The Manoeuvring Committee

Final Report and Recommendations to the 25th ITTC

1. INTRODUCTION

1.1 Membership

The 25th ITTC Manoeuvring Committee consisted of:

- Dr. Andrés Cura Hochbaum (Chairman).
  Hamburg Ship Model Basin, Germany.
- Prof. Frederick Stern (Secretary).
  University of Iowa, USA.
- Mr. Kristian Agdrup.
  FORCE Technology, Denmark.
- Dr. Riccardo Broglia.
  INSEAN, Italy.
- Dr. Sun Young Kim.
  MOERI, Korea.
- Mr. Pierre Perdon.
  Bassin d'essais des carènes.
- Mr. Frans Quadvlieg.
  MARIN, The Netherlands.
- Prof. Hironori Yasukawa.
  Hiroshima University, Japan.
- Prof. Zao-Jian Zou.
  Shanghai Jiao Tong University, China.

1.2 Meetings

The committee met four times:

- INSEAN, Italy, January 2006
- Shanghai Jiao Tong University, China, October 2006
- Basin d'Essais des Carenes, France, April 2007
- MARIN, The Netherlands, January 2008

1.3 Tasks and Report Structure

The following lists the tasks given to the 25th Manoeuvring Committee (MC) together with explanation of how the tasks have been executed.

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

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

State-of-the-art reviews are given covering overview of manoeuvring prediction methods (Section 2); progress in systems (Section 3) and CFD (Section 4) based manoeuvring simulation methods; and new experimental techniques and extrapolation (Section 7).

2. Review ITTC recommended procedures 7.5-02-06-01, 7.5-02-06-02, 7.5-02-06-03 and 7.5-02-05-05.

   a) Determine if any changes are needed in the light of current practice.
   b) Identify the requirements for new procedures.
   c) Support the Specialist Committee on Uncertainty Analysis in reviewing the procedures handling uncertainty analysis.

3. Rewrite the sea trials procedure for manoeuvring 7.5-04-02-01 to make it more self-consistent.

   a) Give attention to: IMO requirements, new elements such as high-speed craft, podded propulsors (liaise with the Specialist Committee on Azimuthing Podded Propulsors) and new technologies such as improvements to GPS.
   b) Include the limiting environmental conditions for sea trials, and how to correct for non-optimum environmental conditions.

Section 10 reviews current status MC Quality Manual Procedures.

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

5. Help to organise the workshop on verification and validation of ship manoeuvring simulation methods. Assist the workshop organisers in the collection of data for validation of ship manoeuvring simulation methods and make this available to ITTC Members.

Section 5 provides an overview of the recent SIMMAN 2008 Workshop: Validation of Simulations & Benchmark Data.

6. Monitor developments in manoeuvring criteria at IMO and clarify their implications on ITTC.

Section 9 reviews current status standards and safety.

7. Give support to the Specialist Committee on Azimuthing Podded Propulsion on reviewing methods for the prediction of manoeuvring of ships with podded propulsion and in investigating manoeuvring criteria for them.

MC contacted Specialist Committee on Azimuthing Podded Propulsion, but found no support required at this time.

8. Continue to review the state of the art for prediction methods and possible criteria for slow speed manoeuvring in shallow and confined water.

Section 8 reviews current status shallow and confined waters and ship-ship interactions.

9. Investigate the developments on manoeuvring and course keeping in waves. Report on developments in this field, and on how these should be taken into account by the ITTC in the future.

Section 6 reviews current status manoeuvring and course keeping in waves.

Lastly, Sections 11 and 12 provide conclusions and recommendations, respectively, and references are listed at the end of the report.

2. OVERVIEW OF MANOEUVRING PREDICTION METHODS

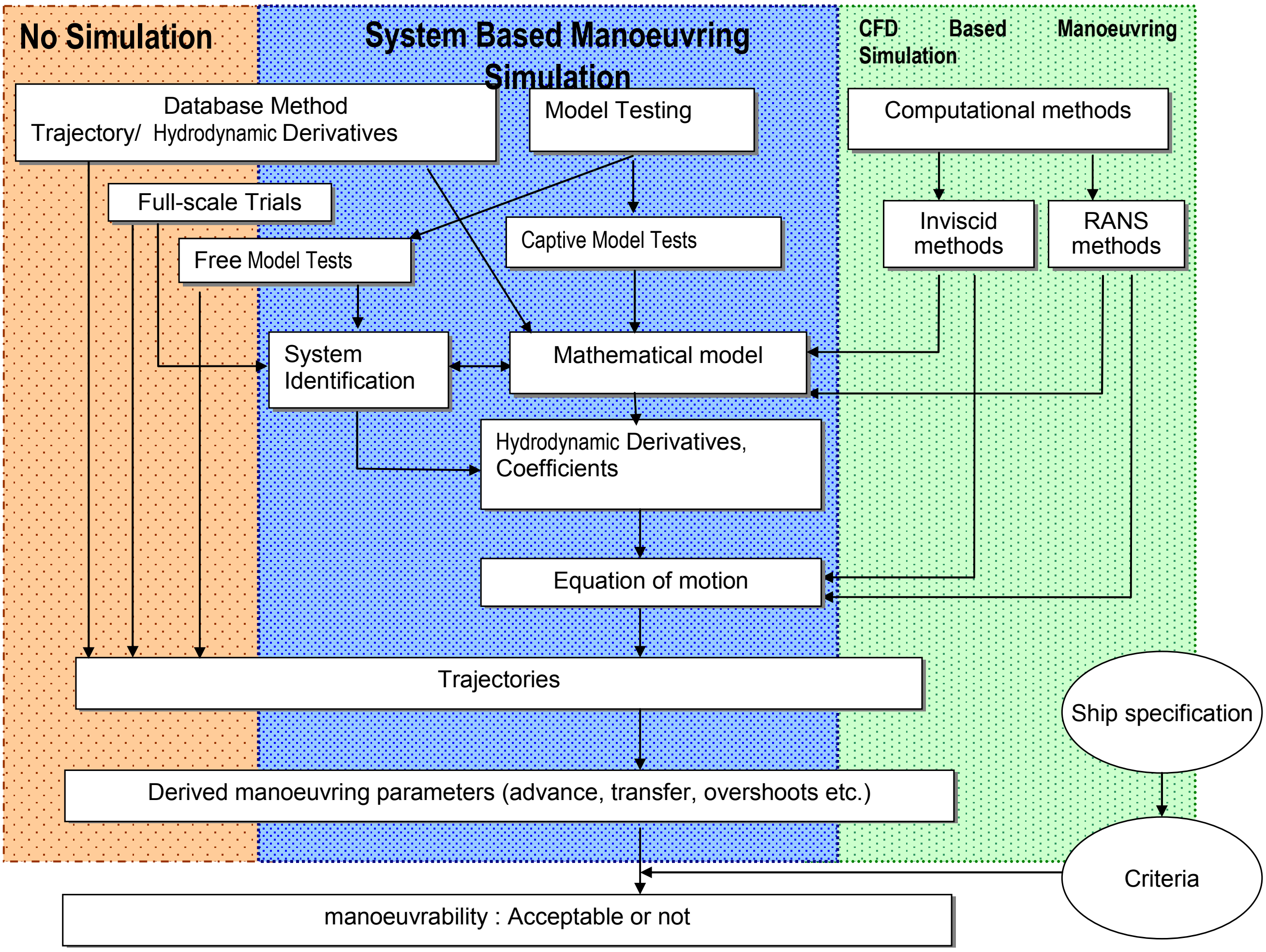


Figure 1 Overview of manoeuvring prediction methods

2.1 Introduction

The objective of this section is to give an overview of the state-of-the-art of the methods that are in use in practical applications for the prediction of the manoeuvring properties of ships and floating structures.

Opinions in this section are not proven by papers, but represent our general state-of-the-art opinion. This is supported by benchmarks evaluated by the SIMMAN 2008 workshop, co-organised by the ITTC Manoeuvring committee.

2.2 Overview of Methods

Figure 1 gives an overview of all different methods to come to manoeuvring predictions.

The ITTC MC observed a necessity to raise overview of methods as used within ITTC. Each method has merits in terms of accuracy and cost. The accuracy and cost of the methods will change during the years as technologies are advancing. This overview is based on the experience of the manoeuvring committee and insights obtained from the SIMMAN 2008 workshop. Giving an overview means that generalization takes place. Therefore one should be careful in generalising the statements in this section. There are variations possible with respect to ship type. In the workshop SIMMAN 2008, very important information is obtained on the required efforts and the relative accuracy of the methods (see Figure 2). The accuracy indicated in Figure 2 is not definitive, depending on the experience of each institute with a certain method and ship type. This section gives guidance to people that have to use these methods. Users have to know the risk of the use of a certain method and have to evaluate the possible accuracy against the cost (effort, time scheme).

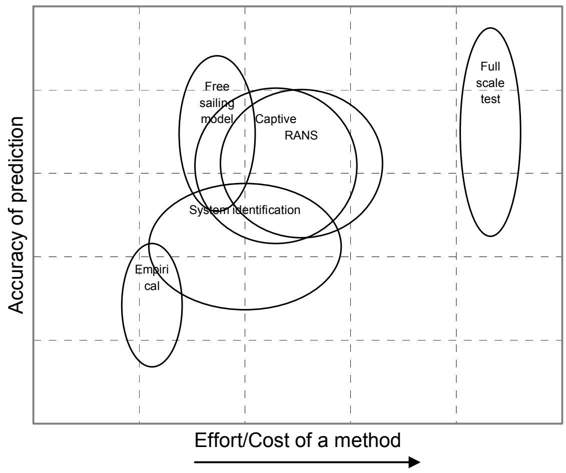


Figure 2 Effort/cost versus accuracy of manoeuvring prediction methods

The use of a certain method means that a risk is involved: the risk that a method is not giving entirely accurate results. Figure 3 illustrates that in general, a higher risk can be allowed only when the cost and effort of a method are significantly lower. This balance needs to be present.

Predictions Based on Free Model Tests. Free model tests are used to perform definitive manoeuvres where the ship's actuators act according to a pre-defined script, such as zig-zag or turning circles tests or where the actuators act according to autopilots, following a trajectory or dynamic tracking.

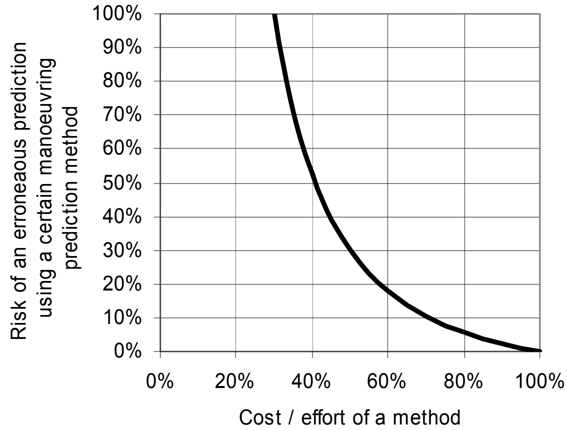


Figure 3 Risk on erroneous predictions versus cost and effort

In general manoeuvres using free model tests are believed to be as close as possible to reality. There are (apart from any possible scale effects) no assumptions made by hydrodynamicists, and as such, it is the most correct reflection of reality. Recent developments include the correct behaviour of engine controls during manoeuvres.

Advantages are:

- The closest reflection of reality.
- The answer to tests is directly available during the tests.
- Once tests are made, retesting with a slightly modified ship or rudder is very easy. As such these tests are very easy for decision making.
- Relatively low cost.
- In a basin (not in a lake) there is a strict control of environmental conditions (shallow water, wind, waves).

Disadvantages are:

- Require relatively large basin (or less desirable: a lake).
- Do not deliver physical insight in why a ship manoeuvres the way it does.
- Do not give direct information that allows creation of a mathematical model that can be used for (open loop) simulations. It gives however independent validation material for validation simulations.
- For simulating a ship in a certain environ-

ment (for example a harbour), channel walls etcetera should be modelled to scale as well. This requires typically more budget.

Predictions Based on Captive Model Tests, Followed by Simulations. As illustrated in Figure 1, a matrix of captive tests is carried out with a scale model of the ship. These tests are analysed to obtain so-called mathematical model and manoeuvring coefficients. Using this mathematical model, closed-loop simulations or man-in-the-loop simulations are made either in fast time or in real time. The captive tests may comprise PMM, CPMC, CMT/rotating arm or captive drift tests (and often a combination of them), and may include rudder force measurements. Often, a selection of free model tests is used to serve as validation case for the mathematical model.

In the SIMMAN 2008 workshop, an overview was given of the mathematical models that are in use at the moment. These are Abkowitz-type models, component-based models or tabular models. The component based models (such as the MMG-model) typically describe hull, propeller and rudder forces and their interaction coefficients. The hull model can be based on Abkowitz approximation (valid only within the tested range, such as Kijima's method) or full 4-quadrant approximations (with a supposedly wider range of application).

Advantages are:

- Tests can be done using a towing tank equipped with PMM or a basin with captive capabilities (rotating arm basin or CMT or CPMC).
- Is focussed on the creation of a mathematical model that can be used for (closed-loop or open-loop) simulation. When the model is covering a wide enough range of motions (such as rotation rates and drift angles), it can be used for trainings or researches using bridge simulations.

Disadvantages are:

- The answers regarding performance are not given directly. It requires post-processing before an answer can be given. As such, a re-test with an alternative configuration is not immediately possible.
- The quality of the mathematical model is directly related to the amount of tests in the test matrix (for example to quantify propeller-rudder-hull interaction), and hence to the cost. As such there is a large difference in approaches possible: higher cost, wider range of applicability versus lower cost and smaller range of applicability.
- Extrapolating, i.e. using the results of the mathematical model outside the tested range of drift angles and rotation rates, has to be done with great care.
- The performing of this technique requires experience with the methodology of performing tests, correction of measurements for inertial contributions, harmonic analysis of the results, selection of appropriate mathematical model, derivation of coefficients and finally simulation. Each of these steps has to be controlled.

Predictions Based on Empirical Methods. In Figure 1, it can be seen how these methods are used. Methods in this group use a dedicated mathematical model (usually modular) and manoeuvring coefficients. Usually, the manoeuvring coefficients will be based on either empiricism or a mix of empiricism and semi-theory/semi-empirical. Using this mathematical model, closed-loop simulations or man-in-the-loop simulations are made (fast time or real time). Known methods are the Kijima method (Kijima et al., 2003), the cross flow drag model (Hooft et al., 1996), or database methods (Petersen et al., 2000), or regression methods (Clarke, et al., 1982). Recently (Martinussen et al., 2008, Toxopeus et al., 2008), the slender body theory, is used together with the cross flow drag theory. Empirical methods are typically only applicable to ships which are similar to the ships that the method is based upon. Moreover, the accuracy is always restricted to the sensitivity of the parameters used in the regression. Recent investigations have indicated that flow straightening is an important matter and are dominating the accuracy of the outcome (Ishibashi, 2003).

Advantages are:

- Very quick to use and low cost.
- Allows easy reruns with alternative rudders.
- Depending on the type of mathematical model, it can be used apart from the known closed-loop simulations (prediction of zig-zag and turning circle tests) also for different manoeuvre simulations (closed-loop or open-loop simulations). When the model is wide enough, it can be used for trainings or researches using bridge simulations.

Disadvantages are:

- The accuracy and reliability of the answers is fairly limited.
- Often, these models do not take into account the hull form details, which often are important in the assessment of the manoeuvrability.
- The shallower the water, the less reliable these methods are.

Predictions Based on System Identification Methods. On a number of manoeuvres (trajectories), a mathematical procedure is released. This mathematical procedure optimises the hydrodynamic coefficients in a mathematical model in such a way that this mathematical model will reproduce the manoeuvres. This method works better as more and 'richer' tests are available for the system identification (rich means that a sufficient wide range of speeds, drift angles, rudder angles, rotation rates needs to be present in the manoeuvres). A well known method is HSVA's ISI method (Oltmann, 2000). There is a distinction to be made between a classical mathematical model and a neural network (Hess, 2008). The first one can contain restrictions to the mathematical model to include well-understood physical phenomena. Other methods are under (academic) investigation including fuzzy logic. Anecdotal evidence suggests good progress in the application to underwater vehicles.

Advantages are:

- After a first set of free model tests relatively low cost to generate more manoeuvres.
- Can be applied to model-scale and to full-scale manoeuvres.

Disadvantages are:

- The coefficients which are found do not have to be physically correct, but mathematically correct. This means that in principle no manoeuvres can be generated with ranges of rudder angles, drift angles and rotation rates which are outside the original data range. This implies for example that applying a SI technique based on one 10/10 zig-zag test will not give enough data to create a mathematical model for a zig-zag test at other rudder angles such as a 20/20 zig-zag test.
- The data used must be rich enough and should be clean (i.e. free from GPS-jumps as sometimes present in data from full-scale tests).

Predictions using Viscous Flow CFD. The different types of RANS are explained in Section 4. In Figure 1, it can be seen that there are two types of viscous flow CFD calculations used for manoeuvring predictions. The most used method is where RANS-calculations are used as replenishment for captive tests, and furthermore the same trajectory is used as described previously for these tests. A matrix of conditions is simulated. Results are analysed to obtain coefficients in a mathematical model, which in turn is used for simulations (e.g. Cura Hochbaum et al., 2008, and Toxopeus et al., 2008). A second type of RANS application uses actually full time domain simulation with a steered rudder with body force propeller (Carrica et al., 2008a) and actual rotating propeller (Carrica and Stern, 2008b) just like a free model test. Of this second type of simulations, only few applications have been performed till now.

Advantages are:

- It does not require the manufacturing of a physical model, but of a numerical model.
- It gives physical insight in why a ship manoeuvres the way it does, and even on top of captive tests, the RANS simulations can provide insight in the flow around a ship, which raises the understanding of manoeuvres even more.
- Although up to now most simulations are carried out on model scale Reynolds numbers, it is possible to carry out these simulations on full-scale (this occurs more and more). This would allow an understanding of possible scale effects.
- A demonstration is given that it is possible to achieve very good results (Cura Hochbaum et al., 2008; Carrica et al., 2008a).

Disadvantages are:

- At the moment, much experience needs to be gained to have a good knowledge about the settings of the RANS solvers: which grids and which turbulence models lead to converged results (RANS solvers are also empirical). This implies that there is a variety of answers possible depending on the operators of the code.
- A large amount of expertise and code development is needed to achieve results.
- Required computer resources can be prohibitive.

Predictions using Potential Flow CFD. Potential flow CFD is the name used for codes that are not RANS. In this category panel codes, vortex lattice and vortex blob codes are observed. Similar to RANS codes, a certain amount of empiricism is needed to know gridding and adjust certain settings to achieve reliable predictions. Potential flow CFD methods require less effort than RANS methods, but the reliability is significantly less. There are however certain niche areas in which these methods are working and producing efficiently good results. Manoeuvrability of high-speed vessels (Calix et al., 2007) is such an area. Also various aspects related to bank suction and ship/ship interaction can be calculated very well using potential flow methods (Varyani, 2004).

Hybrid Methods. Hybrid methods are using combinations of more than one method to be able to make predictions. One can think of captive tests for hull forces in combination with potential CFD for bank suction effects. Or RANS CFD for wind forces and hull forces combined with empirical relations for propulsors (Toxopeus, (2008)). The combination of these methods can provide for end-users a cost-efficient way in which the most critical issues are described using tests and the aspects, which are less critical but important to describe, are calculated using other calculations.

2.3 Dealing with Wind, Waves and Current and Constrained Water

A well-manoeuvring ship is required especially in critical circumstances: restricted waterways, in areas with many other vessels and cases where the environment becomes critical: high wind velocities, high waves and strong current.

The present state of the art in mathematical models is that wind is approached as a quasi-steady external force. It can be a function of a gusting wind velocity. In basins (model tests) this is usually modelled using wind fans and occasionally using winches applying constant tension forces.

