speed on waterjet models in open water conditions. The test results were presented for different cavitation numbers. Kim et al. (2007) present a study of a flush-type waterjet propulsion unit for an amphibious tracked vehicle. Gap effects were investigated. Resistance and self-propulsion tests were conducted so that the full-scale effective and delivered power was estimated. The efficiency difference according to the gap variation (1.5% and 0.7% of diameter) was about 25% in their overall efficiency. Wilson (2008) presented a waterjet inlet wake scaling procedure based on the similarity of thrust loading coefficient for self-propulsion at model and full scale. Results from a specific example of a self-propulsion test were also presented. It was found that Reynolds number wake-scaling introduces significant changes in basic model-predicted thrust interaction factors. Cheng et al. (2008) aimed to discover the real cause that leads to a broken grid of waterjets. Vortex-induced vibration may be one of the most important reasons. Analyses by CFD method and LES turbulence model were presented. Model computation was carried on by FEA means at the same time. The comparison between the vortex-induced force frequency and the nature vibration frequency showed that vortex-induced vibration is one of the most important reasons which will cause a violent vibration of the structure.

Many investigations were performed numerically and some of these include also experimental verification of numerical analysis. Berghult (2005) explain the physics behind the domination of certain orders of the blade-passing frequency harmonics. It was explained why such frequencies are commonly found onboard ships installed with water jets. A simple theory is found by CFD-studies together with experimental investigations. The mechanism of the blade frequency impacts in terms of increased forces for some overtones is shown. Kerwin (2006) reviewed the state-of-the-art of experimental and computational hydrodynamics as applied to the design and analysis of waterjet propulsions systems. He concluded that a range of computational tools is beneficial - from fast and simple to computationally intensive. Sun C. et al. (2008)

studied hybrid propulsion system of a waterjet and two propellers with results being validated by experimental data. The flow region of the hybrid propulsion system is simulated by solving RANS equations and interactions of the two kinds of propulsors are analysed. Bulten et al. (2007a) presents results of fully transient CFD calculations of flow through waterjet pumps. Calculations with non-uniform inflow velocity distributions were made to determine the steady radial forces. Rotor-stator blade interaction forces turned out to be dependent on flow rate, but were hardly affected by the level of non-uniformity of the inflow velocity profile. Bulten et al. (2008) presented simulations of the effects in off-design conditions of waterjets using a CFD code. The paper gives an overview of the different phenomena occurring at the various off-design conditions and how this will affect overall performance. Yang et al. (2008) performed CFD analysis to study the effects of changing the number of blades of both rotor and stator on the characteristics of flow pattern and waterjet propulsion performance. Wang et al. (2008) present a mathematical model describing the dynamic characteristics of a waterjet propulsion plant. The rotating-speed vs. power curves of the engine and the vessel speed vs. thrust curves of waterjet were modeled by means of the neural networks. Rhee et al. (2009) used a RANS code to calculate the flow field around a High Speed vessel bare hull and bare hull with axial-flow waterjets. The bare hull is used for baseline calculations. Then the waterjet is added to characterise its effect on the viscous flow field around the ship. Calculations are compared with measurements. Calculated total resistance and residuary resistance showed good agreement with measurements. Delaney (2009) present the application of RANS methods to analyse waterjet pump performance for two different high speed hull forms. RANS calculations at certain flow stations within the waterjet system were integrated into experimentally determined powering performance predictions for the entire system. RANS full and model scale boundary layers are compared to give insight into scaling effects. Full scale RANS calculations are compared to values that are scaled from model scale experimental results. The Station 1A RANS predicted boundary layer differs from measurements around the inboard capture area, but agrees well around the outboard capture area. RANS calculations suggest that Station 1A capture area sizes are also dependant on other factors, such as inlet spacing on the hull.

Several studies were performed on the cavitation behaviour of waterjets. Brandner et al. (2007) presented results of an experimental investigation of the flow within a waterjet inlet. Tests were performed in a cavitation tunnel, and the effects of thickening the ingested tunnel wall boundary layer were investigated. The ramp pressure distribution and boundary layer development, lip incidence, and pump face flow properties were investigated. Observations of lip and duct cavitation inception and behavior were also made. The results showed the inlet performance to be generally improved with the ingestion of a thicker boundary layer. Sun H. et al. (2008) present a viscous/inviscid interaction method to predict the viscous flow inside waterjet pumps, including the effects of sheet cavitation. The circumferentially averaged interaction between the rotor and the stator was accounted for in an iterative manner. The effect of viscosity on the blade forces and pressures was evaluated by coupling with a 2-D boundary layer analysis on each blade strip. Comparisons of the predicted and the measured rotor torque are presented. Liu et al. (2008) obtained hydrodynamic performance of a waterjet at non-cavitating and cavitating conditions using CFD. The calculation results show that mass flow rate and total head of the waterjet pump are reduced when cavitation occurs on rotor blades, and thrust declines. Steden et al. (2009) describe a method for carrying out an optimised design of a so-called linearjet propulsor towards high efficiency and good cavitation behaviour at a ship velocity range between 25 and 35 knots. An evolutionary optimisation algorithm with a tool for the generation of the propulsor geometry was coupled with two flow-solvers.

They showed that the range of operation of linearjet with the high efficiency is wide. Schroeder et al. (2009) present preliminary progress that they have made towards prediction of waterjet torque and head rise and the effects of cavitation and thrust breakdown using an internally developed version of RANS code OpenFOAM and give comparisons with the measured data. Lindau et al. (2009) present computed single phase and cavitating flow fields for a ducted waterjet. Modeling is performed using a RANS solver with homogenous-multiphase modeling and turbulent simulation capabilities. Computations assume steady, periodic flow conditions with body forces to represent the effect of the downstream stator row. Computed performance parameters and cavity shapes are compared with experimental observations.

The effect of air injection into a water jet is presented by Tsai et al. (2005) for a two-phase nozzle for a jet ski waterjet system. The compressed air is injected into the nozzle through the porous ring attached on the inner surface of the two-phase nozzle. The hydrodynamic performances of the jet ski with the original nozzle and with the two-phase nozzle were measured. The results showed that the thrust of the two-phase nozzle increases due to the injecting compressed air. Gany et al. (2008) present test results of a concept of an air-augmented waterjet propulsion system. They showed an increase in waterjet thrust in the range of 15-30% due to the injection of air bubbles.

Kwang et al. (2006) present results of stereoscopic particle image velocimetry (PIV) measurements of a waterjet in a wind tunnel. Pressure distributions along the ramp and lip sides inside the duct were measured for three jet velocity to vehicle velocity ratios. Three-dimensional velocity fields were obtained at the intake entrance and the nozzle exit. Murrin et al. (2006) present results of an investigation of a waterjet in a wind tunnel. Measurements were compared to CFD analysis of the unit. Pros and contras of testing waterjets in wind tunnel were discussed. Donnelly et al. (2008) report on the development and upgrading of testing facilities at NSWCCD, which are related to waterjet and waterjet propelled craft testing. They also present some results of testing performed in the new facilities including LDV measurements. Hino et al. (2009) applied CFD analysis to free surface flow around a waterjet propelled ship. A waterjet propulsor is implemented as an actuator disk model placed inside a duct. The actuator force is given based on the estimated thrust. Computations are performed with and without waterjet in operation. Effects of a waterjet duct and a waterjet propulsor to flow fields are discussed.

Surface Piercing Propellers. Kinnas et al. (2004) presented a three-dimensional low-order boundary element method for the performance prediction of surface-piercing propellers. The negative image method is used to account for free surface effects. Detachment locations of ventilated cavities are searched for iteratively using a modified smooth detachment condition. Results from parametric studies and validations with experimental measurements are shown.

Achkindze (2005) presents a historical review of some of developments in the field of supercavitating propellers and surface piercing propellers both experimental and theoretical with the emphasis on research performed in Russia. Several works were presented on different surface piercing propeller series. Nozawa et al. (2005) presents an investigation of applicability of surface piercing propeller on high speed craft. Propulsive performance and the running attitude of high speed craft equipped with SPP are simulated, solving equation of motions, using database of measured three components of hydrodynamic forces and moment acting on the two kinds of high-speed craft models. Propeller open characteristics of four kinds of SPP with different pitches were tested and used. Comparison between power performance of SPP crafts and conventional propeller crafts showed that SPP crafts have superior performance in the high speed range over about 40kts. Ding (2007) presents results of an investigation into the development of a methodical series of SPP with six blades. The influence of cavitation number and Froude number on the hydrodynamic performance of SPP was investigated by means of tests in the depressurised towing tank in CSSRC. A group of design charts has been established for design purpose. Ferrando et al. (2007) report that experimental tests have been performed on a systematic series of 4 and 5 bladed surface piercing propellers with varied pitch ratio (from 0.8 to 1.4). The influence of immersion ratio and shaft inclination is discussed. Regression equations are given describing the relationship of the thrust and torque coefficients for advance coefficients above the critical values. Influence on Weber number is briefly considered, confirming results of their previous works. Pustoshny et al. (2007) present the results of the development of 5-blades SPP series at KSRI for fast speed boats with maximum speed of 45 – 60 knots. They report on a systematic investigation performed in a depressurised towing tank to obtain data on the impact of various geometrical and operational parameters on SPP hydrodynamic characteristics. However only some data from the tests of SPP behind dummy hull for determination of propeller – hull interaction is presented. Ghassemi et al. (2008) present numerical results of analysis of a 3 bladed and a 6 bladed surface piercing propeller using a potential flow boundary element method.