Currents are either treated as a translation of the system of axes, which is applicable in deep water. In shallow water, this is not always the same.

In the case of laterally constraint waters such as banks, this is usually taken into account as a separate bank suction force and moment. These forces and moments are functions of speed and distance, but also of bank shape, ship shape and many others.

Vertically constraint waters have direct influence on many aspects of manoeuvrability. Therefore, dedicated investigations in shallow water are carried out in cases where this is important.

Waves are dealt with separately in this report in Section 6. For this overview, a couple of aspects can be distinguished: for low waves, waves can be treated as a separate mean and second order wave force. For higher waves, the vessel will react also in motions and the wave induced motions are also inducing manoeuvres. Effects related to course keeping in stern quartering waves are falling in this category. To describe these effects a fully 6 degrees of freedom model needs to be present.

2.4 Scaling

Scaling of all results (model tests, empirical methods based on model tests, or CFD results which are at some point calibrated with model tests) to full scale causes a risk.

At the same time, it is fair to include here that the results from full scale measurements are not always unquestionable due to reproducibility biases due to environmental conditions and inaccuracies in measuring equipment.

2.5 Concluding Remarks

The amount of methods for manoeuvring predictions has significantly grown over the last decades. This opens the possibility for the naval architect to compare and select from multiple methods. Each method has its advantages and disadvantages of which the consensus is written down in this section. The SIMMAN 2008 workshop provided very valuable insight in the applicability of these methods.

Despite all knowledge & experience it is difficult to quantify the relative accuracy of each method. Therefore the selection of the most appropriate method is difficult. The experience of the experts remains necessary.

3. PROGRESS IN SYSTEM BASED SIMULATIONS

This section describes progress on all methods, except CFD methods, which are described in Section 4.

3.1 Conventional Vessels

Papers and reports are presented on individual investigations for specific ships, such as training ships (Yasukawa (2004a and 2004b and 2005), tankers (Lee (2006b), Kang (2007)), container vessels (Eloot (2006a)), Sung (2005), Okano (2004). Especially the behaviour in shallow water is of increasing interest. This section is divided into the main streams of manoeuvring prediction methods as indicated in Figure 1, Section 2.

Free Model Test Methods. Usually, the free model test method is used to describe accurately the behaviour of a certain vessel. Levine (2006) reports how investigations are used to study the manoeuvring behaviour in disabled conditions of a tanker. Many of these investigations were conducted because specific insight needed to be obtained on the behaviour of ships in a certain environment. Gaillarde (2006), gives an overview for motor yachts.

This method is also used to describe the performance of special rudder types or unconventional propulsors (Hasegawa, 2006).

Empirical Calculations. Empirical methods are methods that are in general used to predict the manoeuvring properties for a specific ship type. A generalisation often has to take place in order to achieve this.

Aoki et al. (2006) proposed approximate formulae of the classical flow-straightening coefficient and the wake fraction factor at rudder position (w_R) obtained by comparing the predicted manoeuvring motion with the measured results of the sea trial for 20 full-scale ships. The formulae seem to be useful for simulating the ship manoeuvring motions at design stage, although this approach should be validated for many kinds of ships.

The results of the calculations are sometimes used as input for other studies, such as the engine loads or the cavitation behaviour of the propellers during manoeuvres (Schulten, 2004).

CFD Calculation Techniques. Toxopeus (2006b) and van Oers (2006) are using RANS-CFD as a means to increase the insight in the coefficients and use RANS to calculate the distribution of lateral forces over the hull of the ship. The ultimate purpose is to achieve an improved cross flow drag technique. Simonsen et al. (2006) made a similar comparison between CFD and the results of captive model tests.

Hybrid Methods. Hybrid methods are a combination of pure CFD and other calculation techniques. Toxopeus (2006b, 2007) describe how this method is used by determination of the bare hull forces from CFD and the propeller and rudder forces from empirical methods.

The research towards a twin screw container ship described by Kim et al. (2006) is in particular useful because due to the insights obtained by CFD, flow field measurements and PMM tests together, the insight in what is actually happening at the location of the propellers and rudders is increased.

Captive Tests and Mathematical Modelling. Eloot (2006b) reported extensively the experimental techniques necessary to carry out properly captive tests in shallow water. She uses non-conventional tests (i.e. tests using a CPMC which is not steered to achieve sinusoidal or circular trajectories, but any trajectories) to achieve a proper matrix of drift angles and rotation rates and rudder angles. In this way, the amount of information that can be obtained from one test has grown significantly. Also the fact that transient phenomena are measured in this way is certainly a very interesting approach to the ITTC community.

De Jong (2006) describes how a special 6-DOF oscillator is used to obtain coefficients for a combined seakeeping/manoeuvring model.

Sutulo et al. (2004) and Milanov (2007) describe also the challenges that arise when captive model tests are used for manoeuvring predictions. Sutulo et al. (2006) describes how with optimised captive test, a regression model can be generated.

The SIMMAN 2008 workshop has stressed the need for manoeuvring models in 4 degrees of freedom (DOF). Yasukawa et al. (2004a) carried out the captive model test using a ship model of the training ship "Hiroshima-Maru" to examine the effect of the ship's heel on the hydrodynamic force characteristics, particularly, rudder normal force, interaction parameters and so on as used in the MMG model. The experimental results showed that the heel effect on the normal force, hull rudder interaction coefficients (a_H, x'_H) and effective wake fraction in manoeuvring motions is small. Using the hydrodynamic force characteristic, Yasukawa et al. (2004b) carried out various manoeuvring simulations of the “Hiroshima-Maru”. The simulation results were compared with the full scale test results measured using GPS. The simulations can roughly capture the usual manoeuvring motions, such as turning motion and zig-zag manoeuvre. However, it was difficult to predict the turning trajectory within the accuracy of several meters, or the overshoot angle of zig-zag manoeuvre within the accuracy of several degrees.

That sometimes a 4 DOF model is not enough is demonstrated by Jurgens (2006b). For ships sailing in very shallow water, the squat becomes so significant that the hull forces and rudder forces are significantly influenced. This followed from full-scale measurements and was confirmed in PMM tests and subsequent simulations. It is hence proposed that for such vessels operating in shallow water a 6 DOF model needs to be used.

System Identification. The use of system identification is not as commonly spread as the other methods. There is however an increasing interest, certainly in academic circumstances on this subject. System identification can be applied on the measured trajectories of a model (or a real ship). The latter can then be used to calculate the mathematical model.

Published works in this field are from Selvam (2005), Bhattacharyya (2006), Ross (2006), Viviani (2007) and Hess (2008).

3.2 High Speed Vessels

High speed vessels are more complex to study than conventional vessels. This is mainly because the manoeuvring behaviour needs to be analysed in 6 degrees of freedom, not in 3 or 4 degrees of freedom.

Yasukawa et al. (2005) investigated the influence of outrigger position on the manoeuvrability of a high speed trimaran. The circular motion tests were conducted to capture the hydrodynamic force characteristics of the trimaran model with 3 different outrigger positions. The manoeuvring simulation based on the force characteristics showed that the turning circle becomes large and the course-keeping ability is improved with shifting the outrigger position rearward.

Hackett (2007) and Calix (2007) reported on a semi-planning HSV and a hybrid (foil supported monohull). For the foil-supported monohull, a vortex lattice method is used to estimate the manoeuvring forces on the ship (hull and foils). These forces are used in simulations. The results are compared to the results of PMM tests and of free model tests. The results show a remarkable good comparison between the foil theory and the experiments, indicating that these potential flow methods may be used for foil supported vessels. For foil supported craft, the control is of course a very important factor. Apart from the above papers, also Hatzakis (2006) is reporting on this.

Ueno (2006) reports on how the manoeuvring behaviour of a planning vessel is measured in full scale. Perez (2006) reports on a 4-DOF model for a fast patrol vessel based on a theoretical approach.

High speed vessels often have a tendency for directional instability due to the trends in hull form design. In the design of these vessels this is an important factor. Issues related to this are described by Yasukawa (2006a) and Umeda (2006). Yasukawa et al. (2006a) designed the skegs attached to the stern part of a high speed monohull with water jet propulsion system for improving the course-keeping ability, and carried out the circular motion tests for capturing the hydrodynamic force characteristics of the model with and without skegs. The manoeuvring simulation based on the force characteristics showed that the skegs are effective in the wide range from slow to high speed (near 40 knots) for improving the course-keeping ability, Figure 4.

That the rudders may generate different forces than for conventional ships is reported in a detailed manner by Jurgens (2005).

3.3 Other Vessels

In this subsection, some vessel types are considered which do not fall under earlier categories.

Tugs. Tugs obviously need to be very manoeuvrable. Apart from that, often the hull of these vessels is used to generate forces which assist during manoeuvres, as described by Quadvlieg (2006) for an ASD type tug. Agdrup (2006) reports similar work, for a VWT tug, with an extensive description of the way that a Voith Schneider propeller (VSP) is generating forces in kinematic mode.

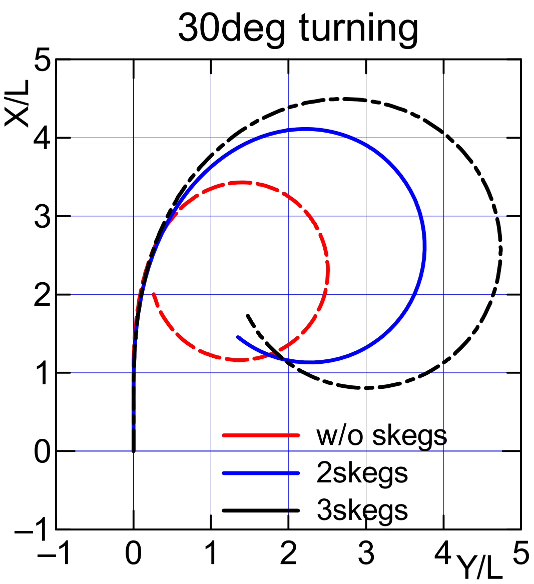


Figure 4 Effect of skeg on turning circle (Yasukawa)

Less Conventional Vessels. The manoeuvrability of ships with air-lubrication is discussed by Thill (2005). Results of captive (PMM) tests and free model tests are compared to each other and the effect of the air layer on hydrodynamic aspects including manoeu-vrability is discussed.

3.4 Towing and Pushing

Yasukawa et al. (2006b) presented a simulation method for the manoeuvring motion of a towed ship in still water. A 2D lumped mass method was employed for expressing the dynamics of the towing cable. The motion of a towing ship was assumed to be given. The results of the slewing motion frequency, changes of heading angle and yaw rate in time domain agreed well with the model test results as demonstrated in Figure 5.

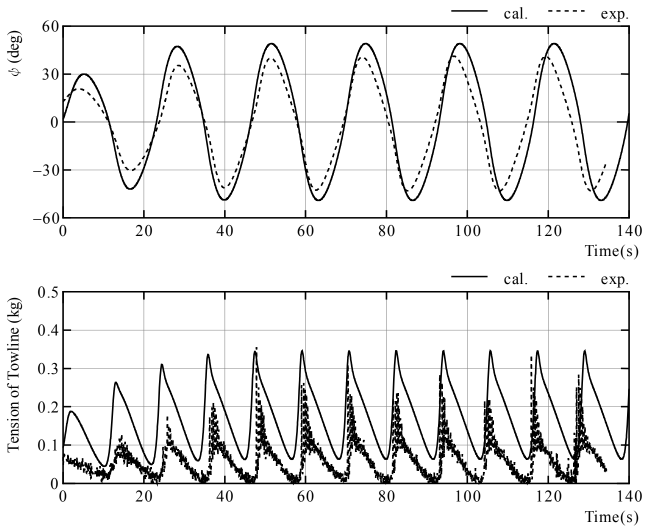


Figure 5 Motions of a towed ship (Yasukawa)

Yasukawa et al. (2007) studied pusher-barge systems in 9 different combinations. Hydrodynamic derivatives of the various pusher-barge combinations were captured through the model tests and compared with Inoue's formula for estimating linear hydrodynamic derivatives. It is found that Inoue's formula (1981) is insufficient in estimating N'_r for pusher-barge system because the ship's breadth is not taken into consideration.

Hara et al. (2004a) carried out a full-scale experiment towing a training vessel. A kinematic GPS system was used to measure the distance between the tug and the towed ship. Towline tension was also measured, and the relation between the tension and the measured distance was investigated. Hara et al. (2004b) developed the Optimum Towing Support System (OTSS), which is a computer simulation system to provide the information for the drift motion prediction, towline tension, manoeuvring motion and needed horse power in waves, wind and current for tow and towed ships. Kuroda et al. (2006) applied the OTSS to estimate the behaviour of tow and towed patrol vessels in calm and rough seas. The estimated results were compared with the full-scale towing test data.

Yang (2006) and Eda (2006) are further reporting to issues related to the towed stability of ships.

3.5 Environmental Conditions

For the ranking of the quality of a manoeuvring vessel, it is important that vessels can withstand the environmental circumstances they have to operate in. To judge those problems, use is made of simulations. Ye (2005) discussed the effect of wind and how escort tugs can assist. Hasegawa (2005) and Oura (2007) discussed respectively a car carrier and a high speed ferry. Both vessels have a considerable wind area and their steering tools have to be able to withstand these challenges.

3.6 Concluding Remarks

For conventional vessels the manoeuvring prediction methods seem well established for standard manoeuvres. Some developments are reported on the fine tuning of empirical models. The SIMMAN 2008 Workshop provided a first step on the relative performance of these methods and their validation.

For less conventional vessels other procedures are developed resulting in new types of manoeuvring prediction methods dedicated to these types of ships. However these mathematical models require further development and validation for more robust application.

Unfortunately, not much research is reported on scale effects for predictions which are based on model scale results.

Validation and documentation is needed for mathematical models used in ship-handling simulators, especially regarding non standard manoeuvres, e.g. at slow speed and in shallow waters.

4. PROGRESS IN CFD BASED MANOEUVRING SIMULATION METHODS

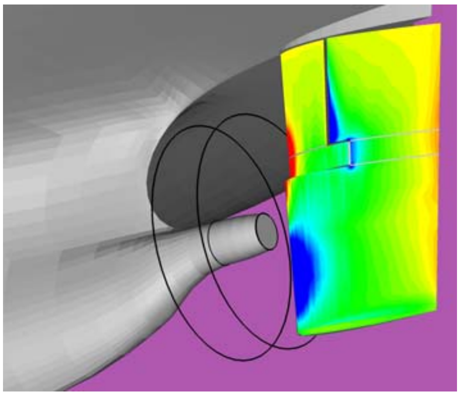
4.1 Introduction

Numerical methods have been applied for manoeuvring prediction since long time ago. Techniques based on the strip theory or on the panel method are still frequently used in practice and can yield useful information in the early design stage. Such methods are fast and can yield estimates of characteristic parameters like overshoot angles, tactical diameters, etc. However, these methods are based on potential flow theory and consider important effects for manoeuvring, e.g. sharp edges, straightening of the flow by hull and propeller slipstream and viscous effects in general, rather coarsely. As a consequence, they are inadequate for issues concerning yaw stability and often do not yield accurate quantitative predictions, e.g. for compliance of IMO recommendations.

RANS codes originally developed in the eighties were used to simulate the flow around a ship moving steadily straight ahead. Since the late nineties, these methods have been extended and adapted for handling more complicated cases like steady drift motion (static drift) and steady turning motion (static yaw). Since then, significant progress has taken place in the area of RANS methods for manoeuvring applications. This includes both the capability to simulate unsteady flows, as well as to enforce prescribed motions or to predict the ship motion in all relevant degrees of freedom during the simulation. Meanwhile it has even become possible to directly predict rudder manoeuvres like zig-zag and turning circle tests, including the turning propeller(s) and steering the rudder(s) in the course of the simulations.

To achieve these goals several improvements were necessary:

- Block-structured grids including non-matching interfaces widely replaced the single block grids, allowing for analysing real ship forms with appendages, Figure 6.



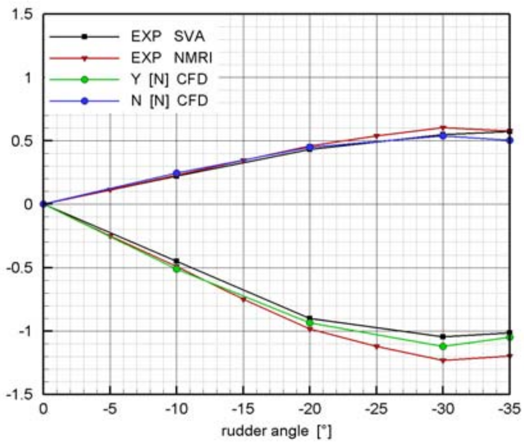


Figure 6 Virtual model of KCS with rudder deflected 10° (top) and comparison of predicted and measured side force and yaw moment due to rudder deflection.

- Moreover, modern codes can work with unstructured grids, sliding grids and/or even with dynamical overset grids where fixed or moving parts of the grid may overlap, see Figure 7. This offers maximum flexibility for complex cases, e.g. for considering a turning horn rudder, ship-ship interactions, etc.
- Local refinement strategies allow for saving computational time by increasing the grid resolution in those regions where required, e.g. at a free water surface varying it's shape and position in the grid during the simulation.

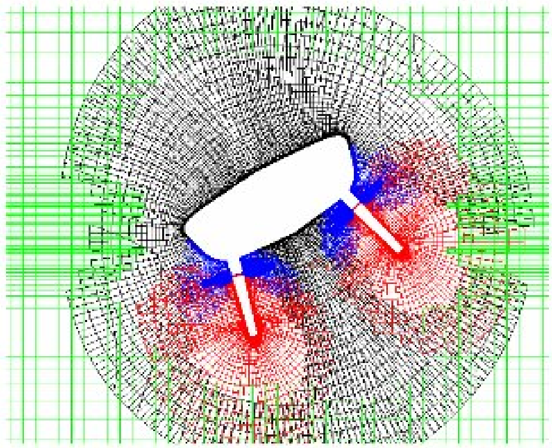


Figure 7 Overlapping grid system for rolling ship (from Noak (2007)).

- Turbulence models, mostly still two-equation models but also Reynolds-Stress models (RSM), Algebraic Stress models (ASM) and Detached Eddy Simulations (DES), have become more robust and have been improved for complicated flows with flow separation and vortex shedding.
- Interface capturing techniques, e.g. Volume of Fluid (VOF) or Level Set methods prevailed over tracking techniques, where the grid is fitted to the free surface in the course of the simulation, making complex simulations with breaking waves, water on deck and/or changing boundary topologies possible.
- Moving grids in an inertial coordinate frame or the inclusion of centrifugal forces, Coriolis forces, etc. together with continuous updating of the boundary conditions when working in a non-inertial coordinate frame allow for considering/predicting ship motions.
- Body Force models, which approximate the forces and moments acting on the propeller and yield as a function of time the force components of an equivalent force distribution in those grid cells inside of the region which replaces the propeller, make simulations more affordable.
- Control algorithms are needed for direct manoeuvring simulations. For IMO manoeuvres simple open-loop controllers suffice. Auto-pilots, speed controllers and

waypoint controllers require much more complex forms of closed-loop controllers to simulate realistic ship behaviour (Fossen 2002).

Methods mainly based on potential flow theory are covered in subsection 4.2 while those based on the simulation of the viscous flow around the ship are found in subsection 4.3. The latter have been split into methods for virtual PMM tests, which represent an intermediate step towards the direct prediction of ship manoeuvres, and methods for predicting manoeuvres. Concluding remarks about the progress in CFD methods are included in subsection 4.4.

4.2 Inviscid Methods

Inviscid methods for determining the hydrodynamic forces on a manoeuvring ship include small aspect ratio wing theory, slender body theory and 3D panel methods (Boundary Element Method). During last years, most efforts with regard to inviscid methods have been devoted to simulation and prediction of ship manoeuvring behaviours using CFD based 3-D panel method.