Koushan (2006) and Koushan et al. (2009, 2011) present an experimental investigation of a partly-submerged propeller. Results are relevant for surface piercing propellers, though the propeller used for the investigation is a conventional propeller. An extensive series of tests was performed at different propeller submergence and advance ratios in calm water and in waves and with forced heave motion. Single blade forces and moments were measured with high sampling frequency to capture the dynamics in a single propeller rotation. The paper reports that a high speed camera was used for visualisation and in addition scale effects are discussed.

2.7 Air Drag

Little work has been completed in the field of aerodynamic drag. On the basis of the experimental results derived by Katayama et al. (2001) the aerodynamic drag acting on prismatic planing model accounts for 10 to 20 percent of total drag and the percentage depends on running trim and forward speed. Anosov et al. (2008) proposed a scale effect correction method for aerodynamic drag acting on planing craft, since the Reynolds number of water and air are different due to their density. Molland et al. (2003) investigated the aerodynamic drag of a family of fast catamaran superstructures and above water hulls travelling in still air, using experimental and a commercial CFD code as a theoretical technique.

2.8 Far Field Waves and Wash

A comprehensive review on work in the area of near and far-field wash was reported by the Resistance Committee of the 25th ITTC. Therefore only developments published since that review are included in this section.

The impact of vessel generated waves continues to be investigated, in particular through site-specific full scale measurements. Soomere, Parnell and Didenkulova (2009) and Parnell et al. (2008) have studied the impact of waves generated bay large high speed craft operating in Tallinn Bay in the Baltic Sea. This is an area of great interest since high-speed ferries have been operating for about 10 years close to the shoreline, with up to 50 sailings per day. The properties of ship waves were measured continuously over a four week period at approximately 2700 m from the sailing line with waves of up to 1.5 m in height being measured. Ship wakes were found to alter the natural beach processes with significant loss of sediment across the beach profile being evident. Similar work in Puget Sound, USA, was carried out by Osborne et al. (2009) were beaches were seen to respond differently to wakes from slow and high speed operations. Despite small differences in wave height, the wakes from fast vessels were found to contain more wave energy due to their longer periods resulting in altered sediment dynamics.

The impact of vessel generated waves on moored vessels and the hindrance that they cause their operators was investigated in Holland by Luth et al. (2009). Many different combinations of moored ships, passing ships and shore configurations were examined, with an expert panel scoring the hindrance due to the motions of the moored vessel. A guideline for maximum ship motions was developed based on maxima of vertical displacement and total acceleration.

An investigation into the correlation between experimental results and full scale measurements for a 24 m catamaran operating at a range of Froude length numbers was conducted by Macfarlane (2009). The results confirmed that good correlation was found between the predictions from model scale experiments within a controlled environment and a series of full scale trials data up to a Froude length number of 0.8. Therefore a correlation factor close to unity was recommended to be applied when using model scale experimental data to predict full scale maximum wave heights and related wave periods for similar vessels operating in the range $0.3 < Fr < 0.8$, provided the Fr_h remains subcritical. Macfarlane (2009) also provided several recommendations for good practice when undertaking full scale vessel generated wave measurements. An experimental investigation was conducted by Robbins et al. (2009) into the waves generated by a catamaran operating in the trans-critical region. Water depth was shown to have a significant effect on the vessel wake characteristics including wave height, bow wave angle and rate of decay coefficient. Using the model experiments a new simple method for predicting catamaran wave wake was developed and presented.

A numerical method for predicting vessel-generated waves was presented by Ohashi et al. (2008) using an in-house RANS-based CFD code. The computations used experimentally-derived values of vessel sinkage and trim, whilst the transom stern was modelled using an extension of the hull aft of the ship, with the length of this extension varying with vessel speed. The numerical predictions were validated through comparison with towing tank test results for a high speed monohull, agreement for the wave profiles and maximum wave heights was found to be good.

Belibassakis (2009) presented a combined panel method/coupled-mode technique to predict the evolution of the ship wave system over variable bathymetry regions. It uses the assumption that the ship’s track is straight and parallel to the depth contours, and relatively far from the bottom irregularity. The spatial evolution of the ship wave system in a coastal environment was found to be efficiently calculated.

2.9 Wigs and Hydrofoils

Numerical Methods. CFD methods have been used by several researchers to investigate the performance of WIGs, including Grillo et al. (2009, Xing et al. (2007) and Yang et al. (2010). Xing et al. (2007) found that CFD techniques are an effective tool for the analysis of aerodynamics of WIG vehicles. They analysed the aerodynamics and longitudinal stability of a WIGS project using the FLUENT code and the results show that the data which is calculated with RNG k-ε turbulence model and fine grid approach is superior. Yang et al. (2010) investigated the aerodynamic characteristics of WIG craft near curved ground. The numerical techniques included sliding meshing and dynamic meshing. The results show that the effect of curved ground is reflected by periodic aerodynamic forces and changes of pressure effect below wing.

Other numerical methods include the work of Dessi et al. (2005) who analysed the flow around a wing in ground effect or around a hydrofoil near the free surface. The AERMOD code is used for 2D and 3D configurations in ground effect. If moderate ground effects are considered, the potential-flow analysis appears to provide accurate results for the lift correction without the need to include viscous effects. A validation of the AERMOD code was performed for the steady case.

Rozhdestvensy and Fridman (2008) summarise some results for the aerohydrodynamics of lifting systems using the method of matched asymptotic expansions (MAE). The examples include flow problems for a wing in extreme ground effect, gliding and supercavitating large-aspect ratio wings and wings with interceptors (spoilers). Numerical results obtained show the effectiveness of the approach and are in good agreement with experimental data.

Zhi-gang Yang et al. (2009) present a numerical study in an effort to provide detailed insight into schemed power-augmented flow for WIG craft in view of the concept of cruising with power assistance. Flow features with different deflected nozzle angles were studied. It was found that the technique of blowing air under the wing for PAR engine is not efficient in cruise mode and that the optimal scheme of power-augmented flow with respect to the craft depends on the specific engines and the flying regime.

Simulations of WIG performance to investigate their flight characteristics have been developed by several researchers. Grillo et al. (2005) built a general model for longitudinal stability analysis permitting the study of aircraft motion either in or out of ground effect or out of ground effect. The A-90 Orlyonok was used as the reference WIG craft for sample simulations and the results show that this general model can be successfully applied to study the longitudinal stability of WIG craft in the complete flight envelope. Grillo et al. (2007) present research on a particular ultralight WIG and the design of a flight control system that fixes the control variables trend through a non-linear mathematical model. This model has been built to evaluate aerodynamic coefficient variation laws due to altitude. The study shows that the WIG should have good behavior either in or out of ground effect because of the big distance between lifting surfaces.

Qian Zhou et al. (2007) simulated WIG craft space motion whereby the linear space equations of motion and disturbing signals, such as handling and launching are described. The simulation is programmed using MATLAB/GUIDE and the results indicate that stability and handling quality of WIG disturbed can be evaluated by means of mathematical simulation.

The condition and designing countermeasure which the aerodynamic parameter must meet for a WIG craft to self-maintain a certain flight height, by using the concept of gradient for level required power to flight height, was analysed by Changhua and Yajun (2007). They determined that flight height stability can be achieved by choosing comparatively small flight pitching angle, moving CG aft and by choosing comparatively big wing loading.

Murao et al. (2009) propose a design simulation model for a C-type WIG. For a WIG given weight and CG position, the necessary combination of elevator angle, angle of attack and required thrust can be found both in and out of ground-effect. As the result of the simulation, it is found that there is the restricted zone of the attack and the elevator angles corresponding to CG position. Accordingly the required thrust and longitudinal stability can be deduced. Experiments using a radio controlled-model seem to support these characteristics qualitatively.

Hydrofoil performance has also been investigated using CFD techniques by Li et al. (2010a), Li et al. (2010b) and Lu et al. (2010).

Li et al. (2010a) present a study of using a modified k-ε model to predict the unsteady cavitating flows around 2D and 3D hydrofoils in the framework of multi-phase mixture flow RANS approach. The cavitation is modeled by Schnerr-Sauer's cavitation model. It is found that the RANS method is able to predict the essential features like re-entrant jets, the periodic shearing and shedding of cloud cavities. Li et al. (2010b) conducted a numerical study of steady and unsteady cavitation on 2D hydrofoil. using the multiphase RANS code FLUENT. The cavitating flow around the Delft twisted hydrofoil, with unsteady inflow condition, was numerically simulated by Lu et al. (2010). Using a large eddy simulation, in combination with a volume of fluid implementation, they were able to capture the liquid-vapor interface and Kunz's model for the mass transfer between the phases.

The performance of foils in motion was investigated by Bai and Kim (2007) and Hsin et al. (2007). Bai and Kim (2007) considered the motion control of fully submerged hydrofoils in waves. The change of lift force due to the orbital motion of fluid particles is included as time-varying disturbance in the equation of coupled heave-pitch motion, and the corresponding state space equation is derived. Several control algorithms, including PID, LQR, and sliding mode control are applied for regular and irregular wave conditions, and the resultant motion responses are compared. Ching-Yeh Hsin et al. (2007) analysed a hydrofoil such as a stabilised fin or a T-foil in waves computationally. The influences of hydrofoil geometries were investigated by parametric analysis using an unsteady flow boundary element method linked to a ship motion analysis program.