Roux et al. (2005) made an attempt to derive a full sailing boat model by coupling an aerodynamic solver with a hydrodynamic solver. The numerical approach for the hydrodynamic forces acting on the hull is based on Green functions fulfilling automatically a linearized free-surface condition.

Wang and Zou (2006) computed the linear sway and yaw damping coefficients of a modified Wigley ship by using a higher-order Rankine panel method based on Non-Uniform Rational B-Spline (NURBS). A 3D forward-speed radiation problem was formulated and solved in frequency domain to simulate PMM tests with small amplitudes. The computed linear hydrodynamic coefficients enable to evaluate the dynamic stability.

Varyani and Krishnankutty (2006) used slender body assumptions in conjunction with a singularity distribution technique to research the hydrodynamic interaction forces/moments acting on a moored ship due to the passage of another ship in its proximity by considering the influence of ship form against the idealized approach of the use of parabolic sectional area distribution.

Toxopeus (2006a) presented a validation of a slender body method for predicting linear manoeuvring coefficients for a state-of-the-art fast time simulation model by using the results of viscous flow calculations and experimental values.

Sclavounos et al. (2006) developed state-space optimal control methods which are coupled with the Rankine panel method SWAN for the stable steering of a ship advancing parallel to a vertical wall and the motion reduction of a catamaran vessel equipped with actively controlled bow and stern hydrofoils. The hydrodynamic suction force and yaw Munk moment that would cause the vessel to crash into the wall in the absence of rudder control are modelled by SWAN using potential flow theory and assuming a double-body flow free surface condition.

Hong (2007) used a three-dimensional panel method to compute the hydrodynamic forces and moments acting on undersea vehicles with non-body-of-revolution hull forms moving in deep water.

de Koning Gans et al. (2007) developed a 3-D panel method for predicting the interaction forces on passing ships sailing with drift angle. The method is based on a mixed source/dipole representation of the flow and a wake model is implemented which enables the lifting effects to be partly represented.

Chahine et al. (2007) developed a boundary element method code for numerical simulation of the hydrodynamic behaviour of multiple ships in harbours. Harbour boundary conditions including wave inlet and absorbing boundary, six degree of freedom rigid body motion for ships, self propulsion forces and viscous drag of the body are implemented. A fast multipole method and an improved grid scheme for complex free surface geometries are applied.

Zhang et al. (2007) performed a numerical simulation of multiple ships travelling in close proximity to each other at the same forward speed. The fully coupled 3-D body-wave hydrodynamics and rigid-body dynamics with consideration of external forces and constraints are solved using a special adaptation of the LAMP time domain potential-flow panel code.

4.3 RANS Methods

Papers which deal with the numerical solution of the RANS equations for predicting the flow field around the ship hull in prescribed steady and dynamic manoeuvres and for predicting manoeuvres are reviewed. Results from these simulations are used to investigate a wide range of features in the naval hydrodynamics context, e.g. for computing forces on the hull, to derive manoeuvring derivatives, or for performing detailed analyses of the manoeuvring characteristics of the hull, since the simulations provide an insight into the entire flow field during the manoeuvre.

Most reviewed papers have been presented at the last ONR symposium held in Rome in 2006 and at the 9th Numerical Ship Hydrodynamics Conference held in Ann Arbor, Michigan, and can be considered, together with contributions from the SIMMAN 2008, as the state of the art in this field.

Simulations of Captive Model Tests. Mulvihill and Yang (2007) presented numerical simulations of steady pure yaw manoeuvres of a submarine, showing the capabilities of the steady overlapping grid approach. Also Benson and Fureby (2007) presented some numerical simulations of a submarine in steady yaw manoeuvre. They employed an LES approach with a wall model and showed that the model is able to predict some peculiarities of the flow field such as unsteadiness, cross flow separation and presence of horseshoe vortices. Good agreement with experiments, in terms of skin friction coefficient along cross sections in steady yaw manoeuvre, is observed.

An example on how the prediction of forces and moments by means of CFD calculations can be used for deriving manoeuvring derivatives and how these can be used in a simulator can be seen in Toxopeus (2006b). Numerical simulations were carried out for steady drift, steady yaw and combined yaw/drift motions for different ship hulls. Based on the coefficients computed from the viscous flow calculations and from empirical formulae, the author developed a mathematical model for the lateral force and the yaw moment. The results agree better with experiments than the approximation provided purely by an empirical model.

Xing et al. (2007) performed numerical simulations of the DTMB 5415 and KVLCC2 in steady drift motion. Numerical tests were performed at 0, 12, 30 and 60 degrees of incidence. These tests were considered to analyse different turbulent models: an isotropic blended $\kappa-\varepsilon/\kappa-\omega$ model (BKW), a Reynolds Stress model (RSM). Steady and unsteady analyses of the flow were performed, the latter within a Detached Eddy Simulation (DES). With both turbulence models, BKW and RSM, the RANS simulations yielded a better prediction of resistance, axial velocity and turbulent kinetic energy distribution at the propeller plane than the DES. At higher drift angles, the DES approach allowed for capturing the unsteadiness of the flow field.

Similar work has also been performed by Bhushan et al. (2007) including simulations at model and full scale Reynolds number for the Athena R/V.

Simonsen et al. (2006) and Simonsen and Stern (2006) carried out an analysis of forces and vortex structures around the bare hull of the KVLCC2 tanker during steady drift motion in deep and shallow water. They showed shallow water effects on the hull pressure which leads to a significant increase of the hydrodynamic forces and moments for both straight-ahead and static drift motion. The pronounced blockage effects observed in shallow water could explain the scatter in experimental data observed in the previous Manoeuvring Committee report.

Hyman et al. (2006) performed simulations for steady straight ahead and steady turn manoeuvres of a fully appended model of the R/V Athena taking into account the transport of bubbles due to air entrainment at the free surface. Simulations were carried out with CFDSHIP-IOWA using a two phase level set algorithm coupled with a gas phase solver called CFDShipM. Propeller effects were taken into account by a non-interactive body force model. Results from unsteady RANS simulation and Detached Eddy Simulation (DES) show that the method is able to predict the bubbly flow around the vessel. However, some input parameters such as a bubble size distribution and bubble source intensity at the entrainment location have to be specified.

In Broglia et al. (2006), simulations of the KVLCC2 model in pure sway motion have been considered. Numerical simulations of pure sway motions with different amplitudes were carried out in order to analyze blockage effects during PMM tests. The analysis was conducted for three virtual basins with different widths. Since the sides of the basin were included in the computations, the dynamic overlapping grid algorithm was crucial for performing the computations effectively. Blockage effects were found to be relevant only for the narrow basin with a width of $3.55B$, where differences in amplitude and phase of the forces and moment were observed when compared to the unbounded basin.

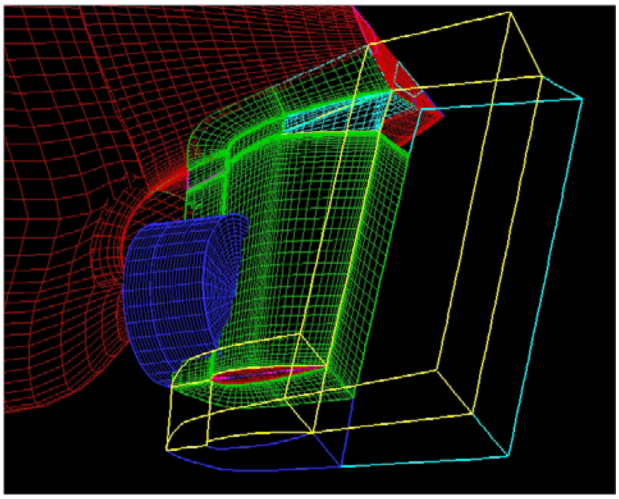


Figure 8 Overlapping grid around the KVLCC2 hull, detail of the rudder region.

Di Mascio et al. (2007), carried out a detailed analysis of the flow field around the KVLCC2 during a pure sway test in fully appended configuration. Overlapping grids were used for the discretisation of such a complex geometry; the grid around the rudder is shown in Figure 8. The results show the capabilities of the CFD based simulation for the detailed analysis of the flow field. In Figure 9 the axial velocity contours in a cross section just behind the rudder are shown.

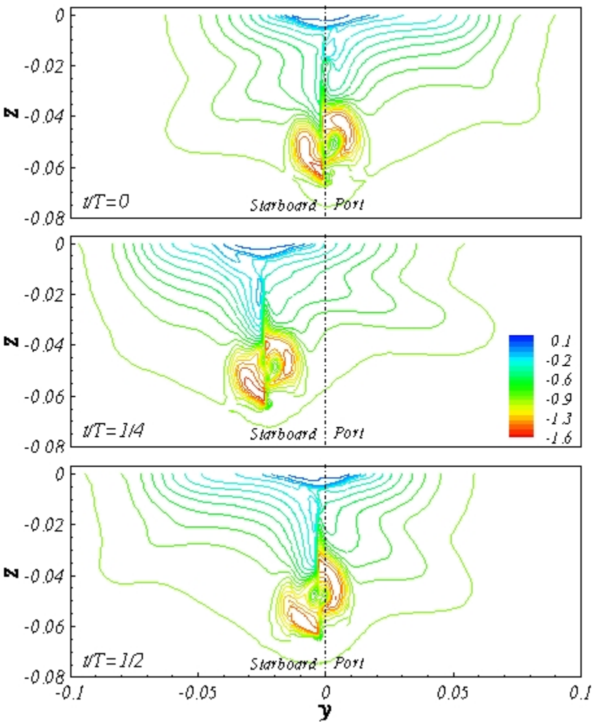


Figure 9 Axial velocity field on a cross plane behind the rudder during a pure sway test.

Queutey and Visonneau (2007) presented and applied an interface capturing method for simulating the flow around the Series 60 model in steady straight ahead and pure drift motion. The results show good agreement with experimental data.

The use of an unstructured solver for the computation of forces on a surface piercing hull with enforced PMM motion can be seen in Wilson et al. (2007) where simulations of dynamic manoeuvres of a surface combatant are presented. Pure sway and pure yaw tests are analysed, results show good agreement with experimental data in terms of both global quantities (forces and moments) and local quantities (velocity components on different cross sections with PIV measurements).

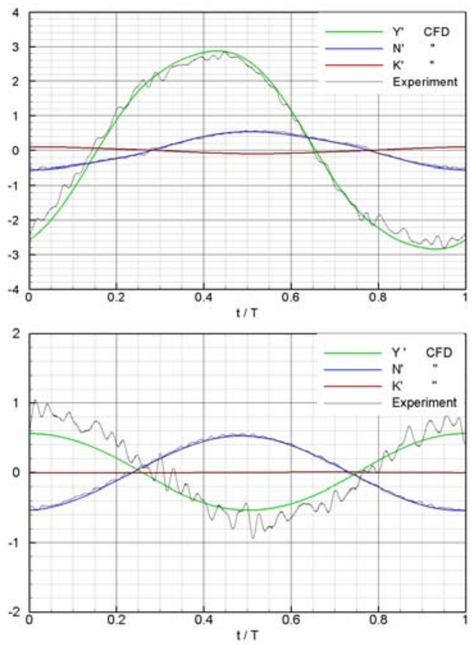


Figure 10 Predicted and measured time histories of side force, yaw and roll moment during pure sway (top) and pure yaw motion.

Cura-Hochbaum (2006) performed simulations of the flow around the model of a twin screw ferry during forced motions like those carried out during a captive model test campaign. Simulations of pure surge, pure sway, pure yaw, combined sway-yaw, as well as static rudder tests were performed, neglecting free surface effects. Dynamic tests were simulated on very coarse grids, while refined grids were used for the static rudder tests. Time histories of the forces and moments agree well with experimental data collected at HSVA, see Figure 10. Disagreements were observed in the prediction of the longitudinal force in the pure surge test and in the side force and yaw moment for large rudder angles. Manoeuvring derivatives obtained from the time histories of computed forces and moments were used to simulate zig-zag, turning circle and spiral tests. Results were compared with free model tests. The agreement is in general very satisfactory.

In Carrica et al. (2006) the capability of the CFDShip-IOWA version 4 in dealing with various problems of the marine hydrodynamics, including the prediction of motion in waves are presented. Dynamic overlapping grids as described in Carrica et al. (2007) were used. Examples are presented for the steady drift motion of the DTMB 5512 model and the KVLCC2 model in deep and shallow water. The KVLCC2 at high drift angle was also simulated with the EASM/DES turbulence model. Steady turn computations were performed for the DTMB 5512 model. Dynamical PMM computations (i.e. pure yaw and pure sway) were performed for the HSSL trimaran and for the DTMB 5512 model. For the pure sway motion of the DTMB 5512 model, the agreement in terms of predicted forces and moments with measurements was very satisfactory, Figure 11, while some discrepancies were observed when comparing velocity fields. Less good agreement can be noted for the pure yaw simulations, Figure 12.

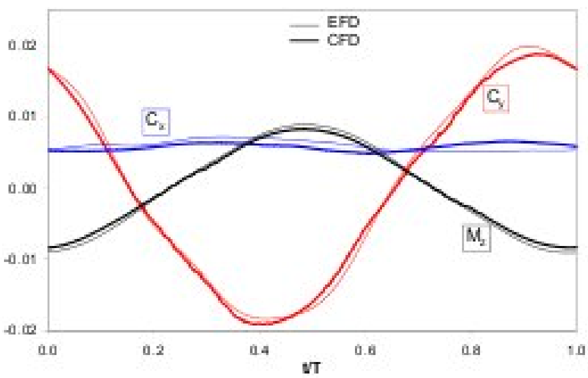


Figure 11 Forces history over one period for model 5512 in pure sway motion, free to heave, pitch and roll.

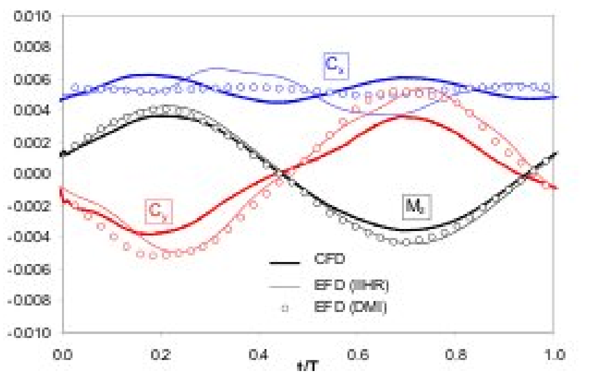


Figure 12 Forces history over one period for model 5512 in pure yaw motion, free to heave, pitch and roll.

Seakeeping computations in regular and irregular waves, with the prediction of 6-DOF motions for the DTMB 5512, Figure 13, for the HSSL trimaran and for two hulls following each other were also presented. These numerical simulations, even if they do not directly deal with the prediction of standard manoeuvres, can be considered an important step forward in the prediction of the trajectory using CFD solvers.

Prediction of Manoeuvres. Even if only few authors have performed numerical simulations based on the unsteady RANS equations for the direct prediction of ship manoeuvres, the reliability of this technique for the study of such a complex problem is evident, e.g. from SIMMAN 2008 where Carrica and Stern showed challenging simulations with steering rudder(s) and rotating propeller(s) showing very promising results for zig-zag and turning circle tests.

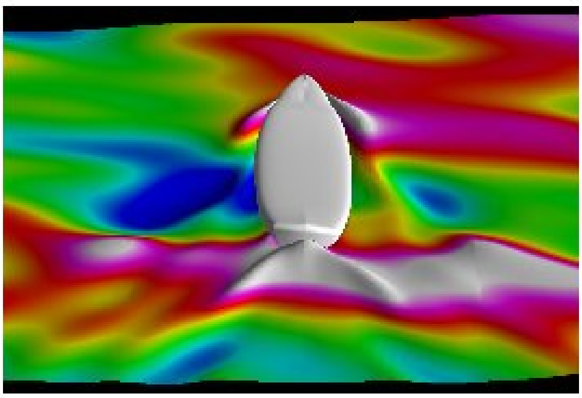


Figure 13 DTMB 5512 free to heave, pitch and roll advancing in irregular seas (Fr = 0.41 , 45 degrees encounter angle).

Xing-Kaeding and Jensen (2006) performed numerical simulations for the steady drift motion and prediction of turning circle and zig-zag tests for the CBOX container ship model in full appended configuration. For the static drift case good agreement with measurements in terms of global forces and yaw moment were observed. Discrepancies were stressed on the computation of the side force on the rudder. Also for the zig-zag tests the overall agreement with experiments were reasonable satisfactory. Larger errors were observed in the prediction of the reach time, the maximum transverse deviation and the drift angle.

The prediction of the turning circle test for a Series-60 ship is presented in Jacquin et al. (2006a) and Jacquin et al. (2006b). The authors also presented results for steady drift motions of the KVLCC2M and the HTC ship hull. Results agree fairly well with experiments for the KVLCC2M, whereas the agreement for the HTC ship hull was less satisfactory. The authors stated that this is due to free surface effects which were neglected in both cases. Since the Froude number is higher in the second case, larger disagreement can be expected. In the same paper validation of the numerical scheme is conducted also for dynamic PMM tests (pure yaw, pure sway) and for steady yaw motions.

4.4 Concluding Remarks

The developments described throughout this section have made RANS simulations affordable for practical industrial applications in towing tanks already.

A promising technique for manoeuvring prediction consists in performing RANS simulations of the flow around the ship carrying out prescribed motions resembling PMM, CPMC or CMT tests (see ITCC procedure 7.5-02-06-02 on captive model tests). The predicted time histories of the forces and moments acting on the model during the simulation are used to determine manoeuvring derivatives for simulating rudder manoeuvres in the same way as from measured time histories. Moreover, once thoroughly validated, the method can be applied for the full scale ship as well, avoiding scale effects. The body force models used to replace the propeller seem to work satisfactorily and could be accurate enough for manoeuvring prediction purposes. However, since just a few applications of this technique for manoeuvring prediction have been shown till now, more experience is needed to take definitely conclusions.

The direct simulation of manoeuvres by means of RANS simulations taking into account the rotating propeller(s) and steering rudder(s) within the computational grid have shown to be possible and yield promising results already. Considering the enormous computational time required for this, the use of a body force model instead of rotating propeller(s) could be an interesting variant for practical use.

Systematic validation of used methods is needed and simulations of unsteady cases relevant for manoeuvring prediction still demand large computational time and man effort. Working on typical grids of 1 to 5 million cells the simulation of a virtual PMM test for instance may take one to several weeks, depending on if they are performed on a computer cluster or on a single processor PC. Calculations are mostly performed for the ship model instead of the full scale ship, because the validation of the latter is rare and because calculations are easier for model scale. Moreover, a large part of these applications are done for research purposes and compared with model tests.

Thus, besides the impressive progress of the numerical techniques for prediction of ship manoeuvrability, there is a need of a comprehensive validation of the used methods. This fact stresses the relevance of the Workshop on Verification and Validation of Ship Manoeuvring Simulation Methods, SIMMAN 2008, held in Copenhagen in April 2008, see Section 5 of this report, and of similar future workshops.

5. VALIDATION OF SIMULATIONS & BENCHMARK DATA: SIMMAN 2008

5.1 Introduction

The Workshop on Verification and Validation of Ship Manoeuvring Simulation Methods (SIMMAN 2008) was held in Copenhagen, Denmark on 14th-16th April 2008. SIMMAN 2008 was the outgrowth of discussions and planning conducted by the 24th ITTC Manoeuvring Committee, which continued into the 25th ITTC Manoeuvring Committee. The workshop was hosted by FORCE Technology, Lyngby, Denmark.

The purpose of the workshop was to benchmark the prediction capabilities of different ship manoeuvring simulation methods including systems and CFD based methods through comparisons with results for tanker, container ship and surface combatant hull form test cases. Systems based methods were compared with free-model test data using provided PMM and CMT (circular motion mechanism/rotating-arm) data, whereas CFD based methods were compared with both PMM/CMT and free-model test data. The comparisons for the PMM/CMT and free-model tests were *blind* in the sense that the PMM/CMT and free-model test data was not provided prior to the workshop unless data was required as input to the simulation method. A website was used to facilitate the workshop organization and dissemination of information and instructions to participants: http://www.simman2008.dk/.

The workshop was the first of its kind for several reasons. Manoeuvring simulation methods have yet to be benchmarked for their prediction capabilities through systematic quantitative validation against EFD. Benchmarking was conducted for both systems and CFD based methods. The simulations were blind for all test cases. The international collaboration for captive and free model EFD validation data was noteworthy, as it involved 11 ITTC institutions and ten countries from Europe, Asia, and America. The approach followed most recent workshops for benchmarking CFD methods for resistance and propulsion in adopting the KVLCC, KCS, and DTMB 5415 (tanker, container, and surface combatant) test cases and as in previous CFD workshops directly comparing multiple methods to the same test cases for quantitative comparisons and evaluation, but with focus on manoeuvring test cases, blind submissions, and poster presentation of methods with more workshop time devoted to validation discussions. For the KVLCC test case two stern shape variants named KVLCC1 and KVLCC2 with different instability loops were included.

5.2 Overview of Workshop

Organization. Executive and sub committees were formed for the overall organization of the workshop. Eight organizing committee meetings were held between September 2005 and April 2008 (just after the workshop). Table 1 provides an overview of the SIMMAN 2008 organization. Eight MC member institutes were co-organizers.

Table 1 Organization SIMMAN 2008 overview

Executive Committee			
IIHR F. Stern		FORCE K. Agdrup	
Sub-committees: Coordination of model tests			
KVLCC	MOERI S.Y. Kim	INSEAN P. Bulgarelli	
KCS	HSVA A.Cura Hochbaum	SVA M. Steinwand	
5415	FORCE K. Agdrup	IIHR J. Longo	
Sub-committees: Comparison of Systems based methods			
KVLCC	SNU K.P. Rhee		
KCS	MARIN F. Quadvlieg		
5415	BEC P. Perdon	NSWCCD D. Hess	
Sub-committees: Comparison of CFD based methods			
KVLCC	NMRI T. Hino		
KCS	INSEAN R. Broglia		
5415	NSWCCD J. Gorski		
Co-organizers			
BEC	BSHC	CEHIPAR	CTO
FORCE	HSVA	IIHR	INSEAN
MARIN	MOERI	NMRI	NSWCCD
SNU	SVA		

Hulls Chosen for the Benchmark. The hulls chosen for the workshop were those recommended by the 24th ITTC. No full-scale ships exist of these hulls.

The MOERI KVLCC (Figure 14) was conceived to provide data for flow physics and CFD validation for a 1997 tanker hull with a length of 320 m, bulbous bow and transom stern. Two stern variants were designed: KVLCC1 has barge type stern frame-lines with a fine stern end bulb i.e. relatively V-shaped frame-lines, while KVLCC2 has more U-shaped stern frame-lines.

Models of the two KVLCC variants have been built first by MOERI in 1999 to the scale of 1:58.00 and tested at ship self-propulsion point in the PMM at MOERI. In 2006 NMRI manufactured a set of models to the scale of 1:110.00 for CMT tests at the model self propulsion point, and finally INSEAN built a set of models to the scale of 1:45.71 also in 2006. The latter models have been tested in the PMM at INSEAN at the model self propulsion point and then transported to HSVA, CTO and MARIN for free model tests. Photographs of the INSEAN models are shown in Figure 15.

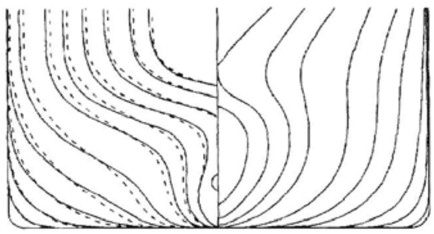


Figure 14 KVLCC bodyplan. KVLCC1: solid line; KVLCC2: dashed line

Figure 15 KVLCC models built by INSEAN, scale 1:45.71, left: KVLCC1, right: KVLCC2

The MOERI Container Ship KCS (Figure 16) was conceived for same reasons as KVLCC, but for a 1997 container ship with a length of 230 m, bulbous bow and transom stern.

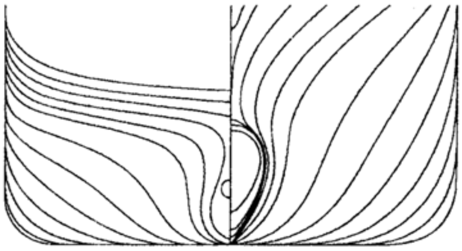


Figure 16 KCS body plan

A model of the KCS was first built by MOERI in 1999 to the scale of 1:31.60, however, the tests with this model was not part of the present workshop. NMRI manufactured a model to the scale of 1:75.50 and conducted CMT tests at the model self propulsion point in 2005. The PMM tests at CEHIPAR at the model self propulsion point and the free model tests at SVA and BSHC have been performed with the model built by SVA in 2006 to the scale of 1:52.67. A photograph of the SVA model is shown in Figure 17.

Figure 17 KCS model built by SVA Potsdam, scale 1: 52.67

Model 5415 (Figure 18) was conceived as a preliminary design for a 1980 Navy surface combatant with a length of 142 m. The hull geometry includes both a sonar dome and transom stern. Propulsion is provided through twin open-water propellers driven by shafts supported by struts.

A model of the 5415 was built by MARIN in 2000 to the scale of 1:35.48 and used for free model tests. This model was transported to FORCE for PMM tests at the ship self propulsion point later that year. In 2004 the appendages were removed in order to perform bare hull PMM tests including uncertainty assessment at FORCE and later rotating arm tests at BEC. Bare hull PMM tests have also been performed at IIHR with a smaller model (scale 1:46.59) and at INSEAN with a larger model (1:24.83). All bare hull tests have been carried out without rudders and propeller arrangement, but with bilge keels and a skeg of a somewhat different design than in the appended hull tests at MARIN and FORCE. Photographs of the MARIN model in both appended and bare hull configuration are shown in Figure 19 and Figure 20.

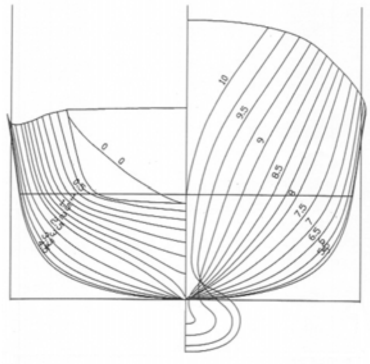


Figure 18 5415 body plan

Figure 19 5415 model, built by MARIN, scale 1:30.48, appended hull

Figure 20 5415 model, bare hull with bilge keels

Model test overview. An overview of the performed model tests is given in Table 4. Column headers in grey are "focus tests" that form the primary basis for comparisons at the workshop. All raw model test data was stored on an FTP server.

Test cases. Test cases were selected that the participants should make simulations following detailed instructions given on the workshop website, as summarized in Table 2 and Table 3 for the comparisons of free manoeuvre simulations and forced motion simulations, respectively, with the EFD validation data.

Instructions, Proceedings and Workshop Program.
All participants were required to submit:

a) simulation results as time series of motions and forces following specific instructions,
b) a filled out questionnaire used for categorization of the used method,
c) a paper describing method and results,
d) a poster presenting method and results.

Prior to the workshop sub-committees for coordination of model tests evaluated the model test data and sub-committees for comparison of results processed the submitted simulation results and compared them to the benchmark data for free model test and captive model test results, respectively. These evaluations of model tests and comparison results formed the main part of the workshop, where each chairman presented an overview of the results followed by discussion between chairman, submitters and the remaining participants. The results of the comparisons were included in the proceedings (Stern and Agdrup, 2008), of which the participants were given a preprint at the start of the workshop. The questionnaire answers were compiled and included in the proceedings to provide an overview of the different methods. The submitted papers formed another part of the proceedings, which also contains documentation of the test cases and the benchmark hulls.

Table 2 Summary of test cases for free manoeuvre simulations

Hull	Test type	Approach speed	Helm rate
KVLCC1 KVLCC2	10/10 zig-zag	15.5 kn	2.32 deg/s
	20/20 zig-zag		
	5, 10, 20, 35 deg turning circle		
KCS	10/10 zig-zag	24.0 kn	2.32 deg/s
	20/20 zig-zag		
	5, 10, 20, 35 deg turning circle		
5415	10/10 zig-zag	30.0 kn	9.0 deg/s
	20/20 zig-zag		
	5, 10, 20, 35 deg turning circle		

Table 3 Summary of test cases for forced motion simulations (CFD based methods)

Hull form	Simulation conditions	Test type	Test condition
KVLCC1, KVLCC2	Appended[1)] Heave and pitch free; roll fixed	Static rudder	$\delta = 0°$
			$\delta = 10°$
		Static drift	$\beta = 12°$
		Pure sway	$v' = 0.0852$
		Pure yaw	$r' = 0.30$
KCS	Appended[1)] Heave and pitch free; roll fixed	Static rudder	$\delta = 0°$
			$\delta = 10°$
		Static drift	$\beta = 8°$
		Pure sway	$v' = 0.140$
		Pure yaw	$r' = 0.40$
5415	Bare Hull[2)] Fixed[3)]	Static drift	$\beta = 10°$
		Pure sway	$v' = 0.174$
		Pure yaw	$r' = 0.30$
	Appended[1)] Heave and pitch free; roll fixed	Static drift	$\beta = 10°$
		Pure sway	$v' = 0.174$
		Pure yaw	$r' = 0.410$

1) Appendages: Rudder and propeller, 2) with port and starboard bilge keels, 3) Fixed at dynamic sinkage and trim corresponding to straight running at test speed

Table 4 Model tests overview

Hull	PMM app. deep	PMM app. shallow	PMM bare deep	PMM bare shallow	CMT app. deep	CMT bare deep	Free app. deep
KVLCC1	MOERI (1999) INSEAN (2006)	INSEAN (2006)	-	-	NMRI (2006)	-	HSVA (2006) CTO (*) (2007) MARIN (2007)
KVLCC2	MOERI (1999) INSEAN (2006)	INSEAN (2006)	INSEAN(2006)	INSEAN(2006)	NMRI (2006)	-	HSVA (2006) CTO (*) (2007) MARIN (2007)
KCS	CEHIPAR (2006)	-	-	-	NMRI (2005)	-	SVA (2007) BSHC (2007)
5415	FORCE (2000) MARIN (2007)	-	FORCE (2004) IIHR (2005) INSEAN (2005)	-	MARIN (2007)	BEC (2006)	MARIN (2000)

(*) Data pending

Participants and Submissions. The total number of participants (including observers) was 68, representing 37 organizations from 14 countries. The number of submissions of free manoeuvre simulations and forced motion simulations for each hull are given in Table 5. All MC members participated.

Table 5 Number of submissions for each hull

	Free manoeuvres	Captive motions
KVLCC1	22	3
KVLCC2	21	6
KCS	11	2
5415	10	5
total	64	16

The submissions are listed in Table 6, where the submissions have been divided into those based on systems and CFD based methods. The systems based and blue highlighted CFD based submissions were compared with the free model data, whereas the green highlighted CFD based simulations were compared with the captive model data.

It should be noted that a number of results, including both captive and free model tests as well as submitted simulations, were not suitable for direct comparison either due to misunderstanding of the instructions, different propeller RPM or helm rate, different hull configurations or errors in the post-processing. These results will be revisited for the final workshop proceedings.

5.3 Comparison Results for Free Manoeuvre Simulations

A small extract of the comparisons of free manoeuvre simulations are given in this subsection. The following comments should be considered when evaluating the results:

- The number of submissions is large, especially for KVLCC1 and KVLCC2, and there is a wide variation of methods being used.
- A large scatter in the results is observed, especially for KVLCC and less so for 5415. This is partly connected to the number of submissions and the fact that 5415 is a course stable ship.
- The choice of RPM i.e. model/ship self-propulsion point and applied strategy during manoeuvre (constant RPM/constant torque) is different from the free model tests for a number of submissions. This plays a role for the prediction results, but the quantitative influence is not fully clarified.
- Some of the free model tests were carried out with non-stationary initial conditions and others at different helm rate than nominal value. This makes the evaluation of the submissions difficult in some cases.

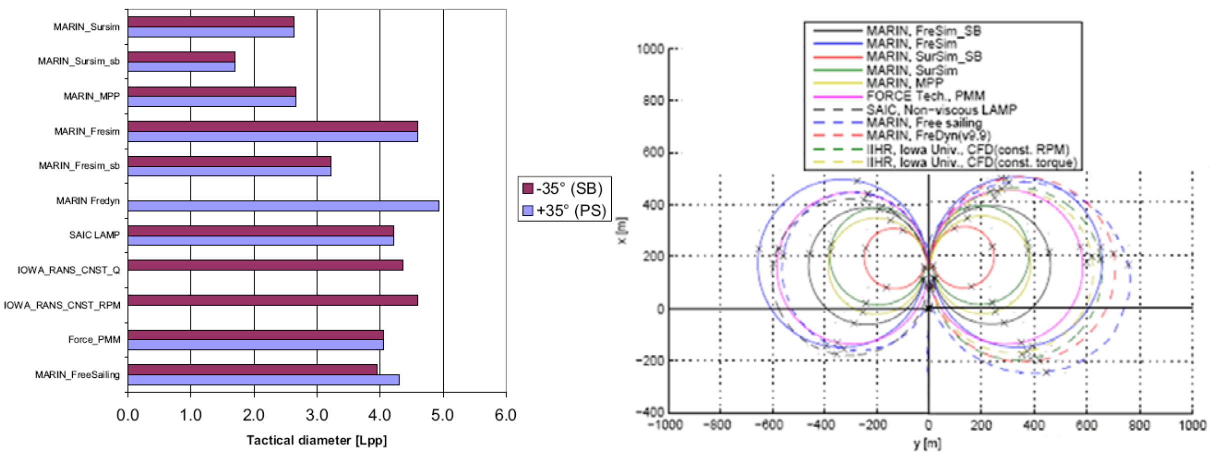


Figure 21 5415, +35 deg turning circle, tactical diameter results for different simulation methods (left) , ±35° deg turning circle, track plot for different groups of simulation methods (right), compared to EFD results (MARIN free model tests)

Table 6 Overview of submissions split into Systems based and CFD based methods. All submissions of free manoeuvre simulations are highlighted in blue, while submissions of forced motions are highlighted in green

No simulation	Systems Based Manoeuvring Simulation						CFD Based Manoeuvring Simulation		
KVLCC1&2	KVLCC1&2			KCS			KVLCC1		
HSVA	Organiz.	Method	DOF	Organiz.	Method	DOF	Organiz.	Method	Code
MARIN	FORCE	PMM_MOERI	3	FORCE	SY_SIMP	6	HSVA	RANS	NepIII
	FORCE	PMM_INSEAN	3	FORCE	SY_ADV	6	HSVA	RANS	NepIII
KCS	FORCE	SY_SIMP	6	Hiroshima	CMT	4	IIHR	DES	CFDSHIP-IOWA
SVA	FORCE	SY_ADV	6	Hokkaido	CMT	3	INSEAN	RANS	Xnavis
BSHC	Hiroshima	CMT	3	MARIN	SURSIM	4	MARIN	RANS	Parnassos
	HHI	PMM	3	MARIN	FRESIM	4	MOERI	RANS	WAVIS
5415	Hokkaido	CMT	3	MARIN	SURSIM-SB	4	KVLCC2		
MARIN	Kyushu	Emp.	3	MARIN	FRESIM-SB	4	HSVA	RANS	NepIII
	MARIN	SURSIM	4	MARIN	MPP	4	HSVA	RANS	NepIII
	MARIN	FRESIM	4	MOERI	PMM	3	INSEAN	RANS	Xnavis
	MARIN	SURSIM-SB	4	NMRI	CMT	3	MARIN	RANS	Parnassos
	MARIN	FRESIM-SB	4	5415			MOERI	RANS	WAVIS
	MARIN	MPP	4	FORCE	PMM	4	NMRI	RANS	NEPTUNE
	MARIN	KIJIMA	3	MARIN	SURSIM	4	SJTU	RANS	FLUENT
	MARINTEK	SIMAN	3	MARIN	FRESIM	4	SOUTHAMPT.	RANS	CFX
	MOERI	PMM	3	MARIN	SURSIM-SB	4	KCS		
	NMRI	CMT	3	MARIN	FRESIM-SB	4	FORCE	URANS	CFDSHIP-IOWA
	SNU	Regression	3	MARIN	MPP	4	HSVA	RANS	NepIII
	SNU	MMG	3	MARIN	FREDYN	4	5415		
				NSWCCD	Neural Network	6	BEC-ECN	RANS	Icare
				SAIC	LAMP	6	ECN/CNRS	RANS	ISIS-CFD
							IIHR	URANS	CFDSHIP-IOWA
							IIHR	URANS	CFDSHIP-IOWA
							NSWCCD	RANS	CFDSHIP-IOWA
							UMNSWCCD	URANS	FLUENT

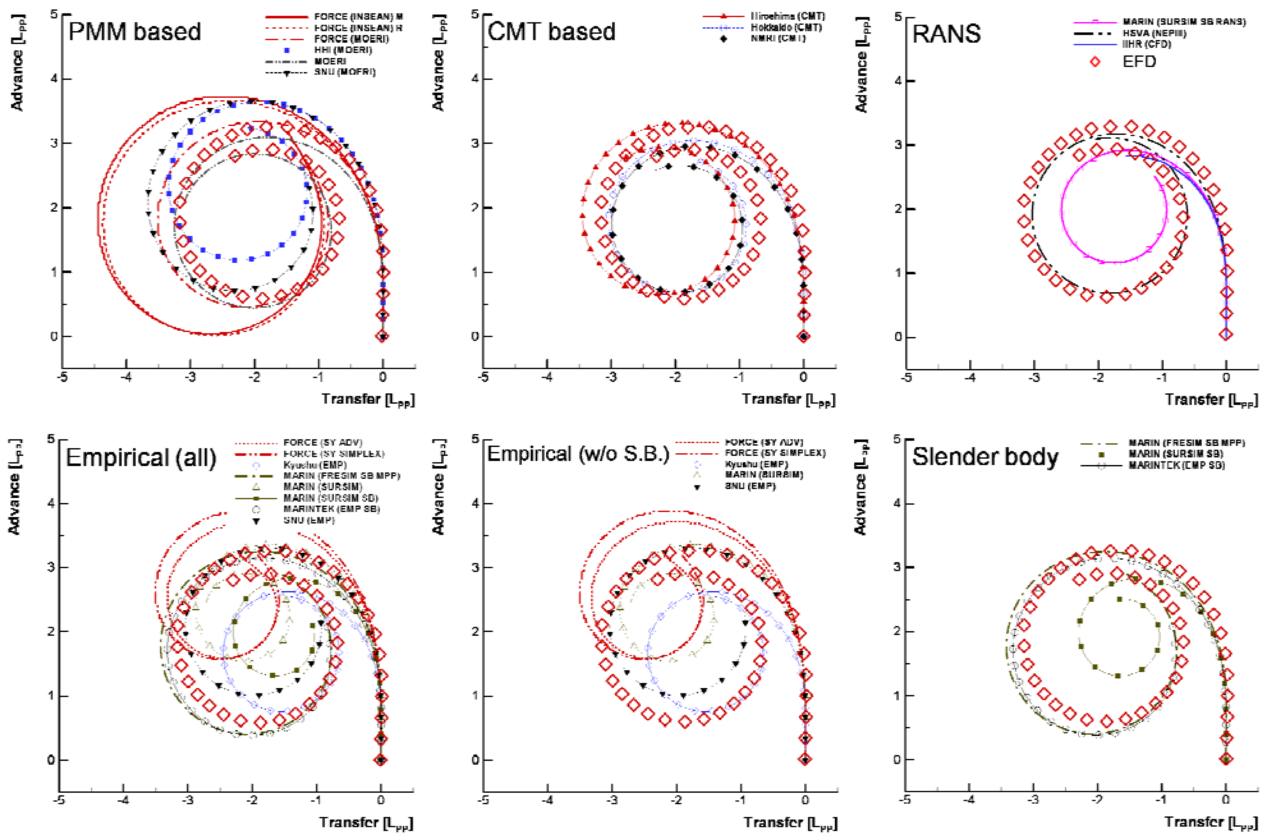


Figure 22 KVLCCl, 35 deg turning circle, track plot for different groups of simulation methods, compared to EFD results (MARIN free model tests)