Alexander S. Achkinadze (2008) provide formulae for the approximate computation of ascension force factor for supercavitating and partially cavitating elliptical hydrofoil with plane pressure surface at arbitrary cavitation index obtained from open linear model of cavitational flow. These formulae were obtained by using the method of matched asymptotic expansions and the method of lifting-line theory. The presented comparison between these formulas and experimental results demonstrates the acceptability of the proposed approach.

Model Tests. Pustoshny (2008) discusses the role of experimental studies in the development of superfast vehicles. He presents an overview of the opportunities offered by experiments using as examples some of the studies conducted by the Krylov Shipbuilding Research Institute. Experimental research is still playing an important role in the design of new high-speed craft particularly when faced with more complicated issues.

Model tests using radio control models are an effective method for testing the performance of WIGs, examples include Akimoto et al. (2005, 2007), Murao et al. (2005) and Shin et al. (2007). Akimoto et al. (2005, 2007) investigated a canard type WISES model for its potential in takeoff from rough seas. This model has a capacity of measurement equipments such as flight data recorders, GPS and the onboard camera. Slow flight data indicated the good takeoff/alighting performance of the concept by the effective utilisation of the propeller slipstream. The simple manual control of the elevator and rudder attained steady flight implying that the control of a real scale ship is an easy task. Murao et al. (2005) studied propeller-deflected slipstream (PDS) using an electric-powered radio-controlled WIG model to evaluate its take-off characteristics. The experiments demonstrated the very short take-off capability of the PDS PAR-WIG compared with a conventional seaplane model. Shin et al. (2007) tested a radio control model of a 20-passenger class WIG with planning-hull form and transom stern. The R/C test results demonstrated the stable and smooth running attitude at designed speed.

Doss and Natarajan (2006) conducted an experimental investigation into the effectiveness of a hydroski as a takeoff aid for WIG craft. The study, carried out in a towing tank clearly demonstrated that the hydroski has serious shortcomings as a takeoff aid. Nguyen et al. (2007) carried out a series of wind tunnel tests using a model of scale 1:6.2. The purpose of the tests was to determine experimentally the lift, drag and moment coefficients of the model.

Anosov et al. (2008) present a modified method for determining the aero-hydrodynamic characteristics of a fast ship. This method take into account the difference between the real aerodynamic characteristics of the model in the basin and the model aerodynamic characteristics, obtained in the wind tunnel. The modified method can be utilised for investigating dynamics of WIGs and hydroplanes during take-off and landing operations, as well as dynamics of racing boats and other special craft subject to strong aerodynamic effects.

Hydrofoils have been the subject of many experimental investigations in recent years. Tests on foils in isolation have been completed by Jing-Fa et al. (2005), Korulla et al. (2009) and Liu et al. (2010). Jing-Fa et al. (2005) designed a lift and drag measurement system for use in a cavitation tunnel to measure the performance of two-dimensional hydrofoils under cavitation condition. The performance curves of super-cavitating hydrofoils were developed from the tested results.

Korulla et al. (2009) conducted model tests on a NACA 66_215 foil to determine foil characteristics under ventilation conditions. The results obtained show that it is possible to develop an automated ride control system for foil assisted vessels using ventilated foils. Liu et al. (2010) investigated the unsteady cavitating flow and the dynamic shedding of cloud cavitation from the 3D elliptical foil in cavitation tunnel tests.

Model experiments have also been conducted on full hydrofoil craft models. Misra et al. (2006) evolved two hydrofoil concepts and carried out model tests. Brizzolara and Bruzzone (2007) assessed a new hybrid vessel concept, Small Waterplane Area Mono Hull (SWAMH) assisted by a tandem hydrofoil system.

Full-Scale Tests. Zhao et al. (2008) researched a new hydrofoil craft fitted with triple longitudinal hydrofoils. When compared with a tradition hydrofoil craft, it was found to have similar resistance performance but improved sea-keeping performance without the use of a control system. The authors built two full-open sight tourism craft with the triple-hydrofoil craft technology as a technology demonstrator.

3. BENCHMARK DATA

The committee was tasked with identifying validation data for new designs appropriate for benchmarking purposes. Such benchmark data, in the public domain, would need to include relevant data about the ship geometry including hull form (both above and underwater if necessary), model scale, appendage definitions, displacement and mass distribution, hydrostatics including draft and trim, and loading condition. It should specify full details on the tests including facility size, towing arrangement and instrumentation. The presented results should include details on the units and sign convention used, clear definitions of presented data and uncertainty analysis.

Whilst there are examples of published experimental data e.g. NPL catamaran (Molland et al., 2001), NTUA Series (Grigoropoulos and Loukakis, 2002, Grigoropoulos et al., 2010), unfortunately it was found that there is a complete lack of appropriate benchmark data available in the public domain for researchers to undertake independent validation studies. In particular high speed hull form designs are often proprietary and so data sets are usually incomplete. Therefore the committee cannot recommend any benchmark data in the public domain and there is a strong need for the production of quality benchmark data.

4. PROCEDURES

The committee initially reviewed all procedures pertaining to the testing of high speed craft. Following this and after receiving guidance form the Advisory Council two procedures were reviewed in detail:

- No. 7.5-02-05-02 Testing and Extrapolation Methods - High Speed Marine Vehicles - Propulsion Test.
- No. 7.5-02-05-03.3 Testing and Extrapolation Methods - High Speed Marine Vehicles, Waterjets - Uncertainty Analysis - Example for Waterjet Propulsion Test.

4.1 ITTC Procedure 7.5-02-05-02 Testing and Extrapolation Methods - High Speed Marine Vehicles - Propulsion Test.

Apart from several minor changes mostly for clarification purposes, the following modifications have been made:

- Guidance on the appropriate size of model to be used was clarified. The procedure points out that care should be taken when tests at high length Froude numbers are conducted at depth Froude numbers greater than 0.7 as shallow water effects will exist, particularly with low water depth to draft ratios (if h/T is less than approximately 16 then shallow water effect becomes significant).
- For the scaling of wake it is clarified that the model wake is essentially the same as the full-scale wake for exposed, raked shafts and that different arrangements, e.g. propeller driven SWATH's, show a quite different wake. The viscous flow is then important. Moreover, rotational and wave components are present in the wake.
- The method of controlling the flow over the propeller blades should be treated with extreme care. Previously the procedure stated that turbulence tripping on the propeller blades is not recommended. However although turbulence stimulation causes extra resistance and affects lift, it does deliver more consistent results by reducing variability and sensitivity. It is recommended that it is better to have larger, but known scale effects than to have smaller, but unknown scale effects.

4.2 ITTC Procedure 7.5-02-05-03.3 Testing and Extrapolation Methods - High Speed Marine Vehicles, Waterjets - Uncertainty Analysis - Example for Waterjet Propulsion Test.

The updating of this procedure focussed on correcting errors in the tables e.g. parameter values and symbols, as well as providing some additional text to aid clarification and explanation.

5. SYMBOLS

All of the high speed craft procedures were reviewed with respect to symbols. Changes were required in all three procedures applying to water jets: 7.5-02-05-03.3, 7.5-02-05-03.3 and 7.5-02-05-03.3. This resulted in changes to several equations, tables and diagrams.

In addition, two changes were recommended to the ITTC Quality Systems Group with respect to the ITTC Symbols List. Firstly that A_6 [nozzle discharge area] be removed since A_n [nozzle discharge area] is also defined in the Symbols List and this is the symbol used in all the waterjet procedures. Secondly, that the symbol T_{jetx} [jet thrust] be changed to T_{jx} [jet thrust] for consistency with all the waterjet procedures: 7.5-02-05-03.3, 7.5-02-05-03.3 and 7.5-02-05-03.3.

6. CONCLUSIONS

6.1 General Technical Conclusions

As expected, the prediction of resistance of high speed craft has been the focus of significant recent work. Although much of this work has focused on numerical predictions using CFD techniques and other methods (e.g. slender ship theory, improved Dawson method and 3-D Green's function), there have also been many experimental investigations carried out. Work on reducing resistance has mainly been orientated towards the use of air injection and artificial cavity techniques. Vessel generated wash remains a key focus for high-speed craft, with several numerical and experimental studies being conducted, including full scale measurements.

Powering performance of high speed craft has been investigated sufficiently for high-speed vessels fitted with waterjets or high-speed (partially cavitating or supercavitating) propellers. However, much less information is available regarding the powering with azipods, surface-piercing propellers and other novel propulsors (e.g. fans and multi-prime-mover ship propulsion power trains). The interest in this respect is focused on the larger high-speed vessels where the power requirements are quite demanding, while at the same time these vessels should comply with the contemporary IMO resolutions for the Green Ship (emission restrictions) and they also should be able to operate at a considerably lower economic speed.

For predicting the motions of semi-displacement vessels, 2.5D (i.e. a 2D strip theory in the time domain) techniques provide a practical method with a significant improvement in accuracy over conventional strip theories and faster computational times than full three-dimensional calculations. Three-dimensional potential flow methods are capable of predicting motions reasonably accurately and progress is being made in the simulation of high speed craft motion responses using Reynold's Averaged Navier-Stokes (RANS) methods, although computational times remain too long for practical applications.