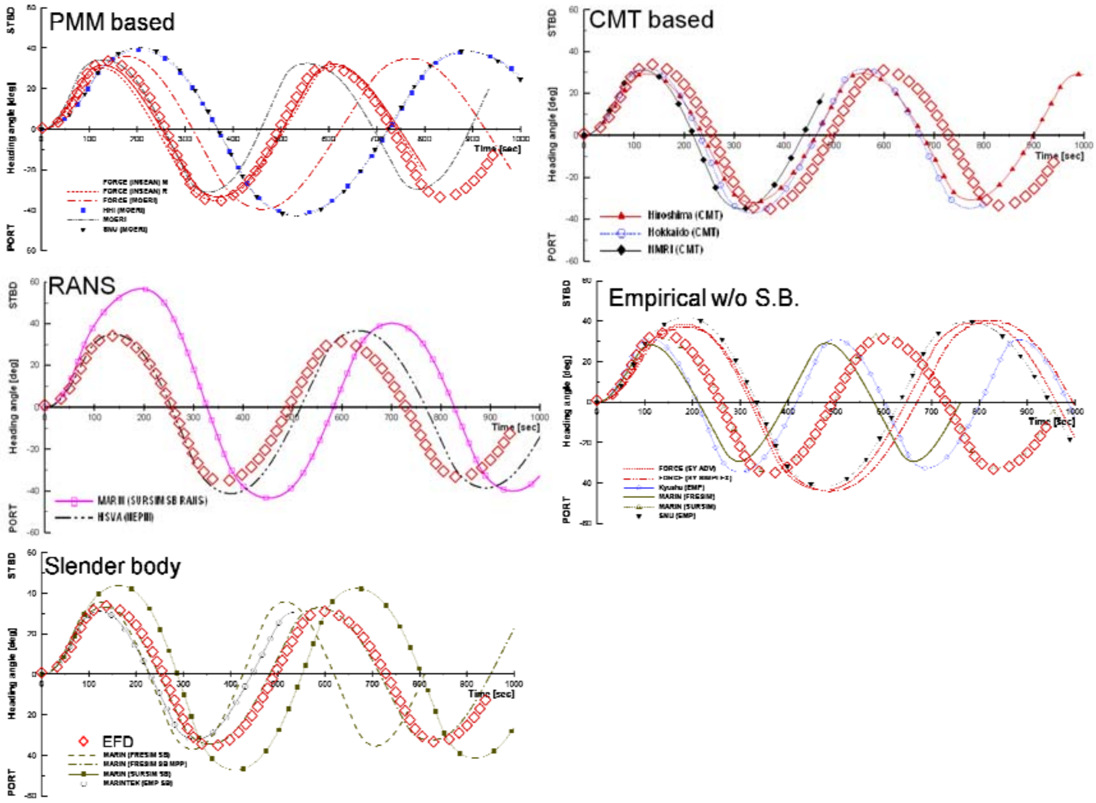


Figure 23 KVLCCl, 20/20 zig-zag, plot of heading angle for different groups of simulation methods, compared to EFD results (MARIN free model tests)

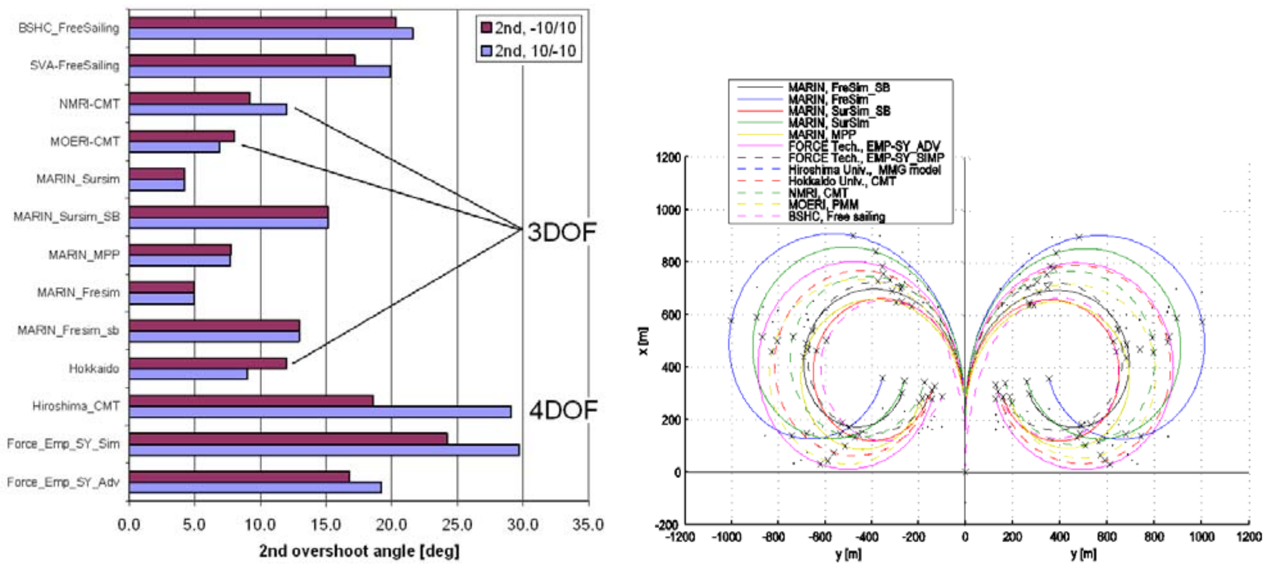


Figure 24 KCS, 10/10 zig-zag, 2nd overshoot angle (left) and ±35° deg turning circle, track plot for different groups of simulation methods (right), compared to EFD results (SVA/BSHC free model tests)

5.4 Comparison Results for Forced Motion Simulations (CFD Methods)

An extract of the comparisons of forced motion simulations are given in this subsection. The following comments should be considered when evaluating the results:

- The number of submissions is less than anticipated, making evaluation more difficult.
- Some of the captive model test data still has questions that must be resolved before final comparison can be made in these cases.
- EFD uncertainty analysis results are not available for other model test series than 5415 bare hull.

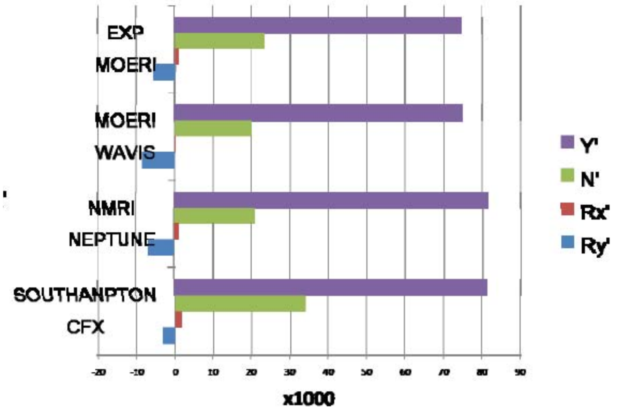


Figure 25 KVCC2, static drift for β=12 deg, non-dimensional thrust/hull/rudder forces and moments for different CFD-based methods, compared to EFD results (MOERI PMM)

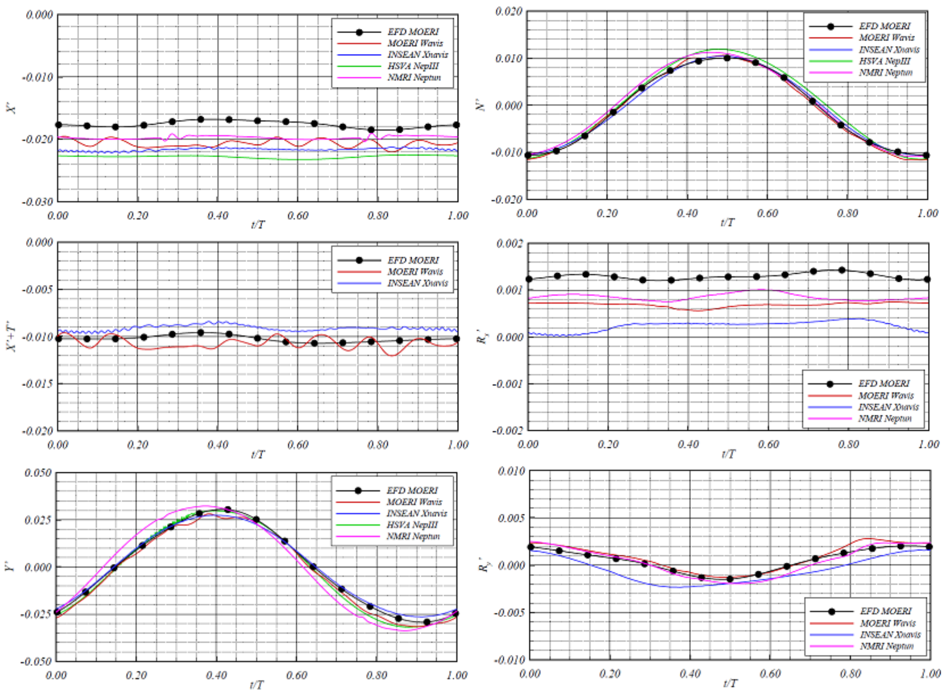


Figure 26 KVLCC2, pure sway, time series of non-dimensional thrust/hull/rudder forces and moments for different CFD-based methods, compared to EFD results (MOERI PMM)

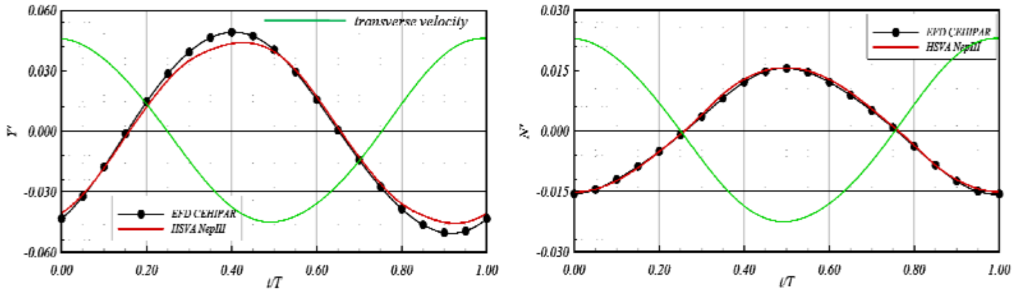


Figure 27 KCS, pure sway, time series of non-dimensional thrust/hull/rudder forces and moments for different CFD-based methods, compared to EFD results (CEHIPAR PMM)

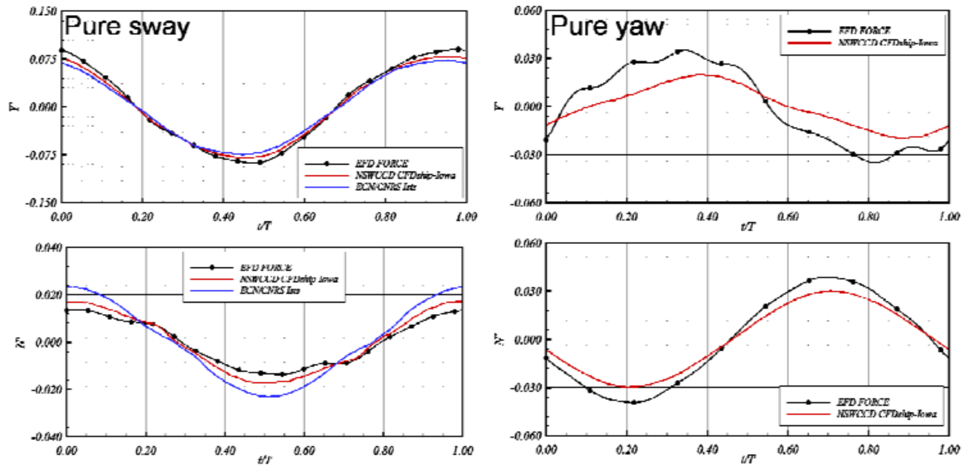


Figure 28 5415 appended hull, pure sway/pure yaw, time series of non-dimensional hull forces and moments for different CFD-based methods, compared to EFD results (FORCE PMM)

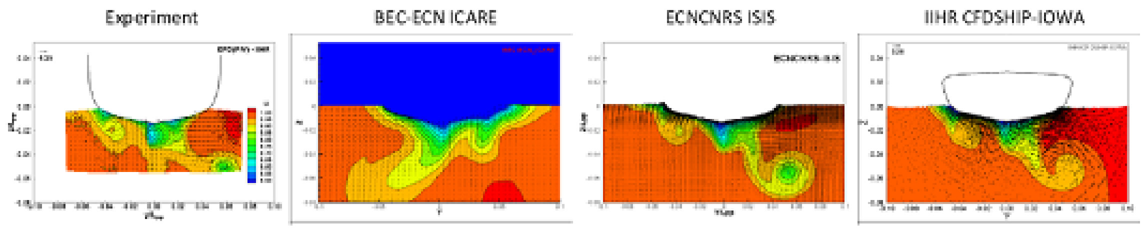


Figure 29 5415 bare hull, pure sway, axial velocity contours and cross flow vectors in nominal-wake plane at 90 deg phase angle of the PMM cycle for different CFD-based methods, compared to PIV measurements (IIHR PMM and PIV)

5.5 Preliminary Conclusions

Due to the mentioned unresolved questions to both EFD data and simulation results revealed during the workshop as well as in view of the short time from the date of the SIMMAN 2008 workshop to the deadline for the present report, final conclusions and recommendations are not yet available. However, some preliminary conclusions and trends were evident.

Benchmark Data.

- KVLCC1&2: Clarification and corrections are needed for PMM data. Free model data show agreement.
- KCS: Additional 4 DOF PMM and CMT data should be pursued. Clarification regarding initial conditions and repeatability of free model data is required and possibly additional tests.
- 5415: Clarification and correction is needed for free model data. Bare hull PMM data show agreement, as discussed in Section 10.

System Based Methods.

- There is a large number and variety of both "players" and methods, which are capable of predicting IMO manoeuvres for conventional ship types.
- The majority of contributions were based on empirical formulae or on captive model tests, either PMM/ CPMC or rotating arm.
- Clarification is needed regarding trends in the predictions after corrections and grouping have been done and after mathematical models have been documented for all submissions.
- One trend is that "homegrown" methods, i.e. those using own model test data following in-house procedures and formats, give better results.
- It is critical for the prediction that there is consistency between the model test program and the applied mathematical model. Extrapolation outside the range of model test data should be avoided.
- It is important to include the 4th degree of freedom, i.e. roll, for ships with low GM_T.
- Empirical methods are used widely and can give good predictions; however, only when restricted to the ship type for which they were developed.
- A distinction was made between modular model methods (e.g. MMG) and whole ship model methods (e.g. Abkowitz), but no conclusions could be made regarding their comparative performance. Global system methods were very sensitive to the choice of mathematical model (derivatives).

CFD-Based Methods.

- CFD methods are being used in the field of manoeuvring, but at this stage mostly for simulation of (selected) captive model tests.
- The increased complexity in calculations for manoeuvring compared to (bare hull) resistance seems to give increased error levels and scatter in the results.
- The side force and yaw moment are generally better predicted than the longitudinal force.
- Fourier series decomposition of forces and moment will provide additional quantitative comparison with the EFD data.
- Forces and moment coefficients should also be converted into manoeuvring derivatives.
- It is possible to use RANS CFD to obtain data fully equivalent to captive model test data to serve as basis for simulations.
- Direct simulation of manoeuvres using RANS CFD with dynamic overset grids for handling rudder deflections and rotating propellers yields promising results, but (still) very time consuming for the case with rotating propeller(s).
- More verification is still needed.

General Conclusions.

- Workshop program for full use of sessions for analysis and discussion of results along with poster presentation of methods was successful.
- There is a general need for more quantitative verification and validation.
- There is a general need for a definition of how to validate a manoeuvring prediction method, i.e. which accuracy is acceptable? If possible, a "prediction quality index" should be defined.

5.6 Plan for Final Proceedings

The final proceedings will address issues related to questions on the model test data and comparisons of system and CFD based methods, include papers describing the model tests, summary and conclusions of the sub-committee reports, and final overall conclusions and recommendations. The final proceedings will be distributed on CD-ROM by end of 2008 or early 2009.

6. MANOEUVRING AND COURSE KEEPING IN WAVES

6.1 Introduction

Ship manoeuvrability in waves is of vital importance for navigation safety of seagoing ships. Since this topic has not been covered recently by the MC, the review period has been extended to the last ten years in this section.

Manoeuvrability is nearly associated with seakeeping performance. However, manoeuvring and seakeeping problems are traditionally dealt with separately due to the complexity of these problems. Relevant researches of ship motion in waves are mainly concentrated on dynamic stability problems such as rolling, broaching and capsizing.

A traditional method of research on ship manoeuvring and course keeping in waves is to use a system based simulation method, which determines the hydrodynamic forces by a seakeeping method in frequency or time domain and then simulates the manoeuvring motion to predict the ship manoeuvrability in waves. This kind of method still plays an important role in research on manoeuvring and course keeping in waves.

With the progress achieved in the field of ship hydrodynamics there is an increasing trend to investigate manoeuvring and seakeeping problems together by using a unified theory and method. Moreover, with the advent of modern CFD methods, direct simulation of manoeuvring motion in waves by using CFD based methods becomes possible.

6.2 Experimental Methods for Manoeuvring in Waves

At present, experimental methods are still the most reliable method to investigate the problem of manoeuvring and course-keeping in waves.

Lundbäck and Rutgersson (2000) conducted full scale trials including zig-zag tests and course-keeping tests in following seas for use in the prediction of broaching.

Yasukawa and Adnan (2006) measured added resistance, steady drifting lateral force and yaw moment acting on an obliquely moving ship in regular waves using the S-175 container ship model. The influence of the hull drift on the wave drifting lateral force and yawing moment is considerable large, although the influence on the added resistance is small. The lateral drifting force acts on the hull so as to damp the lateral motion.

Yasukawa (2006a) carried out free model tests in regular and irregular waves using the S-175 container ship model and presented simulation results for turning motions in waves using a practical simulation method which takes only wave drift forces into account. The simulation method can predict the turning motions in regular and irregular waves with practical accuracy, although there is some room for improvement in the short wave length region such as wave/ship length ratio 0.5.

Xu et al. (2007) conducted an experimental research on ship manoeuvrability in waves. A series of PMM tests was carried out in waves to measure the forces on the model.

6.3 Manoeuvring in Waves by System Based Simulation Methods

Traditionally, manoeuvring in waves is investigated by system based simulation methods using 4-DOF or 6-DOF mathematical models. The hydrodynamic coefficients are determined by seakeeping theory such as strip theory, slender-body theory or 3D panel method in frequency domain or time domain. The simulation of manoeuvring is then conducted by using manoeuvring theory to predict the manoeuvrability in waves.

Ankudinov (1983) developed a nonlinear mathematical model and computer program for predicting the motion of a ship conducting arbitrary manoeuvres in waves. The mathematical model has been applied to deterministic calculation of seakeeping and ship manoeuvring predictions in irregular seas.

McCreight (1986) developed a six-degree-of-freedom time domain theory for predicting the motion of a ship manoeuvring in waves and wind, including wave induced motion. The full nonlinear calm water manoeuvring equations of motion are combined with wave effects derived from linear ship motion theory.

Ottosson and Bystrom (1991) described a strip theory based general time domain seakeeping and manoeuvring simulation program, SEAMAN, developed for different coupled seakeeping and manoeuvring problems for naval as well as merchant vessels operating in arbitrary weather and current condition.