During the last decade some progress has been reported on numerically predicting and experimentally estimating the manoeuvring performance of high speed craft, including multihull vessels. The numerical methods are mainly based on experimental results. Some attempts are underway to use both potential flow 3-D panel and CFD methods (RANS solvers) for the derivation of more reliable results. However, the former ignore the viscous flow in the stern region, while the latter are very time-consuming since the modelling is asymmetric and the grid should be quite large in order to converge to realistic results.

The numerical prediction of wave loads for high speed craft has focused on 2D+t and 3D techniques with model experiments on hydroelastic catamaran and monohulls being conducted for validation purposes as well as standalone investigations. Although conducting full scale measurements is complex and costly significant data has been published for large high speed catamarans. Since slamming loads are the dominant wave load on high speed craft significant work has been conducted in this area; principally using FE explicit codes, SPH and CFD to model the impact.

6.2 Recommendations to the Full Conference

Adopt the updated procedure No. 7.5-02-05-02 Testing and Extrapolation Methods - High Speed Marine Vehicles - Propulsion Test.

Adopt the updated procedure No. 7.5-02-05-03.1 Testing and Extrapolation Methods - High Speed Marine Vehicles, Waterjets - Propulsive Performance Prediction.

Adopt the updated procedure No. 7.5-02-05-03.2 Testing and Extrapolation Methods - High Speed Marine Vehicles, Waterjets - Waterjet System Performance.

Adopt the updated procedure No. 7.5-02-05-03.3 Testing and Extrapolation Methods - High Speed Marine Vehicles, Waterjets - Uncertainty Analysis - Example for Waterjet Propulsion Test.

Update the ITTC List of Symbols in accordance with the committee's recommendations.

6.3 Proposals for future work

The following areas are recommended as foci for work:

- Performance prediction of high speed craft with a view to improve model/ship extrapolation techniques. As also noted by the 25th ITTC Committee on Powering Performance Prediction the HSMV Resistance procedure 7.5-02-05-01 currently applies a form factor k=0 due to the difficulty of determining the value of the form factor from low speed model tests. Therefore the committee recommends a further study of form factors for HSMV, especially those with large transom sterns. Additionally an investigation into the scaling of waterjet and surface piercing propeller propulsion tests to full scale is recommended.

- Vessel generated wash is an important issue, particularly for high-speed craft. Due to environmental and safety concerns operations have been affected by regulatory requirements. However currently there is no ITTC procedure which governs the measurement of vessel generated waves at either model or full scale. The committee recommends that a review of current techniques is undertaken and a procedure developed to cover this experimental work.

- Many high speed craft operate in shallow water and the effect of this environment on their performance is not yet clearly understood, including its effect on propulsion. It is recommended that a review of current practice for resistance and propulsion tests in shallow water be undertaken, including performance prediction techniques based on such tests.

- The committee has found a paucity of benchmarking data available for the validation of numerical tools for resistance and seakeeping performance of high speed craft. Additionally no benchmarking tests have been conducted to compare results between different tanks. Therefore it is recommended that a worldwide comparative study on a catamaran hullform performance in calm water and in waves be instigated, as well as comparative model tests for a modern high-speed monohull at speeds corresponding to Fr =0.4 - 2.5.

- The influences of spray resistance, aerodynamic drag and the effects of trim tabs and interceptors are particularly important for high-speed craft. It is recommended that a review be conducted into their effects and in particular scaling methods used to account for their presence.

7. REFERENCES

Achkinadze, A.S., 2005, "Supercavitating, Highly Cavitating and Surface Piercing Propellers Design", FAST2005, St-Petersburg, Russia.

Allen, D. P., Taunton, D.J. and Allen, R. , 2008, "A Study of Shock Impacts and Vibration Dose Values Onboard Highspeed Marine Craft", International Journal of Maritime Engineering, Vol. 150 No. A3, pp 10.

Amin, W., Davis, M., Thomas, G. and Holloway, D., 2009, "Slamming Quasi-

Static Analysis of an Incat 98-m High-Speed Wave Piercing Catamaran", International Conference for Innovation in High Speed Marine Vehicles, Fremantle, Australia.

Anosov, V.N., Ganin, S.N., Dyakova, T.A. and Lukashevich, A.B., 2008, "Consideration of Aerodynamic Forces and Scale Effects in Model Tests of High-Speed Craft", SuperFAST'2008, St Petersburg, Russia.

Armaoglu, E., Ayaz, Z., Vassalos, D. and Katayama T, 2006, "On Manoeuvrability of Semi-Displacement Craft in Astern Seas", STAB2006, Rio de Janeiro, Brazil

Arribas, F. P. and Fernandez, J.A.C. 2006, "Strip Theories Applied to the Vertical Motions of High Speed Crafts", Ocean Engineering Vol. 33 No. 8-9, pp 1214-1229.

Ayaz, Z., Vassalos, D. and Spyrou, K.J., 2006, "Manoeuvring behaviour of ships in extreme astern seas", Ocean Engineering, Vol. 33, pp 2381–2434

Bailey, P.A., Hudson, D.A., Price, W.G. and Temarel, P., 1999, "Theoretical and Experimental Validation of the Seakeeping Characteristics of High Speed Mono- and Multi-Hulled Vessels", FAST1999, Seattle, USA.

Ballard, E.J., Du, S.X., Hudson, D.A. and Temarel, P., 2001, "Motions of Mono- and Multi-Hulled Vessels in Regular Waves using a Partly Non-Linear Time Domain Method", Proceedings, FAST2001, Southampton, UK ,Vol. 2, pp 219-234.

Belibassakis, K.A., 2009, "A Combined Panel Method / Coupled-Mode Technique for the Spatial Evolution of Ship-Generated Wave Systems over Variable Bathymetry Regions", Proceedings, FAST2009, Athens, Greece, pp 897-909.

Berghult, L., 2005, "Investigation of the Phenomenon of Domination of Certain Orders of the Waterjet Blade-Passing Frequency Harmonics", FAST2005. St-Petersburg, Russia.

Bhushan, S., Xing, T., Carrica, P. and Stern F., 2009, "Model- and Full-Scale URANS Simulations of Athena Resistance, Powering, Seakeeping and 5415 Maneuvering", Journal of Ship Research, Vol. 53, No. 4, pp 179–198.

Blount, D. L., and Schleicher, D.M., 2006, "Seakeeping: An Experimental Study of Accelerations and Motions of a High-Speed, Double-Chine Craft", International Symposium on Marine Design pp 129-136.

Brandner, P.A. and Walker, G.J., 2007, "An Experimental Investigation into the Performance of a Flush Water-Jet Inlet", Journal of Ship Research, Vol.51. pp 1-21.

Brewton, S., Gowing, S. and Gorski, J., 2006, "Performance Predictions of a Waterjet Rotor and Rotor Stator Combination using Rans Calculations", 26th Symposium on Naval Hydrodynamics, Rome, Italy.

Brizzolara, S., Bruzzone, D. and Tincani, E., 2005, "Automatic Optimization of a Trimaran Hull Form Configuration", FAST2005, St-Petersburg, Russia

Brizzolara, S., Capasso, M., Ferrando, M. and Podenzana-Bonvino, C., 2005, "Effect of Hull Form Variation on Hydrodynamic Performance of a Trimaran Ship for Fast Transportation" FAST2005, St-Petersburg, Russia

Bruzzone, D., Gualeni, P. and Sebastiani, L., 2001, "Different Three Dimensional Formulations for Evaluating Forward Speed Effects in Seakeeping Calculations of High Speed Hulls", FAST 2001 , Southampton, UK, Vol. 2, pp 235-241.

Bulten, N.W.H. and van Esch, B.P.M., 2007a "Fully Transient CFD Analyses of Waterjet Pumps", Marine Technology, Vol. 44, No. 3, pp 185-193.

Bulten, N. and Verbeek, R., 2007b, "Development of New Waterjet Installations for Applications with Reduced Transom Width", FAST2007, Shanghai, China.

Bulten, N. and Verbeek, R., 2008, "Off-Design Behavior of Waterjets", Proceedings, International Conference on WATERJET PROPULSION V, London, UK.

Cao, Z. and Wu, W., 2007, "The Effect of Air Cushion on the Slamming Pressure Peak Value of Trimaran Cross Structure", Proceedings, FAST2007, Shanghai, China, pp 608-611.

Caponnetto, M., Soding, H. And Azcueta, R., 2003, "Motion Simulations for Planing Boats in Waves", Ship Technology Research, Vol. 50, pp 182-198.

Cappelletti, A.M., Pino, E., Sebastiani, L., Boccalatte, C., Viviani, M., Bruzzone, D. and Brizzolara, S., 2003, "Experience on the Application and Validation of Theoretical Methods for the Seakeeping Prediction of Fast Ships", FAST 2003, Ischia, Italy, Vol. 2, pp 27-36.

Chang, S., Wang, Y. and Pang, Z., 2008, "Calculation and Analysis for Vortex-Induced Vibration of Waterjet Grid", International Conference on Waterjet Propulsion V, London, UK.

Chen, J.P., Zhu, D.X. and He, S.L., 2006, "Research on Numerical Prediction Method for Wavemaking Resistance of Catamaran／Trimaran", Journal of Ship Mechanics. Vol. 10, No. 2

Chiu, F.C., Tiao, W.C., 2007, "Experimental Study on the Nonlinear Pressure Acting on a High-Speed Vessel in Regular Waves", Journal of Marine Science and Technology Vol. 12, No. 4, pp 203-217.

Chiu, F.C., Tiao, W.C., 2009, "Experimental Study on the Nonlinear Pressure Acting on a High-Speed Vessel in Irregular Waves", Journal of Marine Science and Technology Vol. 14, No. 2 pp 228-239.

Colicchio, G., Colagrossi, A., Lugni, C. and, Faltinsen, O., 2005, Experimental and Numerical Investigation of a Trimaran in Calm Water", FAST2005, St-Petersburg, Russia

Dand, I.W., Barnes, J. and Austen S., 2008, "The speed of fast inflatable lifeboats", HIPER2008, Naples, Italy

Davis, M.R., Holloway, D.S. and Watson, N.L., 2005, "Validation of Nonlinear Wave Loads predicted by Time Domain Method in Sea Trials of an 86m Catamaran", FAST2005, St-Petersburg, Russia, pp 1-8.

Davis, M.R., Thomas, G., Holloway, D.S., Lavroff, J., Amin, W., Matsubara, S. and Roberts, T.R., 2009, "Slamming and Whipping of Wave-Piercing Catamarans", Proceedings, Hydroelasticity in Marine Technology, Southampton, UK.

Davis, M.R., Watson, N.L., 2005, "Measurement of Response Amplitude Operators for an 86 m High-Speed Catamaran", Journal of Ship Research, Vol. 49, pp 121-143.

Davis, M.R. and Whelan, J.R., 2007, "Computation of Wet Deck Bow Slam Loads for Catamaran Arched Cross Sections", Ocean Engineering, Vol. 34, pp 2265-2276.

Davis, M.R., Whelan, J.R. and Thomas, G., 2007, "Computational Modeling of Wet Deck Slam Loads with Reference to Sea

Trials", FAST2007, Shanghai, China, pp 616-624.

Degiuli, N., Werner, A. and Zotti, I., 2005, "An Experimental Investigation into the Resistance Components of Trimaran Configurations", FAST2005, St-Petersburg, Russia

Delaney, K., Donnelly, M., Ebert, M., and Fry, D., 2009, "Use of RANS for Waterjet Analysis of a High-Speed Seal", SMP'09, Trondheim, Norway.

Dessi, D. and Mariani, R., 2008, "Analysis and Prediction of Slamming-Induced Loads of a High-Speed Monohull in Regular Waves", Journal of Ship Research, Vol. 52, No. 1, pp 71–86

Ding, E., 2007, "A Series of Surface Piercing Propellers and its Application", FAST2007, Shanghai, China.

Dong, W.C., Liu, Z.H., Ou, Y.P. and Guo, R.X., 2007 "Experimental study on the hull form of high-speed air cavity craft", FAST2007, Shanghai, China

Dong, W.C., Xia, X., Zuo, W.Q. and Lu, W.L., 2008, "Experimental Study on the Form and the Performance of High Speed and Light Displacement Wave Piercing Catamaran", Journal of Ship Mechanics, Vol.12, No. 03, pp.199-207

Donnelly, M. and Gowing, S., 2008, "Overview of Recent Developments in Testing of Waterjets at NSWCCD", International Conference on Waterjet Propulsion V, London, UK.

Duan, W.Y., Huang, D.B., Hudson, D.A. and Price, W.G., 2001, "Comparison of Two Seakeeping Prediction Methods for High Speed Multi-Hull Vessels", FAST2001, Southampton, UK, Vol. 2, pp 243-250

Dudson, E. and Harries, S., 2005, "Hydrodynamic Fine-Tuning of a Pentamaran for High-Speed Sea Transportation Services", FAST2005, St-Petersburg, Russia

Dudson, E. and Rambech, H.J., 2003, "Optimisation of the Catamaran Hull to Minimise Motions and Maximise Operability", FAST2003, Ischia, Italy, Vol. 2, pp 59-68.

Fakhraee, A., Rad, M. and Amini, H., 2007, "Experimental method for calculation drags reduction in air cavity boat", FAST2007, Shanghai, China

Faltinsen, O.M. and Chezhian, M., 2005, "A Generalized Wagner Method for Three-Dimensional Slamming", Journal of Ship Research, Vol. 49, No. 4, pp 279–287

Fang, C.C. and Chan, H.S., 2007, "An Investigation on the Vertical Motion Sickness Characteristics of a High-Speed Catamaran Ferry", Ocean Engineering Vol. 34 No. 14, pp 1909-1917

Fang, M.C. and Chen, T.Y., 2008, "A Parametric Study of Wave Loads on Trimaran Ships Travelling in Waves", Ocean Engineering, Vol. 35, pp 749-762

Ferrando, M., Crotti, S. and Viviani, M., 2007, "Performance of a family of surface-piercing propellers", ICMRT07, Ischia, Naples, Italy

Friedhoff, B., Henn, R., Tao, J. and Stuntz, N., 2007 "Investigation of Planing Craft in Shallow Water", FAST2007, Shanghai, China

Friedhoff, B. and Tide, A., 2009, "Geosim Model Tests of a Hard Chine Planing Craft on Different Water Depths", FAST2009, Athens, Greece.

Fu, T., Fullerton, A., Terrill, E., Faller, W., Lada, G., Hess, D. and Minnick, L., 2009, "Measurement and Modeling of the Motions of a High-Speed Catamaran in Waves", OMAE, Honolulu, Hawaii.

Fukunaga, K., Nihei, Y. and Ikeda, Y., 2008, "An Experimental Study on Seakeeping Characteristics of a Fast Wave-Piercing Catamaran in Real Seas", 3rd PAAMES, Chiba, Japan, pp 525-530.

Gany, A., Shemer, A., Gofer, A., and Har-Lev, D., 2008 "Testing Air-Augmented Waterjet Propulsion", Proceedings, International Conference on Waterjet Propulsion V, London, UK

Garme, K.,2005, "Improved Time Domain Simulation of Planing Hulls in Waves by Correction of the Near-Transom Lift", International Shipbuilding Progress, Vol. 52 No. 3, pp 201-230

Ge, C., Faltinsen, O.M. and Moan, T., 2005, "Global Hydroelastic Response of Catamarans Due to Wetdeck Slamming", Journal of Ship Research, Vol. 49, No. 1, pp 24–42.

Ghassemi, H. and Ghiasi, M., 2008, "Hydrodynamic Characteristics of the Surface Piercing Propeller (SPP) by using Special Practical and Numerical Approach", ICHD2008, Nantes, France.

Grigoropoulos, G.J. and Loukakis, T. A., 2002, "Dynamic Performance of the NTUA Double-Chine Series Hull Forms in Regular Waves", Trans. SNAME, Vol. 110, pp. 77-113.

Grigoropoulos, G.J., Damala, D.P. and Loukakis, T. A., 2002, "Resistance and Seakeeping Characteristics of a Systematic Series in the Pre-planing Condition (Part I)", 2nd Chesapeake Power Boat Symposium, Annapolis, Maryland, USA

Hadler, J.B., 2005, "On the Development of a Hull Form With Minimum Wetted Surface for High-Speed Catamarans and Trimarans", FAST2005, St-Petersburg, Russia.

Hadler, J., Cain, K. and Singleton, E. 2009, "On the Effect of Transom Area on the Resistance of High-Speed Catamaran Hulls", FAST2009, Athens, Greece.

Hadler, J.B., Kleist, J.L. and Unger, M.L., 2007, "On the Effect of Transom Area on the Resistance of Hi-Speed Mono-Hulls", FAST2007, Shanghai, China.

Han, D.F., Zhang, H.P., and Qin H.D., 2007, "Research on Multi-hull's Configuration Based on New Slender-Ship Wave Resistance Theory", FAST2007, Shanghai, China.

Hashimoto, H., Stern, F., and Hosseini, S., 2008, "An Application of CFD for Advanced Broaching Prediction (2nd Report)", Proceedings, The Japan Society of Naval Architects and Ocean Engineers, Vol. 6.

Heder, M., 2007, "Very Large Waterjet with Adjustable Tip Clearance", FAST2007, Shanghai, China.

Hino, T. and Ohsshi, K., 2009, "Numerical Simulation of Flow Around a Waterjet Propeller", Proceedings, SMP'09, Trondheim, Norway.

Holloway, D. S. and Davis, M.R., 2006, "Ship Motion Computations Using a High Froude Number Time Domain Strip Theory", Journal of Ship Research, Vol. 50, pp 15-30.

Hudson, D.A., Turnock, S.R. and Lewis, S.G., 2007, "Predicting Motions of High-Speed Rigid Inflatable Boats: Improved Wedge Impact Prediction", FAST2007, Shanghai, China, pp 377-383.

Ikeda, Y., Katayama, T. and Okumura, H., 2000, "Characteristics of Hydrodynamic Derivatives in Manoeuvring Equations for Super High-Speed Planing Hulls", 10th International Offshore and Polar Engineering Conference, Seattle, USA.

Ikeda, Y., Kuroda, T. Amd Takeuchi, Y., 2003. "Effects of Seakeeping Quality on Travel Demand of a Fast Ferry", FAST2003, Ischia, Italy, Vol. 2, pp 77.

Inoue, Y. and Kamruzzaman, M., 2008, "Analysis of Hydrodynamic Characteristics for Arbitrary Multihull Ships Advancing in Waves", Journal of Marine Science and Technology, Vol. 13, No. 3, pp 231-243.