Hamamoto and Kim (1993) proposed a new coordinate system and derived the motion equations in this system for describing the manoeuvring motion of a ship in waves.

Kobayashi and Wada (1993) developed a simulation system to evaluate ship manoeuvrability in waves. Both, manoeuvrability and wave-induced ship motion can be calculated simultaneously.

Bailey et al. (1998) discussed the relations between the forces and moments acting on a moving rigid vessel relative to a body fixed axis system or an equilibrium moving axis system with reference to sway and yaw motion. These relations are examined using data derived from oscillatory tests involving a horizontal PMM and hydrodynamic coefficients calculated from a mathematical model adopting a 3D Green's function potential theory accounting for both forward speed and frequency of oscillation.

Lee (2000) calculated 10°/10° zig-zag tests in waves by using the traditional ordinary differential equations with constant coefficients and the integro-differential equations with impulse response function for sway-yaw manoeuvring motion, and discussed the differences between the solutions.

Bailey et al. (2002) described the implementation of a unified mathematical model, which encapsulates the traditional seakeeping and calm water manoeuvring theories, yet is applicable to the more general study of a ship manoeuvring in a seaway, and presented comparisons of the time simulation with the traditional theories.

Ayaz et al. (2002) presented a research study addressing the development of an improved coupled non-linear 6-DOF model with frequency dependent coefficients, incorporating memory effects in random waves with a new axis system that allows straightforward combination between seakeeping and manoeuvring models whilst accounting for extreme motions. In order to provide feedback for the development of a numerical model following theoretical work, extensive captive and free model tests were carried out at the National Research Institute of Fisheries Engineering, Japan for a 712 tonnes Japanese Purse Seiner which operates in the East China Sea and for which extensive seakeeping and manoeuvring data has been collected as part of ITTC Benchmark tests.

Artyszuk (2003) formulated practical issues about wave forces to be included in a ship manoeuvring mathematical model. A current status of research in this field was thoroughly investigated regarding data availability and validity. The impact of first order wave forces was briefly characterized; the major interest was turned upon the second order forces. A strong effect of the latter was proved through simulation of a turning test in regular waves.

Nishimura and Hirayama (2003) investigated the rolling motions that occur on a typical fishing boat in Japan, including considerations on turning manoeuvres by numerical simulation in time domain assuming that the boat runs in long waves.

Nishimura at al. (2004) proposed a practical time domain simulation method for a small ship manoeuvring in regular and irregular waves. A nonlinear Froude-Krylov force approach was applied for estimating the exciting forces acting on the ship. The method was validated through comparison with experimental results in head waves.

Fang et al. (2005) developed a simplified 6-DOF mathematical model encompassing calm water manoeuvring and traditional seakeeping theories to simulate turning circle tests in regular waves. A coordinate system called the horizontal body axes system was used to write the motion equations in waves. All corresponding hydrodynamic forces and coefficients for seakeeping were calculated by strip theory. For simplification, the added mass and damping coefficients were calculated using the constant draft but vary with encounter frequency.

Perez (2005) reviewed the geometrical aspects of ship motion (frames, coordinates and transformations) commonly used in the areas of manoeuvring and seakeeping and introduced the kinematic transformation that relates the coordinate systems used in these two areas. A notation which is consistent with the coordinate systems used in both areas is also introduced.

Fossen (2005) presented a unified state-space model for ship manoeuvring, station-keeping, and control in a seaway. The frequency-dependent potential and viscous damping terms were compactly represented by using a state-space formulation. The separation of the vessel model into a low-frequency model (represented by zero-frequency added mass and damping) and a wave-frequency model (represented by motion transfer functions or RAOs) was hence made superfluous.

Bruzzone and Gancia (2005) conducted a study of a unified model of seakeeping and manoeuvrability in time-domain as an extension to a seakeeping time domain potential flow method. A correction was applied directly to lateral-motions hydrodynamic coefficients in order to couple potential flow seakeeping predictions with manoeuvring models. Two manoeuvring models were used: the Clarke formula and the MMG model. Focusing on a fast monohull sailing both in bow and quartering seas, results were presented for both linear and non-linear Froude-Krylov and restoring forces in the time-domain simulations.

Zeraatgar and Ghazi-Asgar (2005) introduced a method for calculation of rudder forces in waves. The result of this study showed how much the dynamic behaviour of a ship in waves can affect the rudder performance.

Faltinsen (2005) discussed seakeeping, stability and manoeuvrability of surface effect ships, hydrofoil vessels, semi-displacement and planning vessels. The very different physical behaviour in waves of the different types of high-speed vessels was discussed. Physical parameters influencing the hydrodynamic manoeuvring coefficients were discussed.

Kijima et al. (2006a) investigated the effects of external disturbances such as wind and waves on manoeuvring motion by numerical simulation, especially for verification of IMO standards of ship manoeuvrability.

Sutulo (2006a) and Soares (2006b) developed a new manoeuvring and seakeeping 6-DOF mathematical model for a slender ship operating in regular waves. Some simulations of standard manoeuvres (straight-path run, turning circle test, zig-zag test) were carried out for the S-175 hull ship at various combinations of the parameters defining the oncoming waves and the manoeuvres themselves.

Ayaz et al. (2006a) developed a coupled nonlinear 6-DOF model with frequency dependent coefficients, incorporating memory effects and random waves. A new axes system that allows straightforward combination between seakeeping and manoeuvring, whilst accounting for extreme motions, was proposed.

Armaoğlu et al. (2006) investigated the motions of semi-displacement ships travelling in stern seas. A database of dynamic forces acting on the ship depending on the running attitude and ship speed was measured from fully captive model experiments and used to characterize their effect on numerical simulations. A manoeuvring mathematical model using horizontal body axis, which allows for a combination of seakeeping and manoeuvring models, taking into account high-amplitude motions and memory effects, was used and the forces and motions were evaluated in 6-DOF in time domain.

Ayaz and Turan (2006c) enhanced the existing 6-DOF non-linear numerical model for the simulation of manoeuvring and seakeeping characteristics of large pod-driven high-speed ships by introducing thrust and lateral force components of azimuthing and fixed pod drives.

Perez et al. (2006) presented a detailed simulation model of a naval coastal patrol vessel for manoeuvring in waves and described its implementation in Matlab-Simulink.

Skejic and Faltinsen (2006) studied the combined seakeeping and manoeuvring of a monohull in regular waves by a two-scale time formulation. The developed model is verified by comparing with experimental and calculated zig-zag and turning circle tests. Skejic and Faltinsen (2007) generated their method to conduct seakeeping and manoeuvring analyses of two interacting ships.

6.4 Manoeuvring in Waves by CFD Based Methods

Wilson et al. (1998) documented the development of CFDSHIP-IOWA version 3.0 for simulating naval combatants manoeuvring in waves.

Xing-Kaeding (2005) and Xing-Kaeding and Jensen (2006) employed a coupled method of CFD and rigid body dynamics to analyze ship manoeuvres in 6-DOF in viscous fluid. The issues of modelling the rudder, propeller, hull and their interactions were discussed. Steady drift motion cases as well as turning circle and zig-zig tests were predicted.

Lin et al. (2006) conducted numerical simulation of ship manoeuvring in waves by using an approach based on the nonlinear 3-D time domain seakeeping program LAMP. The body-wave hydrodynamic forces are calculated directly from the potential flow theory in the time domain, whereas the forces due to viscous effects and other external forces such as propulsors, rudder etc. were modelled with empirical or semi-empirical formulas.

Yasukawa (2006b) presented a practical method for simulating both ship manoeuvring and wave-induced motions. Separating the basic motion equations into 2 groups where one is for high frequency wave-induced motion problem and the other is for low frequency manoeuvring problem, the total of 10 motion equations which are composed of 6-DOF equations for high frequency problem and 4-DOF (surge, sway, roll and yaw) equations for low frequency problem were derived. A new strip method was used for estimating the high frequency hydrodynamic force components such as added mass, wave damping and wave exciting. Wave-induced motions for the S-175 container ship model in turning condition were predicted. The results were compared with those of free model tests in regular waves. The present method can capture the overall tendency of the wave-induced motions of the turning ship in time domain.

6.5 Course Keeping in Waves

Course keeping in waves are dealt with by experimental method, simplified method and CFD based methods.

Fang and Luo (2005) developed a hydrodynamic numerical model including wave effects to simulate ship autopilot systems by using the time domain analysis. The P-D controller and the sliding mode controller are adopted as the autopilot systems. The differences of simulation results between two controllers are analyzed. Fang and Luo (2006) developed a combined control system with roll reduction and track keeping for the ship moving in waves.

Fujiwara et al. (2005a) evaluated the steady-state navigation conditions such as ship speed, offset rudder angle, hull drift angle and heel angle versus various wind directions and wind speeds for a large passenger ship and a PCC with a very large hull and superstructure above sea level. Fujiwara et al. (2005b) extended the method for evaluating the steady-state navigation conditions to the problem in both heavy wind and waves. Based on the steady-state navigation conditions obtained, the optimum ship routing in wind and waves was calculated by the dynamic programming method in order to find the route for reducing the navigation time of the ships.

Vorobyov and Kosoy (2005) presented a method based on the modem theory of stochastic processes for estimating the values of navigation width (NW) for a given ship under wind and waves with known probability characteristics.

Hover et al. (2005) studied the unidirectional wave, following sea problem in two examples, showing that substantial reductions in heave acceleration are possible through very modest manoeuvring actions.

Ross et al. (2006) discussed the relationship between the classical hydrodynamic equations for manoeuvring and seakeeping and offered insight into the models used for simulation and control system design.

Ayaz et al. (2006b) developed a non-linear 6-DOF numerical model with the inclusion of frequency-dependent terms and a flexible axis system that allows straightforward combination of seakeeping and manoeuvring models while accounting for extreme motions.

Wang et al. (2006) presented a nonlinear robust controller designed with the aid of the theory of Active Disturbances Rejection Control (ADRC) for a ship steering in a seaway.

Sclavounos et al. (2006) coupled methods from optimal control theory with the Rankine panel method SWAN for the stable steering of a ship advancing parallel to a vertical wall and the motion reduction of a catamaran vessel equipped with actively controlled bow and stern hydrofoils.

Hess et al. (2006) described a program to develop and implement a faster-than-real-time software platform for nonlinear time-domain simulation and automatic control of a ship in wind and waves. The potential for a Recursive Neural Network (RNN)-based plant model for use in nonlinear time-domain simulation and predictive control applications on manned or unmanned sea-going vessels was demonstrated.

6.6 Concluding Remarks

More and more attention has been paid to the investigation of ship manoeuvring and course-keeping in waves during the last years. There is a trend that ship manoeuvrability in waves is investigated by unified manoeuvring and seakeeping theory and method. New experimental works have been done to investigate ship manoeuvring and course-keeping in waves. System based simulation methods are still dominant in theoretical and numerical investigation of ship manoeuvring and course-keeping in waves. CFD based methods are becoming available and are expected to play a more important role in the future.

7. NEW EXPERIMENTAL TECHNIQUES

7.1 Introduction

While many efforts are nowadays devoted to applicability of CFD for manoeuvring issues, manoeuvring model tests techniques evolves toward the rising need for CFD validation data.

7.2 Model Tests for Validation Purpose

Validation studies of manoeuvring computation were primarily based on global ship forces and moments which constitute the basic output of conventional captive manoeuvring model tests. In practice this global comparison presents shortcomings since discrepancies between computation and measurements can hardly find definitive explanations on the sole basis of overall forces and moments comparisons.

In order to deepen comparison, access of more local characteristics appears to be suitable. In a paper related to CFD validation, Sung et al. (2004) described experiments conducted on a segmented bare hull of a generic submarine hull form. The experiments were conducted on a 4.57 meters long model sliced into 10 sections in both towing tank and rotating arm facilities. Towing tank tests were performed for three Reynolds numbers (4.7, 9.4 and 11.7 10^6), with incidence angles up to 90°. Rotating arm tests were performed for two Reynolds numbers (7.0 and 11.7 10^6) and four non dimensional angular velocities from 0.15 to 0.30. Measurements consist of normal forces on each of the ten segments. Data related to those experiments can be available for computation validation purposes.

Manoeuvring motions of surface ships and underwater bodies generate large vortices and flow disturbances. While the understanding of those complex flow patterns is required to improve manoeuvring prediction in general, one can also notice a rising demand for studies of the impact of the flow produced by manoeuvres on the behaviour of ship components, especially on propellers and rudders.

In addition to forces measured on the whole ship or submarine, measurements may include some local flow details on the hull. Kume et al. (2006) presented oblique towing test on a 5 meters long KVLCC2 model for which, in addition to hull forces, surface pressure and wake field measurements were performed for 0, 6 and 12° drift angle.

Figure 30 Earth fixed stereo PIV system for submarine static drift tests. (Atsavapranee et al 2004)

Pressure measurements over about 400 points distributed over the hull were repeated eight times and pressure contours were presented for average values. An uncertainty analysis (UA) on pressure measurement was conducted using repeated runs leading to the conclusion that primary source of uncertainty for pressure measurements was standard error coming from the pressure transducers calibration line.

In parallel, the flow measuring and image processing techniques made huge progresses in the past decade. In 2004 a workshop on Application of Particle Image Velocimetry (PIV) to Naval and Industrial Hydrodynamics was organised by INSEAN (Di Felice 2004). This workshop was the occasion to draw a picture of the opportunities offered to the hydrodynamics by this aeronautics born technique.

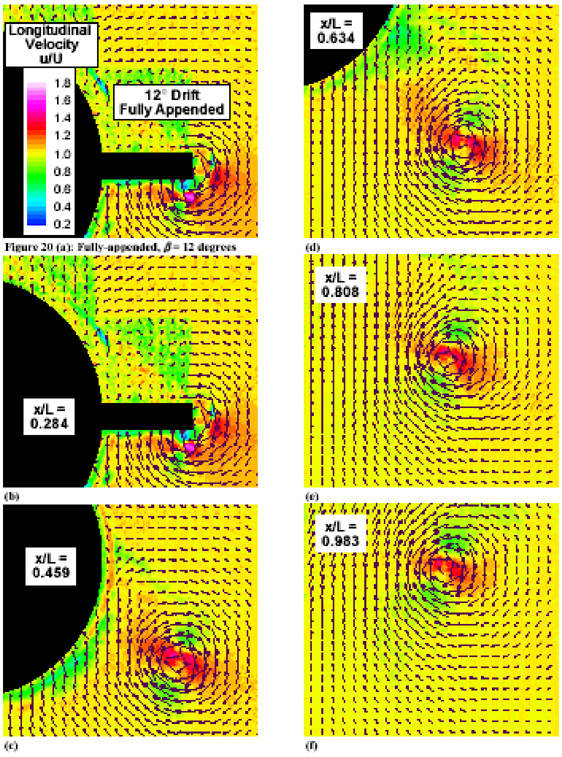


Figure 31 Axial velocity and transverse velocity vectors (Atsavapranee et al 2004)

Over the past years, PIV measurement became a mature technique which found recurrent applications in the manoeuvrability field.

Atsavapranee et al. (2004) presented PIV measurements performed on a submarine towed with steady drift angle. In this experiment, the PIV System, including the laser sheet generation and stereo camera system is fixed on the bottom of the tank, and the model during a run passes through the laser sheet, Figure 30. The measured data therefore consists in flow velocity field characterisation in successive planes distributed along the submerged body.

Figure 31 displays a nice example of measured vortices developing on the tip of the sail for 12° drift angle and influencing the cross flow on the after body leading to the so called “out of plane forces”.

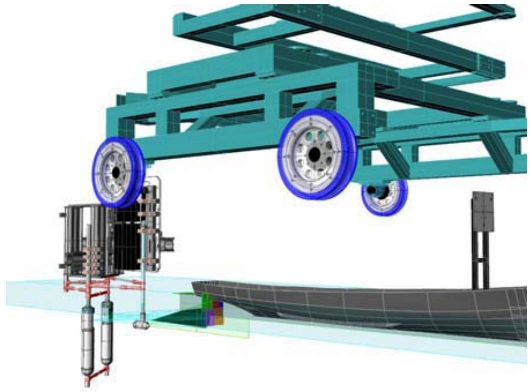


Figure 32 Stereo PIV system towed along a combatant model during PMM experiments (Longo et al. 2006)

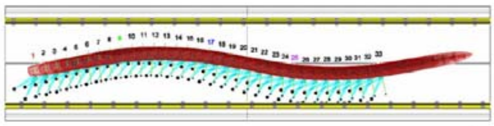


Figure 33 Sketch of model and stereo PIV system path during a period of a pure yaw PMM run (Longo et al. 2006)

Longo et al. (2006) presented a very comprehensive paper on PMM experiments performed with the DTMB 5415 model during which, PIV measurements of unsteady flow were conducted at the propeller location, see Figure 34. In these experiments, the PIV system was supported by the PMM carriage, Figure 32, and followed the model during its harmonic motion, Figure 33.

The PIV was synchronized with the motion of the PMM carriage by the mean of equally spaced trigger pulses; the first pulse of the run being activated at a given position of the PMM carriage.

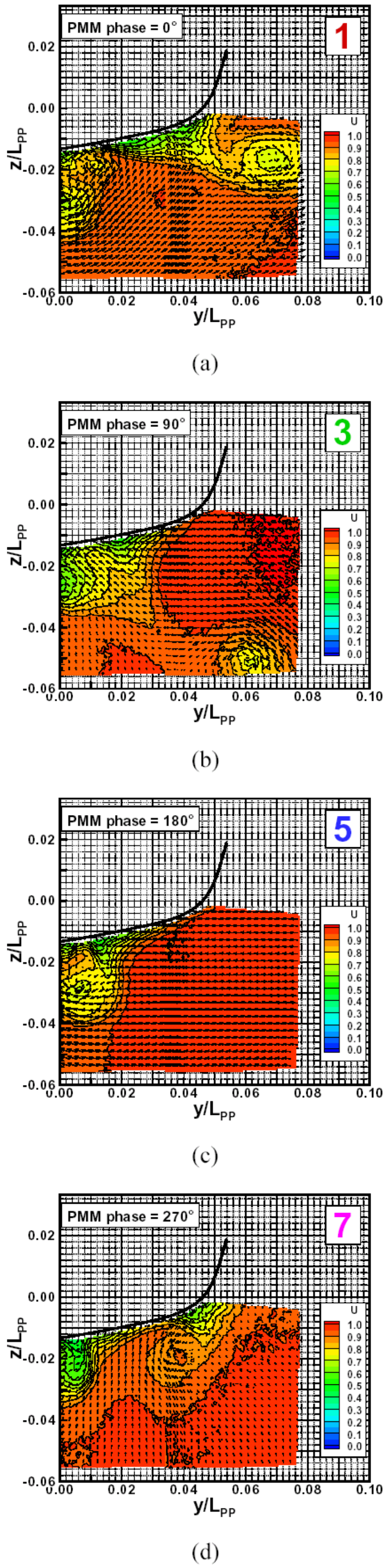


Figure 34 Axial velocity contour during pure sway experiments (Longo et al. 2006)

Runs were repeated to make sure the flow field data sufficiently converge. In addition to the UA for forces and moments coefficients described in the paper, these set of experiments also provide material for the completion of UA for the flow field data.

Jurgens et al. (2006a) also applied PIV technique to the measurement of the flow around a LNG Carrier model obliquely towed in shallow water.

Runs were carried out for three water depths from nearly deep water (h/T=5) to very shallow (h/T=1.3) and two values of drift angle (10 and 15°). The qualitative discussion regarding the uncertainty of the PIV measurement reported a significant influence of the PIV probe on the flow surrounding the model which could be detected through force measurements with and without the probe.

An interesting comparison in the time domain between the lateral location of the bilge vortex centre and the magnitude of the unsteady sway forces is presented in Figure 35.