ISO 2631, "Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration", International Standards Organisation, 2003.

ITTC, 2005, "Final Report and Recommendations of Seakeeping Committee", 24th International Towing Tank Conference, Edinburgh, UK,.

ITTC, 2008, "Final Report and Recommendations of Seakeeping Committee", 25th International Towing Tank Conference, Fukuoka, Japan,.

Javanmardi, M.R., Seif, M.S., Jahanbakhsh, E. and Sayyaadi, H., 2008, "Trimaran manoeuvring simulation based on three-dimensional viscous free surface flow solver", HIPER2008, Naples, Italy.

Jung, K., Kim K., Yoon, S., Kwon, S., Chun, H. and Kim, M., 2006, "Investigation of Turbulent Flows in a Waterjet Intake Duct using Stereoscopic PIV Measurements"; Journal of Marine Science and Technology, Vol.11 Issue 4, pp 270-278(9).

Kashiwagi, M., 1993, "Interaction Force between Twin Hulls of a catamaran advancing in Waves (Part 2: Wave-Exciting Forces and Motions in Waves)", Journal of Society of Naval Archtects of Japan, Vol. 174, pp 181-190.

Katayama, T. and Fujimoto, M., 2008, "A study on directional instability of high-speed planing hull based on simulation", 6th Osaka Colloquium, Osaka, Japan.

Katayama, T., Fujimoto, M. and Kotaki, M., 2007, "An Experimental Investigation on Roll Damping and Manoeuvring Hydrodynamic Forces acting on Multi-hull", Japan Society of Naval Architects and Ocean Engineers, Vol 4. (in Japanese).

Katayama, T., Hayashita, S., Suzuki, K And Ikeda, Y., 2002, "Development of Resistance Test for High-Speed Planing Craft using Very Small Model -Scale Effects On Drag Force", AP Hydro 2002, pp.7-14.

Katayama, T., Iida, T. and Ikeda, Y., 2006, "Effects of Change in Running Attitude on Turning Diameter of Planing Craft", Proceedings, 2nd Pan Asian Association of Maritime Engineering Societies, Korea

Katayama, T. and Ikeda, Y., 2005c, "Development of Experimental Performance-Estimation-Methods for High-Speed Planing Hulls", 5th international forum on aluminium ships, Tokyo, Japan, pp 55-60.

Katayama, T., Ikeda, Y. and Okumura, H., 2000, "A Study on Unstable Motions of a Planing Craft in Maneuvering - Large Amplitude Motion due to Periodic Maneuvering Motion", Journal of the Society of Naval Architects of Japan, Japan, Vol.188, pp 155-162, (in Japanese).

Katayama, T., Kimoto, R., Iida, T. and Ikeda, Y., 2005a, "Effects of Running Attitude on

Hydrodynamic Forces for Oblique Towed Planing Craft", Journal of the Kansai Society of Naval Architects, Japan, Vol. 243, pp 15-22 (in Japanese).

Katayama, T., Kimoto, R. and Ikeda, Y. 2005b, "Effects of Running Attitude on Manoeuvring Hydrodynamic Forces for Planing Craft", FAST2005, St. Petersburg, Russia.

Katayama, T., Kotaki, M. and Ikeda, Y., 2007a, "A Study on the Characteristics of Roll Damping of Multi-Hull Vessels", 9th International Ship Stability Workshop, Hamburg, Germany.

Katayama, T., Kaneko, T. and Hori, Y. 2007b, Development of Estimation Method of Running Performance for Planing Craft with Outboard Engine, Journal of the Japan Society of Naval Architects and Ocean Engineers, Vol. 5, pp. 195-203.

Katayama, T., Taniguchi, T., Fujii, H. and Ikeda, Y., 2009, "Development of Manoeuvring Simulation Method for High-Speed Craft using Hydrodynamic Forces obtained from Model Tests", FAST2009, Athens, Greece.

Katayama, T., Taniguchi, Y. and Kotaki, M., 2008, "A Study on Viscous Effects of Roll Damping of a High-Speed Catamaran and a High-Speed Trimaran", 6th Osaka colloquium on seakeeping and stability of ships, Japan, pp.281-286

Katayama, T., Teshima, A., and Ikeda, Y. 2001, "A Study on Transverse Porpoising of a Planing Craft in Drifting Motion (1st report) – Measurements of motions and mechanism of occurrence –", Journal of the Kansai Society of Naval Architects, Japan, (KSNAJ), No. 236, pp 181-190 (in Japanese).

Katayama, T., Teshima, A., and Ikeda, Y. 2002, "A study on transverse porpoising of a planing craft in drifting motion (2nd report) – Simulation method of transverse Porpoising –", Journal of the Kansai Society of Naval Architects, Japan, (KSNAJ), No. 237, pp 149-154 (in Japanese).

Kerwin, J. E., 2006, "Hydrodynamic Issues in Waterjet Design and Analysis"; 26th Symposium on Naval Hydrodynamics, Rome, Italy.

Kim, M. and Chun, H., 2007, "Experimental Investigation into the Performance of the Axial-Flow-Type Waterjet According to the Variation of Impeller Tip Clearance", Ocean Engineering, Vol. 34, Issue 2, pp 275-283.

Kimoto, R., Katayama T. and Ikeda, Y., 2004, "Effects of Running Attitude on Hydrodynamic Forces for Oblique Towed Planing Craft", 2nd Asia-Pacific Workshop on Marine Hydrodynamics, Korea.

Kimoto, R., Katayama, T., Iida, T. and Ikeda, Y., 2006, "Effects of Change in Running Attitude on Turning Motion of Planing Craft", Proceedings, The Japan Society of Naval Architects and Ocean Engineers, Vol. 2W, (in Japanese).

Kivimaa, S. and Rantanen, A., 2007, "Development of an Integrated Monitoring System and Monitoring of Global Hull Loadings on High Speed Mono-Hull", FAST2007, Shanghai, China, pp 566-573.

Koushan, K., 2006a, "Dynamics of Ventilated Propeller Blade Loading on Thrusters"; WMTC2006, London, UK.

Koushan, K., 2006b, "Dynamics of Ventilated Propeller Blade Loading on Thrusters due to Forced Sinusoidal Heave Motion", 26th Symposium on Naval Hydrodynamics, Rome, Italy.

Koushan, K. and Spence, S.J.B., 2009, "Experimental Investigation of the Effect of Waves and Ventilation on Thruster Loadings", SMP'09, Trondheim, Norway.

Koushan, K., Spence, S.J.B. and Savio, L., 2011, "Ventilated Propeller Blade Loadings and Spindle Moment of a Thruster in Calm Water and Waves", SMP'11, Hamburg, Germany.

Kowalyshyn, D. and Metcalf, B., 2006, "A USCG Systematic Series of High Speed Planing Hulls",Trans SNAME,pp.268-309.

Kumar. M., Subramanian, V.A. and Singh, S.P., 2008, "Performance Prediction and Computaion of Slamming Loads on a Planing Craft Using RANSE Method", HSMV 2008, Naples, Italy.

Lavis, D.R., Forstell, B.G. and Purnell, J.G., 2007, "Compact Waterjets for High-Speed Ships", Journal of Ships and Offshore Structures, Vol. 2, Issue 2, pp 115-125.

Lavroff, J., Davis, M.R., Holloway, D.S. and Thomas, G., 2007 "The Whipping Vibratory Response of a Hydroelastic Segmented Catamaran Model", FAST 07, Shanghai, China, pp 600-607.

Lavroff, J., Davis, M.R., Holloway, D.S. and Thomas, G., 2009 "The Vibratory Response of High-Speed Catamarans to Slamming Investigated by Hydroelastic Segmented Model Experiments", Intl Journal of Maritime Engineering, Vol 151, Part A4, pp. 1-12.

Lawther, A. and Griffin, M.J., 1988, "Motion Sickness and Motion Characteristics of Vessels at Sea", Ergonomics, Vol. 31 No. 10, pp 1373-1394.

Li, Y.B., Chen, K. and Huang, D.B,. 2005, "Viscous Resistance Calculation for a Trimaran and the Comparison Between Different Calculation Methods", Journal of Hydrodynamics, Ser. A, Vol. 20, No. 4.

Li, Y. and Lu, X.P., 2007, "An Investigation on the Resistance of High Speed Trimarans", Journal of Ship Mechanics,Vol. 11, No. 2 , pp. 191-198

Li, G. and Ye, H., 2005, "Wave Making Computation in Time Domain for Multi-Hull Ships", FAST2005, St-Petersburg, Russia.

Lin, J., Shi L., You G. and Qian, J., 2007a, "The Method for Evaluating the Design Wave Loads on SWATH Ships", Proceedings, FAST2007, Shanghai, China, pp 589-594.

Lin, W-M., Collette, M., Lavis, D., Jessup, S. and Kuhn, J., 2007b, "Recent Hydrodynamic Tool Development and Validation for Motions and Slam Loads on Ocean-Going High-Speed Vessels", Proceedings, PRADS07, Houston, USA.

Lindau, J. W., Moody, W. L., Kinzel, M. P., Dreyer, J. J., Kunz, R. F. and Paterson, E. G., 2009, "Computation of Cavitating Flow through Marine Propulsor" Proceedings, SMP'09,Trondheim, Norway.

Liu, C., Wang, Y. and Zhang, Z., 2008, "Numerical Simulation and Analysis of Cavitation Performance of Waterjet", International Conference on Waterjet Propulsion V, London, UK.

Luth, H.R, Bos, J.E. Keuning, J.A. and van der Hout, I.E., 2009, "The Relation Between Motions of Moored Ships due to Wake Wash of Passing Vessels and the Hindrance Thereof", HSMV 2011, Fremantle, Australia, pp. 1- 7.

Macfarlane, G.J., 2009, "Correlation of Prototype and Model-Scale Wave Wake Characteristics of a Catamaran", Marine Technology, Vol. 46, No. 1, pp. 1-15.

Mantouvalos, A., Atlar, M. and Sampson, R, 2009, "Development of the First Systematic Deep-V Hullform Series for Displacement Type High-Speed Catamarans (DVC Series), FAST2009, Athens, Greece.

Mavluidov, M.A., Rousetsky, A.A., and Yakovleva, O.Y., 2005, "Waterjet Research and Optimisation Methods and New Propulsor Developments", FAST2005, St-Petersburg, Russia.

McMorris, T., Myers, S. and Dobbins, T., 2009, "Seating Type and Cognitive Performance After 3 Hours Travel by High-Speed Boat in Sea States 2-3", Aviation, Space and Environmental Medicine, Vol. 80 No. 1, pp 24-28.

Min, K-S., Chang, B-J. and Seo, H-W. 2009, Study on the Contra-Rotating Propeller System Design and Full-Scale Performance Prediction Method, Intl. Journal of Naval Arch. and Ocean Eng., *SNAK*, Vol. 1, pp. 29-38.

Misirlis, K., Sampson, R., Mantouvalos, A. and Atlar, M., 2009, "Hydrodynamic Drag Reduction for an Asymmetric Catamaran", FAST2009, Athens, Greece.

Mizine, I., Karafiath, G., Queutey P. and Visonneau, M., 2009, "Interference Phenomenon in Design of Trimaran Ship", FAST2009, Athens, Greece.

Mizine, I., Thorpe, R. and Deschamps, L. (2010), A Trimaran Trailership for American's Marine Highways Express Service: Design and Design Tools Considerations, PRADS 2010, Rio de Janeiro, Brazil.

Molland, A.F. and Barbeau, T.-E. (2003), "An Investigation into the Aerodynamic Drag on the Superstructures of Fast Catamarans", Intl Journal of Maritime Engineering, Vol. 145, pp. 29-39.

Molland, A.F., Wellicome, J.F., Temarel, P., Cic, J. and Taunton, D.J, 2001, "Experimental Investigation of the Seakeeping Characteristics of Fast Displacement Catamarans in Head and Oblique Seas", Trans. RINA, Vol. 143, pp 79-98.

Morch, H. J. B. and Hermundstad, O.A., 2005, "Planing Craft in Waves – Full Scale Measurements", FAST2005, St. Petersburg, Russia.

Morabito, M. and Snodgass, J. 2010, The use of Small Model Testing and Full-Scale Trials in the Design of Motor Yachts, 2nd Intl. Chesapeake Power Boat Symp., Annapolis, USA.

Muhammad, A.H. and Maimun, A., 2008, "Manoeuvring performance of a planing hull fitted with spray-strake", APHydro2008, Taipei.

Murrin, D.C. and Bose, N., 2006, "Waterjet Propulsion System Tested in a Wind Tunnel and Compared with Numerical Simulation", International Journal of Small Craft Technology, Vol. 148 Issue B2.

Nieuwenhuis, M. R. A., 2006, "The Ultimate Performance of Fast RIBs - An Experimental Investigation into the Influence of the Helmsman", International Journal of Small Craft Technology, Vol. 148, No. B2.

Nozawa, K. and Takayama, N, 2005, " A Research on Propulsive Performance of High-Speed Craft Equipped with Surface Piercing Propellers", FAST2005, St-Petersburg, Russia.

O'Hanlon, J.F. and McCauley, M.E., 1974, "Motion Sickness Incidence as a Function of the Frequency and Acceleration of Vertical Sinusoidal Motion", Aerospace Medicine.

Ogawa, Y., Oka, M. and Tozawa, S., 2007, "NonlinearWave Loads of a High Speed Vessel", Intl Conference on Violent Flows VF-2007, Japan pp 1-9.

Ogawa, Y.A., 2008, "Study on the Prediction Method of Wave Loads of a Multi-Hull Ship taking account of the Side Hull Arrangement", HIPER 08, Naples, Italy, pp 239-247.

Oger, G., Doring, M., Alessandrini, B. and Ferrant, P., "Two-dimensional SPH Simulations of Wedge Water Entries", Journal of Computational Physics, Vol. 213, 803-822.

Ohashi, K.., Hasegawa, J. and Fukasawa, R., 2008, "Numerical Simulation of High Speed Ship Wash Waves", HIPER08, Naples, Italy, pp. 291-300.

Oka, M., Ogawa, Y., Tozawa, S. and Oka, S., 2007, "A Study for the Assessment of Design Loads of a High Speed Vessel Taking Account of the Whipping Vibration", Proceedings, Intl Conference on Violent Flows VF-2007, Japan, pp 1-5.

Økland, O.D., 2002, "Theoretical and Experimental Analysis of Wetdeck Slamming", Ph.D. Thesis, NUST, Trondheim, Norway.

Orihara, H., Iida, T. and Yamasaki, K., 2007, "Evaluation of flows about a fast ship in manoeuvring motion using a CFD simulation method", Japan Society of Naval Architects and Ocean Engineers, Vol. 4.

Osborne, P.D., Côté, J.M., MacDonald, N. and de Waal, N., 2009, "Impact Studies and Criteria for High Speed Operations with Foil-Assisted Catamarans in a Wake Sensitive Area", FAST2009, Athens, Greece, pp 885-896.

Oura, T. and Ikeda, Y., 2007, "Manoeuvrability of a Wavepiercing High-Speed Catamaran at Low Speed in Strong Wind", Proceedings, 2nd International Conference on Marine Research and Transportation, Ischia, Naples, Italy.

Park, D.W., Kim, M.G., Chung, S.H. and Chung, U.K. 2007, Stern Flow Analysis and Design Practice for the Improvement of Self-propulsion Performance of Twin—skeg Ships, PRADS07, Houston, USA.

Parnell, K., Delpeche, N., Didenkulova, I., Dolphin, T., Erm, A., Kask, A., Kelpšaite, L., Kurennoy, D., Quak,E., Räämet, A., Soomere, T., Terentjeva, A., Torsvik, T., and Zaitseva-Pärnaste, I., 2008, "Far-field vessel wakes in Tallinn Bay", Estonian Journal of Engineering, Vol. 14, No. 4, pp. 273–302.

Peterson, R., Pierce, E., Price, B., Bass, C., 2004, "Shock Mitigation for the Human on High Speed Craft: Development of an Impact Injury Design Rule", RTO AVT Symposium on 'habitability of combat and transport vehicles: noise, vibration and motion', Prague, Czech Republic.

Pustoshny, A., Boiutsov, V.P., Lebedev, E.P., and Stroganov, A.A., 2007 "Development of 5-Blade SPP Series for Fast Speed Boat", FAST2007, Shanghai, China.

Radojcic, D. and Bowles, J. (2010), On High Speed Monohulls in Shallow Water, 2nd Intl. Chesapeake Power Boat Symp, Annapolis, USA.

Rhee, B. and Coleman, R., 2009, "Computation of Viscous Flow for the Joint High Speed Seal", SMP'09, Trondheim, Norway.

Robbins, A., Thomas, G., Renilson, M., Macfarlane, G. and Dand, I., 2009, "Vessel Transcritical Wave Wake, Divergent Wave Angle and Decay', Intl Journal of

Maritime Engineering, Vol. 151 No. A2, pp 25-38.

Rosén, A., Garme, K. and Kuttenkeuler, J., 2007, "Full-Scale Design Evaluation of the Visby Class Corvette", FAST2007, Shanghai, China, pp 583-588.

St. Pierre, J.C., Hackett, J.P., Bigler, C. and Quadvlieg, F.H.H.A. (2007), Controllability of High-Speed Craft, PRADS 2007, Houston, USA.

Salvesen, N., Tuck, E.O. and Faltinsen, O.M., 1970, "Ship Motions and Sea Loads", Transactions of the Society of Naval Architects and Marine Engineers, Vol. 78, No. 10, pp 250–287.

Savitsky, D., DeLorme, M.F. and Datla, R. 2007, "Inclusion of Whisker Spray Drag in Performance Prediction Method for High-Speed Planing Hulls", Marine Technology, Vol. 44, No. 1, January, pp. 35-56.

Scherer, J., Patil, S.K.R. and Morton S. 2010, "Use of Commercial CFD Codes to Enhance Performance Prediction Capabilities for Planing Boats", 2nd Intl. Chesapeake Power Boat Symp., Annapolis, USA.

Schleicher, D. M., 2006, "Regarding Statistical Relationships for Vertical Accelerations of Planing Monohulls in Head Seas", Proceedings, RINA Conf. ACV's, WIG's & Hydrofoils, London, U.K.

Schroeder, S., Kim, S. and Jasak, H., 2009, "Toward Predicting Performance of an Axial Flow Waterjet Including the Effects of Cavitation and Thrust Breakdown", Proceedings, SMP'09,Trondheim, Norway.