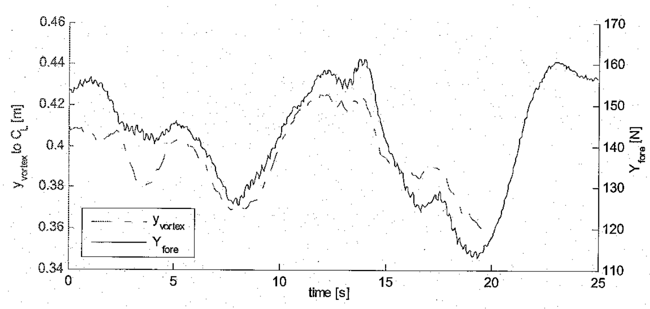
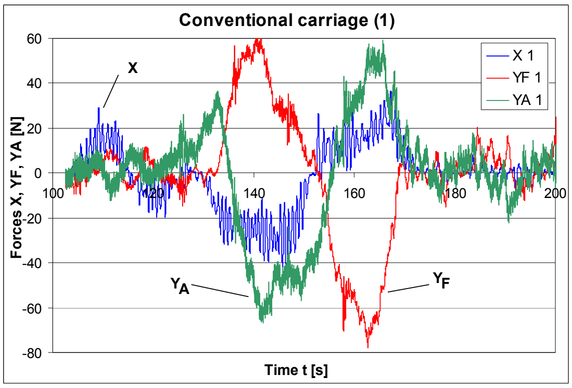


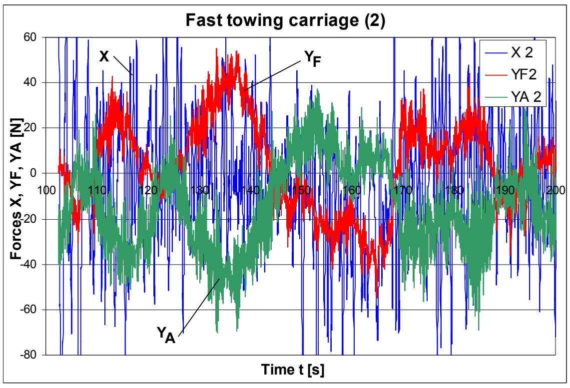
Figure 35 Time trace of sway force and transverse location of bilge vortex centre for 15° drift angle an h/T=1.3 (Jurgens et al., 2006b)

7.3 Captive Model Tests

Gronarz (2006) described ship to ship interaction experiments in shallow water using two carriages. Tests were conducted for overtaking and encountering manoeuvres. Figure 36 reproduces the time traces of forces and moments experienced by each of the two ships during an overtaking manoeuvre run.



Overtaken ship



Overtaking ship

Figure 36 Time trace of forces measured during model experiments of overtaking manoeuvre (Gronarz 2006)

7.4 Full Scale Manoeuvring

Ueno et al. (2006) mentioned the use of a real time kinematics GPS to contribute to the measurements of the 6 DOF motions of a planning craft during manoeuvring sea trials. This mode which requires an onshore antenna in addition to the onboard equipment can significantly improve the accuracy of the conventional DGPS system down to 20 mm in the horizontal plane and 40 mm in the vertical direction. Such figures allowed for the measurement of sinkage and trim during straight path, Figure 37, and during turning circle, Figure 38, where the influence of turning rate (rudder angle) on vertical displacement is clearly recorded although limited to just a few centimetres.

The resolution obtained by the kinematics mode of DGPS for the vertical displacement makes this technique well suited to squat investigation and the use of DGPS for that specific application was reported in several papers on the 2nd Squat workshop 2004.

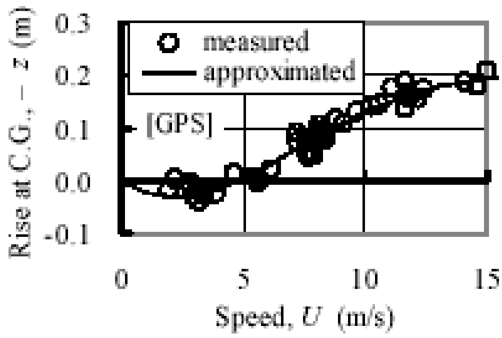


Figure 37 Rise of the CoG of a planning craft measured with Kinematic DGPS during straight path (Ueno et al. 2006)

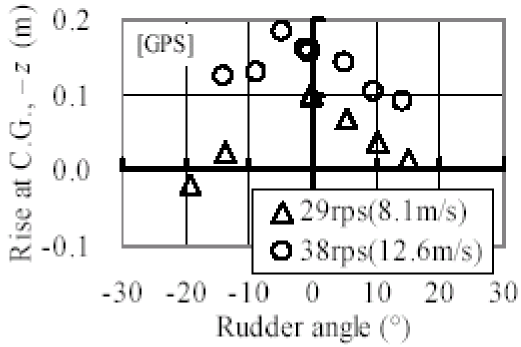


Figure 38 Rise of the CoG of a planning craft measured with Kinematic DGPS during steady turn (Ueno et al. 2006)

7.5 Concluding Remarks

Many efforts in manoeuvrability experimental works over the past years have been devoted to CFD validation. It is noticeable that many of the papers presented for that purpose now include uncertainty analysis.

Stereo PIV has become a mature technique enabling the assessment of the three components of the complex velocity field surrounding a manoeuvring ship or submarine.

DGPS in its kinematics mode provide a useful mean to measure accurately position in both horizontal and vertical plane. This latter should find useful application in full scale squat measurements.

No significant studies were recorded regarding the extrapolation methods for manoeuvrability predictions.

8. SHALLOW AND CONFINED WATERS AND SHIP-SHIP INTERACTIONS

In the 23rd ITTC report by the Manoeuvrability Committee (2002), a thorough overview, analysis and description of various empirical methods for confined waters and ship-ship interaction were given. In this review, as a continuous work of the 24th ITTC report by the Manoeuvrability Committee (2005), the focus is on:

- Shallow water effect on ship manoeuvring
- Hydrodynamic forces and moments in shallow water: mathematical model, captive test and CFD
- Manoeuvrability in muddy bottom area
- Ship-ship interactions
- Bank effect and squat

8.1 Shallow Water Effect on Ship Manoeuvring

Yasukawa and Kobayashi (1995) carried out free model tests (turning tests and spiral tests) in shallow and deep waters for four different kinds of ships as shown in Table 7. Figure 39 shows the comparison of turning trajectories for four ship models. There are two types of shallow water effects on the turning performance:

- Type-S: turning radius becomes large with decrease of water depth (see the test results of Ship A, Ship B and Ship D in Figure 39).
- Type-NS: turning radius becomes small with decrease of water depth (see the test results of Ship C in Figure 39).

Type-S is the typical shallow water effect that is widely known. The main cause of Type-S is due to increase of hull damping force in shallow water. Type-NS was first discovered by Yoshimura and Sakurai (1989) in wide-beam ship with twin propellers and twin rudders. This phenomenon is due to the increase of rudder force in high propeller load condition in shallow water. Figure 40 shows the comparison of spiral test results for full scale and model of Ship D (Esso Osaka Tanker). The full scale test was carried out by Crane (1979). In both full scale and model test results, instability with respect to course-keeping appears in medium water depth (h/d=1.5). Fujino (1968) found that instability appears in medium water depth for full hull form ships in captive model tests. The free model test can capture such instability phenomenon.

Table 7 Principal particulars of tested ship models

Kind	Ship A Container	Ship B LNGC	Ship C Special Cargo	Ship D Tanker
Ship Length (L_{pp})	4.200m	5.000m	5.500m	4.600m
Breadth (B)	0.709m	0.809m	1.531m	0.751m
Draft (d)	0.209	0.210m	0.240m	0.308m
Block Coeff	0.64	0.73	0.88	0.83
No.of Propeller	1	1	2	1
Propeller Dia.	0.158m	0.158m	0.137m	0.130m
No. of Rudder	1	1	2	1
Approach Speed	0.77m/s	0.36m/s	0.37m/s	0.31m/s
Water depth (h/d)	1.3, 1.5, 16.3	1.3, 1.5, 16.2	1.25, 1.5, 14.3	1.2, 1.5, 11.3
Remarks				Esso Osaka

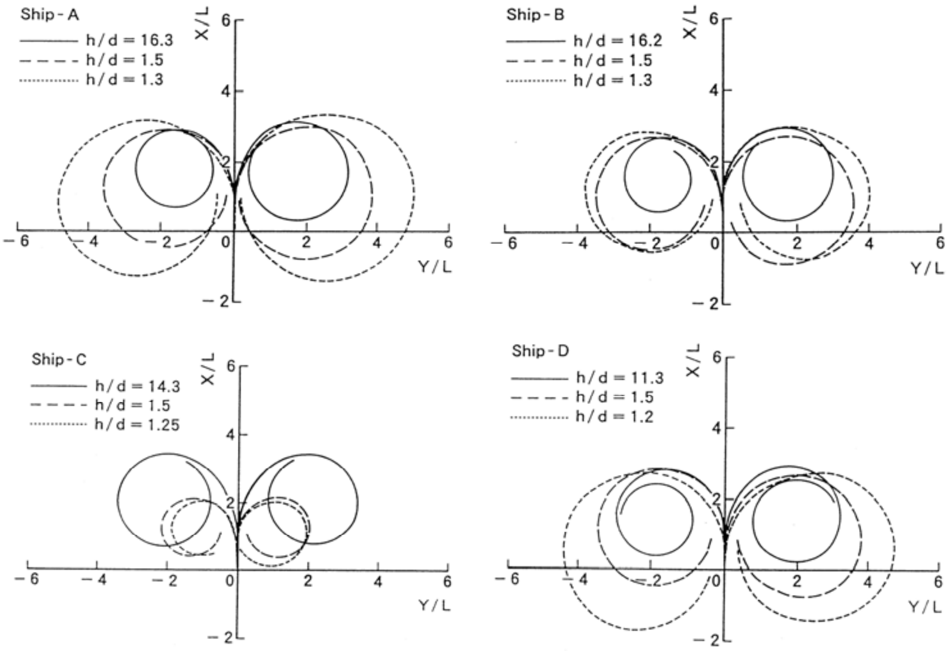


Figure 39 Comparisons of ship trajectories in shallow and deep waters

Lee et al. (2005, 2006a) carried out numerical simulations to investigate ship manoeuvring characteristics as a function of ship's body form in shallow water. Mathematical model proposed by one of the authors was used for the investigation. The most important factor is the ship's body form, especially aft hull form, in ship manoeuvring characteristics in shallow water together with the water depth.

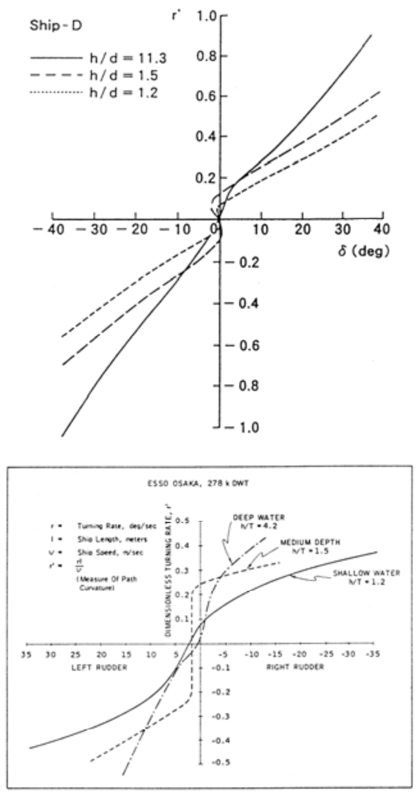


Figure 40 Comparison of spiral characteristics in full scale and model scale, full scale test was carried out by Crane(1979) (upper: model test, lower: full scale test)

8.2 Hydrodynamic Forces and Moments in Shallow Water: Approximate Formula, Mathematical Model, Captive Test and CFD

Kijima and Nakiri (2004) proposed approximate formulae for predicting the hydrodynamic derivatives in shallow water using only ship's particulars, stern form parameter and water depth. The results showed that the formulae are useful for manoeuvring simulations in deep and shallow water at initial design stage.

Okano et al. (2004) extended a component-type mathematical model which is useful to describe the ship hull hydrodynamic forces in slow speed manoeuvring motions in deep water to the hull hydrodynamic force problem in shallow water. The extended model can describe well the hydrodynamic forces within the range of conventional drift angle in shallow water as well as in deep water.

Eloot et al. (2006a) conducted captive model tests using a 4.3m model of an 8000TEU container ship (scale 1:81) combining three distinguished drafts and three under keel clearances from deep to very shallow water. The influence of combinations of draft and under keel clearance on the first quadrant of operation (forward motion, propeller ahead) as discussed based on the simulated characteristic dimensions of a turning circle.

Jurgens and Jager (2006b) carried out extensive captive static and dynamic model tests in a range of water depths to measure the behaviour of trailing suction hopper dredgers. Squat, manoeuvring, course keeping and speed/power relations were then correlated to model test results. A mathematical model describing the manoeuvring characteristics and squat response was developed and validated against the full scale and model scale data.

Simonsen et al. (2006) performed CFD simulations for flow around the bare hull of the KVLCC2 tanker in deep and shallow water using the RANS codes CFDSHIP-IOWA and COMET. The computed results were compared with oblique towing test data, see Figure 41. The two CFD codes capture the same trend showing a strong influence of water depth on the surge and lateral forces and yaw moment at low speed. The effects of free surface, speed, squat and towing tank blockage were also investigated. Further, Simonsen and Stern (2006) discussed the flow field around the KVLCC2 tanker in static drift in shallow water. The low speed results showed that the most significant changes, which also increases the forces and moments, are increased stagnation pressure in the bow, acceleration of the flow along the ship's sides and in the gap between ship and seabed, lower hull pressure and finally, stronger vortices along the bilges and weaker vortices with larger diameters in the wake.

Ong et al. (2007) simulated the ship manoeuvring motions in deep and shallow waters. Hydrodynamic force characteristics were estimated as follows: added masses by slender body theory, lateral force and yaw moment acting on the hull using cross flow model based on the 2D sectional drag, which was computed with a CFD program (FLUENT), and forces and moment arising from the propeller and rudder by semi-empirical approach. The comparison consisted of turning circle motion, zig-zag manoeuvres, and actual sea voyage data for a container ship, and yielded favourable agreement.

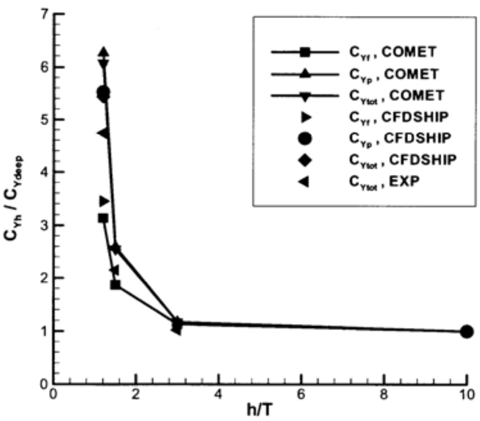


Figure 41 Shallow water effect on hull lateral force for drift angle 4 degrees

8.3 Manoeuvrability in Muddy Bottom Area

Delefortrie et al. (2005) carried out comprehensive series of captive model tests and developed mathematical manoeuvring models suited for simulation of harbour approach and harbour manoeuvres in muddy navigation areas with a broad range of mud characteristics (density, viscosity and layer thickness) in combination with both positive and negative values of under keel clearance (ukc). Some hydrodynamic forces change drastically when the ship's keel penetrates the mud, and other effects change rather smoothly at the transition from positive to negative ukc. The models were qualitatively validated by pilots with a comprehensive real-time simulation program. Using the hydrodynamic derivatives obtained in the captive model tests, Delefortrie and Vantorre (2006) analyzed the ship's straight-line stability in muddy area. Both a smaller ukc and the presence of a mud layer have a positive effect on the straight-line stability, although yaw oscillation appears when the stability indices become complex numbers. Further, Delefortrie et al. (2007) performed the full mission bridge simulation study to assess the manoeuvring of large container vessels in navigation areas with bottom mud deposits.

8.4 Ship-Ship Interactions

Varyani et al. (2004) developed new generic equations to estimate the ship-ship interaction forces and moments during overtaking manoeuvre for a ship manoeuvring simulator. However, the equations did not cover the case for zero velocity. Varyani (2006) presented a guide to the new generic equations for zero velocity (moored-passing ship) and for non-zero speed (ship-ship in encounter-overtaking-overtaken) manoeuvres on parallel courses. The research showed that the new generic equations are more accessible to a navigator, Master or pilot who could use it on a palmtop by keying in a few values relating to estimate of size, position and speed of the neighbouring ship.

Gronarz (2006) derived a mathematical model for overtaking and encountering of inland vessels in shallow water from the extensive test series and incorporated the model into a simulation program which computes the forces calculated by the mathematical model for the ship itself. A manoeuvring simulation in case that a large container ship overtakes a small ship was demonstrated as shown in Figure 42.

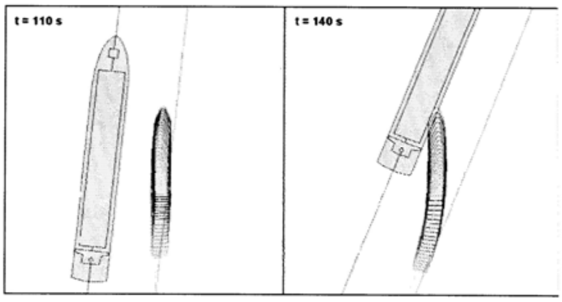


Figure 42 Snapshots of an overtaking manoeuvre (no counteraction)

Soeding and Conrad (2005) discussed a collision accident occurred between a large container ship and a small vessel when the large ship overtakes the small ship in a narrow waterway. A scenario reached to the collision was shown: "the small ship may be accelerated to the speed of the overtaking vessel and thus be caught in the depression of the water surface besides the large, overtaking ship, so that the overtaking can not be completed. If, in this case, the small ship reduces its propeller thrust to allow the passing of the large ship, the reduced rudder effectiveness will often be insufficient to counteract the yaw moment produced by the large ship. This may lead to collision".

de Koning Gans et al. (2007) applied the 3D panel method based on the Morino (1974) formulation to the problems of hydrodynamic interaction forces on passing ships under the hull drift. In the method a wake model was implemented to take lift effect of the hull into account. A double model flow model was used. It became clear that a flow description without the wake model did not represent fully the lift characteristics of a ship hull with a certain drift angle.

Chahine, G.L. et al. (2007) extended DYNAFLOW's boundary element method code for applications of hydrodynamic problems of multiple vessels in harbour. The improved code was applied to various harbour ship interaction problems such as ship to ship interactions of passing ships in a channel. Numerical simulations demonstrated that the code was able to generate useful hydrodynamic information regarding interaction forces and ship response motions.

Zhang et al. (2007) presented a numerical simulation of multiple ships travelling in close proximity to each other at the same forward speed in waves using the 3D time domain panel code LAMP_Multi. A validation for LAMP_Multi was carried out using model tests for two ships travelling. The ship motion and forces predicted by LAMP_Multi agree well with the model test results. Weems et al.(2007) presented sample results for ship-to-ship transfer of cargo in a seaway using the LAMP-based simulation system with models for fenders, cables and other mechanical interaction systems. A validation study for two ships operating close alongside in a seaway suggested that the key hydrodynamic motions and forces were well predicted by the LAMP-based simulation system.

8.5 Bank Effect and Squat

Lataire et al. (2007) carried out model tests to investigate bank effects induced by sloped surface-piercing as well as submerged banks. The influence of the geometry of the bank, and the height of the submerged platform in particular, on the magnitude of the bank effects was investigated, see Figure 43. Based on the test results, a formula was given for the maximal distance between ship and bank to have a significant influence of the bank on ship hydrodynamics.