Sclavounos, P.D., Purvin, S., Ulusoy, T. and Kim, S., 2003, "Simulation Based Resistance and Seakeeping Performance of High-Speed Monohull and Multihull Vessels Equipped with Motion Control Lifting Appendages", FAST2003, Ischia, Italy, Vol, 1, pp 51-66.

Shahraki, J.R., Penesis, I., Thomas, G., Davis, M.R. and Whelan, J.R., 2011, "Prediction of Slamming Behaviour of Monohull and Multihull Forms using Smoothed Particle Hydrodynamics", HSMV, Naples, Italy.

Shan, M. and Wenyang, D., 2009, "A Time Domain Simulation Method for Nonlinear Motion and Wave Loads of Fast Ships", International Shipbuilding Progress, Vol. 56, pp 59–93.

Sikora, J.P. and Klontz, N.B., 2005, "Seaway Load Prediction Algorithms for High Speed Hull Forms", Trans. SNAME, pp.501-510.

Soomere, T., Parnell, K., and Didenkulova, I., 2009, "The Implications of Frequent High-Speed Ferry Wakes, Tallinn Bay, Estonia", FAST2009, Athens, Greece, pp 923-934.

Steden, M., Hundemer, J. and Moustafa A., (2009) "Optimisation of a Linearjet", SMP'09, Trondheim, Norway.

Stenius, I., Rosén, A. and Kuttenkeuler, J., 2006, "Explicit FE-Modelling of Fluid–Structure Interaction in Hull–Water Impacts", International Shipbuilding Progress, Vol. 53, pp 103-121.

Stenius, I., Rosén, A. and Kuttenkeuler, J., 2006, "Explicit FE-Modelling of Hydroelasticity in Panel-Water Impacts", International Shipbuilding Progress, Vol. 54, pp111–127.

Sun, C., Wang, Y. and Li, Z., 2008, "Research on Hydrodynamic Performance of Hybrid Propulsion System", Intl Conference on Waterjet Propulsion V, London, UK.

Sun, H. and Kinnas, S. A., 2008, "Performance Prediction of Cavitating Water-Jet Propulsors Using a Viscous-Inviscid interactive method", Trans SNAME, Vol. 116.

Sutulo, S. and Soares, C.G., 2004, "Synthesis of experimental designs of maneuvering captive-model tests with a large number of factors", Journal of Marine Science and Technology, Vol. 9, pp. 32-42.

Sutulo, S. and Soares, C.G., 2005, "Simulation of a fast catamaran's manoeuvring motion based on a 6DOF regression model", FAST2005, St. Petersburg, Russia.

Sverchkov A., 2005, "Prospects of Artificial Cavities in Resistance Reduction for Planing Catamarans with Asymmetric Demihulls", FAST2005, St-Petersburg, Russia.

Takaki, M., Lin, X., Gu, X. and Mori, H., 1995, "Theoretical Prediction of Seakeeping Qualities of High Speed Vessels", FAST1995, Lubeck-Travemunde, Germany, Vol. 2, pp 893-904.

Taunton, D. J. and Hudson, D.A., 2009," Design of High Performance Craft from a Human Factors Perspective", Proceedings, IMDC 2009. Trondheim, Norway, Vol. 2 pp 1010-1021.

Taunton, D.J., Hudson, D.A. and Shenoi, R.A., 2011, "Characteristics of a Series of High Speed Hard Chine Planing Hulls - Part II: Performance in Waves". International Journal of Small Craft Technology, Vol. 153, pp B1-B22.

Thomas, G., Davis, M., Holloway, D. and Roberts, T., 2005, "The Influence of Slamming And Whipping On The Fatigue Life Of A High-Speed Catamaran", FAST 2005, St Petersburg, Russia.

Thomas, G., Davis, M., Holloway, D. and Roberts, T., 2008, "The Vibratory Damping of Large High-Speed Catamarans", Marine Structures, Vol. 21, No. 1, pp 1 – 21.

Thomas, G., Davis, M., Holloway, D., Roberts, T., Matsubara, S., Lavroff, J., Amin, W., Chamberlin, K. and Dove, T., 2009, "Characterisation of Slam Events of a High-Speed Catamaran in Irregular Waves", FAST 2009, Athens, Greece.

Thomas, G., Lilienthal, T., Magnuson, T., Davis, M., Holloway, D., Doctors, L.J. and Couser, P., 2009, Motions of Catamarans in Oblique Seas at Speed, Intl Journal of Maritime Engineering, Vol. 151, No. A2, pp 77-88.

Tiao, W. C., 2010, "Practical Approach to Investigate the Statistics of Nonlinear Pressure on a High-Speed Ship by using the Volterra Model", Ocean Engineering, Vol. 37 No. 8, pp 847-857.

Townsend, N. C., Wilson, P.A. and Austen, S., 2009, "Sea-Keeping Characteristics of a Model RIB", Intl Journal of Maritime Engineering, Vol. 151 No. A1, pp 35-44.

Tsai, J., Tse, C., Wang, S., and Yeh, D., 2005, "Experimental Study on the Hydrodynamic Performance of a Two Phase Nozzle for Waterjet Propulsion System", FAST2005, St-Petersburg Russia.

Turan, O., Ganguly, A., Aksu, S. and Verveniotis, 2003, "Human Comfort and Motion Sickness Onboard High Speed Crafts", FAST2003, Ischia, Italy, Vol. 2, pp 51-58.

Umeda, N., Araki, M. and Hashimoto, H. 2008, "Dynamic Behaviours of a Trimaran in Astern Seas", Proceedings, The Japan Society of Naval Architects and Ocean Engineers, Vol.6 (in Japanese).

Veen, D.J. and Gourlay, T.P., 2009, "An Investigation of Slam Events in Two Dimensions using Smoothed Particle

Hydrodynamics", FAST2009, Athens, Greece.

Viviani, M., Brizzolara, S. and Savio, L., 2009, "Evaluation of slamming loads using smoothed particle hydrodynamics and Reynolds-averaged Navier-Stokes methods", IMechE Part M: Journal of Engineering for the Maritime Environment, Vol. 223, No. 1, pp 17-32.

Wang, Y., Ding, J., Liu, Z. and Xu, W., 2008, "Simulation of Dynamic Characteristics Waterjet and its Application on Troubleshooting", Intl Conference on Waterjet Propulsion V, London, UK.

Wang, Z., Lu, X.P. and Fu, P., 2009, "Research on the Effect of the Side Hull Position on the Wave Making Resistance Characteristics of the Trimaran", Shipbuilding of China,Vol. 15, No. 2

Wilson, M.B., 2008, "Scaling of Waterjet Propulsor Inlet Wakes", Intl Conference on Waterjet Propulsion V, London, UK.

Wilson, M.B., Gowing, S. and Lin, C.W., 2007, "Performance of a Stern Flap with Waterjet Propulsion", FAST2007, Shanghai, China.

Wu, M.K. and Moan, T., 2006, "Numerical Prediction of Wave-Induced Long-Term Extreme Load Effects in a Flexible High-Speed Pentamaran", Journal of Marine Science and Technology, Vol. 11, No.1, pp 39-51.

Wu, Y.S., Ni, Q.J., Xie, W., Zhou, S.Y., You, G.H., Tian, C., Zhang, Y. and Wu, Q., 2008, "Hydrodynamic Performance and Structural Design of a SWATH Ship", Journal of Ship Mechanics, Vol. 49, No. 03, pp. 388-400.

Yang, Q., Wang, Y., Zhang, Z. and Zhang, M., 2008, "Research on the Optimum Blades Number of Mixed Flow Pump Based on CFD", Intl Conference on Waterjet Propulsion V, London, UK.

Yasukawa, H., Hirata, N. and Kose, K., 2005, "Influence of Outrigger Position on the Performance of a Highspeed Trimaran (2nd Report Wave-induced Motions in Head Seas", Journal of Society of Naval Architects of Japan, Vol. 2, pp 189-195.

Yasukawa, H., Hiritaka, N. and Kose, K., 2005a, "Influence of Outrigger Position on the Performances of a High Speed Trimaran (3rd report: Manoeuvrability)", Japan Society of Naval Architects and Ocean Engineers, Vol. 2, pp 197-203 (in Japanese).

Yasukawa, H., Hiritaka, N. and Kose, K., 2005b, "Improvements of Course-Keeping Ability of a High Speed Mono-Hull by Skegs", Japan Society of Naval Architects and Ocean Engineers, Vol. 3, pp 125-132 (in Japanese).

Young, Y.L. and Kinnas, S.P., 2004, "Performance Prediction of Surface-Piercing Propellers", Journal of Ship Research, Vol.28 Issue 4, pp 288-304.

Zangeneh, M., Daneshkhah, K. and DaCosta, B., 2008, "A Multi-Objective Automatic Optimization Strategy for design of Waterjet Pumps", Intl Conference on Waterjet Propulsion V London, UK.

Zarnick, E.E., 1978, "A Non-Linear Mathematical Model of Motions of a Planing Boat in Regular Waves, Technical Report DTNSRDC-78/032, David Taylor Naval Ship Research and Development Center, Bethesda, USA.

Zhang, Z.H. and Gu, J.N., 2006, "Research on Wave and Pressure Field Caused by Ship Moving at High Speed in Shallow Water" Journal of Ship Mechanics, Vol. 10, No. 2, pp. 15-22.