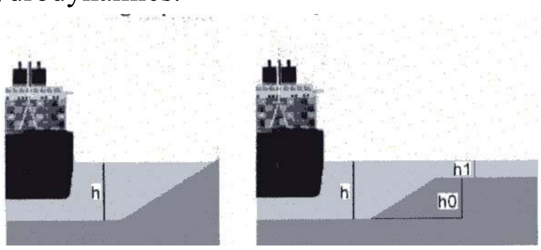


Figure 43 Surface piercing bank and bank with platform submergence

In 2004, "2nd Squat-Workshop: Aspects of Underkeel Clearance in Analysis and Application" was held in Elsfleth, Germany. In the workshop, 13 papers were presented concerning prediction method of squat, full scale measurement of squat using DGPS, model testing, numerical modelling for squat prediction, motion response in waves and ukc management, etc.

8.6 Concluding Remarks

Many studies on shallow and confined waters and ship-ship interactions have been done over the past three years. Extensions have been made for complicated problems such as muddy bottoms and ship-ship interaction in waves.

More effort is needed both, experimentally and numerically, for better understanding of the ship manoeuvrability in the confined waters. Only few significant studies concerning bank effect have been reported.

9. STANDARDS AND SAFETY

Since IMO standards for ship manoeuvrability MSC.137(76) (IMO, 2002) were adopted, there have been no further developments or discussions on this issue at IMO. It looks like that ship designers and ship owners have generally accepted IMO standards as minimum criteria at least for conventional ships to be satisfied for safety of navigation. However, there also have been some concerns that IMO standards are not enough to cover safety for some real situations and for some special ships. This section will review available literature regarding IMO manoeuvring standards and other standards related to safety but not covered by the current IMO manoeuvring standards.

9.1 IMO Manoeuvring Standards

Application of IMO manoeuvring standards. Since IMO adopted new manoeuvring standards MSC 137 (76) in 2002 (IMO, 2002), efforts have been made constantly to meet IMO manoeuvring standards by improving the prediction methods for manoeuvring performance available at the initial design stage or by adopting efficient steering system.

Lee et al. (2003) proposed a new empirical formula of hydrodynamic coefficients to be applicable to modern hulls with stern bulb using PMM test results. They introduced simple parameters representing stern hull forms and improved their prediction. They demonstrated the accuracy of their method by comparing their predictions with sea trial data of 14 ships, including 8 tankers, 2 bulk carriers, three container ships and 1 LNG carrier, at full load and ballast conditions.

Double-ended ferries often have problems in course keeping ability due to unfavourable dimensions. To solve this problem, Krüger et al. (2007) adopted a highly efficient twist flow rudder of FSG type, see Figure 44, that was designed for both the maximum lift and quick rudder actions due to good balancing. The rudder was designed by the application of a nonlinear panel method for rudders in the propeller slipstream. They confirmed by numerical simulations that their ship had a far better manoeuvring performance than IMO standards.

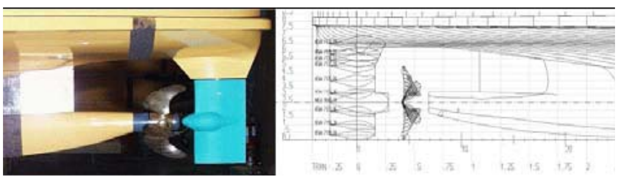


Figure 44 Propulsion and rudder arrangement

IMO standards were developed based on the experience of ships with traditional propulsion and steering systems. But IMO standards are applied also to non-conventional ships for example POD ships and twin-skeg container ships. Therefore, the standards need to be reviewed continually and to be updated, if necessary, based on the results of experience.

POD ships generally have excellent controllability. But some POD ships have difficulty in meeting IMO standards for course keeping due to open stern profile. Kim & Kim (2006) have investigated the manoeuvring performance of an Ice-breaking ship with twin POD propulsion system by free model tests and PMM tests. POD ship showed excellent turning performance but marginally satisfied IMO manoeuvring standards for 10/10 zigzag test.

Ayaz et al. (2006d) studied numerically and experimentally the induced heeling during turning manoeuvre for a high-speed POD-driven ROPAX and Cargo ship. They pointed out that large roll motion can be induced for POD ship due to high turning rate and speed.

Recently the size of container ships has been increased very rapidly. As the size gets larger than 12,000 TEU, twin-screw and twin-rudder system is inevitably required to provide sufficient power. Kim et al. (2006) investigated the manoeuvring performance of this new-type ship with twin-skeg hull form by model tests and simulation. They also compared the manoeuvring performance of a twin-skeg container ship with a single skeg container ship with same principal dimensions. Table 10 shows manoeuvring performance of two ships from free model test. The twin-skeg container ship has better course keeping and yaw checking performance but worse turning performance than the single skeg ship. Both ships satisfy IMO standards with a sufficient margin.

Coccoli et al. (2006) have carried out sea trials for two high speed crafts (a catamaran and a monohull) to determine the steering and manoeuvring characteristics of two vessels. The two ships have different hull forms and different propulsion systems, but they have similar characteristics in terms of displacement, speed and passenger capacity, Table 8. Due to high speed, both ships strongly exceed IMO standards for turning circle parameters, as shown in Table 9. For 10°/10° zig-zag tests, both ships also exceed the initial turning ability and overshoot angle limits. They claim that the present IMO standards are not adequate for high speed craft. They also recommend that more systematic full-scale trial data should be accumulated to develop new standards for high speed craft.

Table 8 High speed craft, Main characteristics

Main Characteristics	Catamaran	Monohull
Overall length	43.70m	46.90m
Length at waterline	36.35m	37.09m
Maximum beam	10.50m	7.6m
Full load displacement	148.75ton	137.66ton
Maximum speed	31.5kts	33kts
Propulsion	2*hydro-jet	2*azipod
Passenger capacity	354	356

Table 9 High speed craft, Turning parameters

	Catamaran	Monohull
Advance	14.2L	10.9L
Tactical Diameter	5.3L	18.8L

Table 10 Manoeuvring indices for twin-skeg and single skeg container ships

Test	Index	Twin	Single	IMO Standards
10°/10° Zig-Zag	1st Overshoot	4.9°	10.9°	19.7°
	2nd Overshoot	6.1°	13.8°	39.6°
	Initial Turning Path	2.2L	1.7L	2.5L
20°/20° Zig-Zag	1st Overshoot	8.9°	15.9°	25.0°
35° Strbd. Turn	Advance	3.7L	3.2L	4.5L
	Tactical Diameter	4.2L	3.0L	5.0L

Trial correction methods. Compliance with the IMO manoeuvring standards should be evaluated at deep water, calm environment and full load, even keel conditions. The calm environment conditions are specified more in detail in the "Explanatory Notes to the Standards for Ship Manoeuvrability" (IMO MSC/Circ.1053(2002) as follows:

1. Wind: not to exceed Beaufort 5
2. Waves: not to exceed sea state 4
3. Current: uniform only

However, it is not practically easy to satisfy the above standard conditions during sea trials. Firstly, most sea trials including speed tests are carried out at the design draught. Thus, the trials at full loading condition require extra time and expenses. Furthermore, in case of dry cargo ships such as container ships, it is much more difficult to carry out sea trials at the full load condition. Secondly, it is not easy to find a sea trial site and weather conditions which satisfy above conditions as reported by Sung, Ahn and Lee (2007).

Considering these problems, IMO Explanatory Notes proposes correction methods from non-standard trial conditions related with loading and environment. However these correction methods are developed somewhat more intuitively than scientifically. So, they need to be improved.

Sung, Ahn and Lee (2007) proposed a new method for the correction of current effects not only from the turning circle test but also from the zigzag tests. Firstly they estimated the magnitude and direction of the current during the sea trials with filtered data of the position, water track speed and heading angle of the ship. Then they estimated the manoeuvring coefficients in the equations of motion by multiple regression analysis. Finally, they predicted the trajectory of a turning circle and the heading angle of a zigzag test at calm sea with those estimated manoeuvring coefficients. With the application of their method to Crude oil tanker, Gas carrier and Container carrier, they showed that their method could be used well for the correction of turning and zigzag tests carried out in current, Figure 45.

Yasukawa (2006a) carried out free model tests in irregular waves using the S-175 container ship model. Table 11 shows turning indices in irregular head waves. As the sea state becomes higher and the wave length becomes longer, the advance becomes smaller. But the effects of waves appear to be small up to sea state 4.

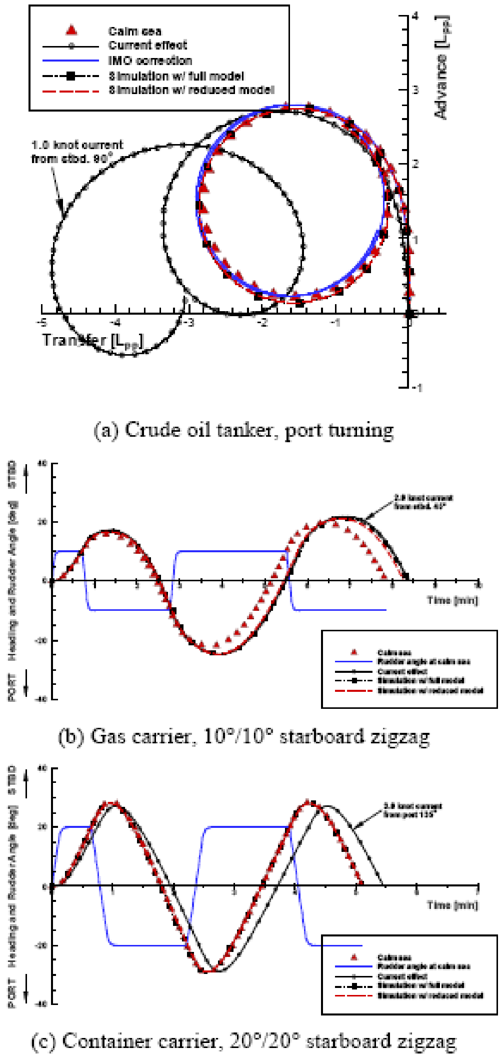


Figure 45 Corrected trajectories of turning circle and heading angles of zig-zag tests (Sung, Ahn and Lee, 2007)

Kijima et al. (2006b) investigated the effect of external disturbances such as wind and waves on manoeuvring motion, especially for verification of IMO resolution MSC.137(76) by numerical simulation. Simulation has been done for turning and zigzag manoeuvres for four ships: container ship, cargo vessel, VLCC and chemical tanker. Figure 46 shows the variation of advance and tactical diameter for the container ship depending on the condition of external disturbance. Radial axes indicate the ratio of advance and tactical diameter under external disturbances to those in calm environment and the direction of each axis represents initial wave direction. It can be seen that the conditions of wind and waves at sea trials have large influence upon the evaluation of ship manoeuvring performance, even if the condition of external disturbances is recognized as "calm environment". Figure 49 displays variation of performance indices for several angles of encounter as function of $(1\text{-}C_B)\ L/d$. This kind of figures can be used to correct the effects of external disturbances.

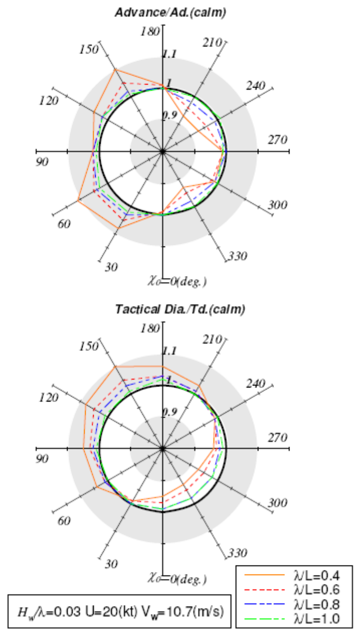


Figure 46 Variation of advance and tactical diameter: container ship, (Kijima et al, 2006b)

Gong et al. (1998) have investigated the effects of loading conditions on the manoeuvring performance by carrying out HPMM test for the Aframax tanker at four different loading conditions. They showed that the manoeuvring performance changed significantly with loading condition, Figure 47. Based on these results, they proposed a method to predict the manoeuvring performance at full load condition using the HPMM data at design draft, Figure 48.

Table 11 Turning indices in irregular waves (χ=0 deg) (from Yasukawa, 2006a)

λ/L	δ=35deg		δ=-35deg	
	A_D/L	D_T/L	A_D/L	D_T/L
Still water	3.61	4.30	3.65	4.22
sea state 4(long)	3.63	4.42	3.55	4.47
sea state 4(short)	3.50	4.35	3.22	4.27
sea state 5(long)	3.37	4.22	3.51	4.40
sea state 5(short)	3.19	4.10	3.24	4.27

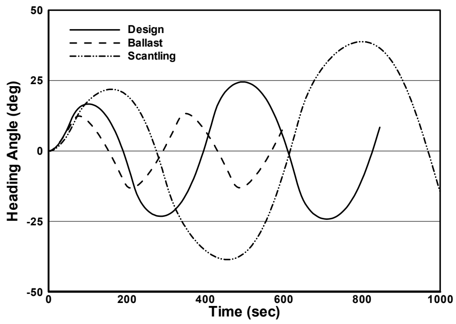


Figure 47 Comparison of $10^o/10^o$ zig-zag Tests at different loading conditions (Gong et al., 1998)

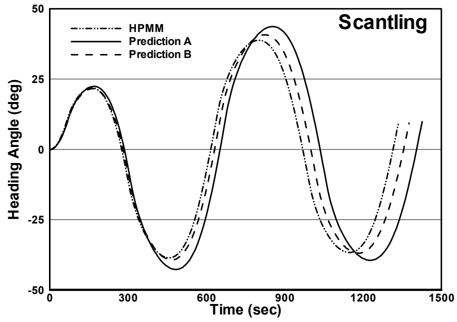


Figure 48 Prediction of $10^o/10^o$ zigzag tests at full load: HPMM represents prediction with HPMM data at full load, prediction A and B represent predictions based on HPMM data at design draft (Gong et al., 1998)

Issues and Shortcomings of IMO manoeuvring standards. Although IMO MSC/Circ.1053 is adopted to prevent accidents from ships with poor manoeuvring performance, they are minimal standards and relate only to a small portion of safe manoeuvring. As shortcomings of the IMO standards, Dand (2003) summarized as follows:

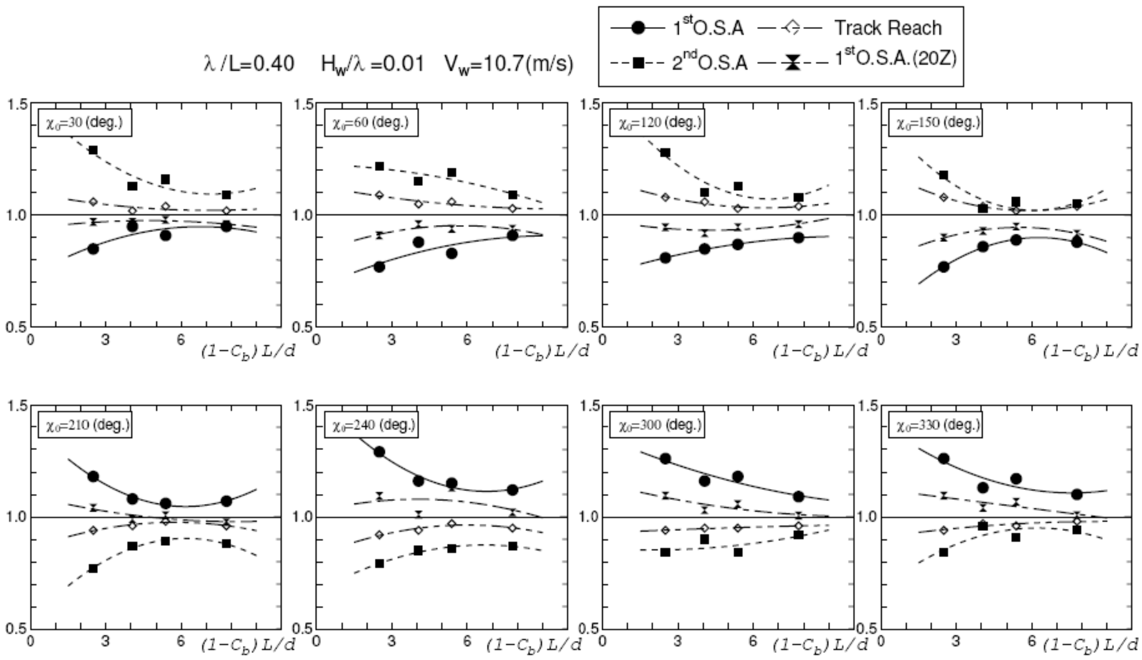


Figure 49 Effects of disturbance on the zigzag indices with function of $(1\text{-}C_B)$ L/d

- IMO standards may not be valid for low speed manoeuvring in ports, because they are for deep water and design speed only.
- They are for calm conditions only and give no indication of the qualities in wind, current or waves.
- They cover standard manoeuvres only and do not necessarily cover the type of manoeuvring normally carried out by most merchant ships.
- The full astern stopping test on trials puts too much strain on the prime mover and propulsion train.
- The criteria are derived from databases heavily biased toward tankers and bulk carriers.

In practice, the following additional matters relating to safety but not dealt with by current IMO standards are stated as important to be investigated (Quadvlieg and Coevorden, 2003):

- Adequate manoeuvrability in shallow waters
- Maximum achievable wind forces for harbour manoeuvring
- Low-speed manoeuvring capabilities
- Steering in wind and waves at relatively high speeds including ability to execute 180 degrees turn in waves.
- Limited heel angles

Nishimura et al. (2003) have investigated the manoeuvrability of unstable ships from the viewpoint of position control. They have carried out a simulation study for passing a narrow waterway using a ship-handling simulator by an experienced mariner. With the results, they concluded that the present standards are not enough for mariners to keep safe navigation in a restricted water area.

Some ships need to have much better manoeuvring performance than IMO standards to fulfil their mission. Belenky and Falzarano (2006) proposed a rating-based manoeuvring standard, which combines the IMO requirements as a minimum with a slightly improved rating-base system.

9.2 Low Speed Manoeuvring Standards

The most critical manoeuvres and accidents occur near harbours with shallow and restricted water and at low speeds. However, IMO manoeuvring standards are based on manoeuvring performance at sea speed and in deep and unrestricted water and they have little relevance at low speed and in shallow water. For this reason the need for low speed manoeuvring criteria have been constantly raised (Landsburg, 2003; Quadvlieg and Coevorden, 2003; Hwang et al, 2003; Dand, 2003; Dand, 2005).

SNAME Panel H-10 performed a study of the issues of characterizing slow ship manoeuvring performance (Hwang et al., 2003). They surveyed senior mariners, simulator operators and other relevant professionals to collect information on the characteristics of slow speed manoeuvring. They also considered that the test procedure should not be complex and the performance indices should be easy to derive, intuitive, quantifiable, and of practical use to both operational people and technical people. Based on the survey results and the requirement of tests, they proposed eleven basic slow speed manoeuvres, Table 12, and eight additional manoeuvres, Table 13, for ships with twin screws and ships with bow/stern thrusters.

It is very difficult to apply low speed manoeuvring standards based on sea trials as for the IMO manoeuvring standards, because it is not easy to find a suitable shallow water area with constant depth. Dand (2003) proposed to use a combination of a simulation model and suitable indices, derived from past best practice, for assessing the low speed manoeuvrability of vessels. He suggested two sets of indices, where one set is derived from the geometry of the ship such as rudder area ratio, lateral ratio and lateral and above-water aspect ratio, and the other set consists of operational indices such as limiting Froude depth number, lateral thruster power per square metre and depth/draught ratio. As for low speed manoeuvring tests which can be assessed relatively easily by either sea trials or simulations, he suggested stopping, breasting and kick ahead tests.

Table 12 Suggested Basic Slow Speed Manoeuvres (Hwang et al, 2003)

NAME OF MANEUVER	TEST PURPOSES
Minimum Effective Rudder(MER)	- Least rudder angle that can be applied and still effect yaw checking at speeds ranging from cruising to slow speed at each engine order
Crash Stop from HALF AHEAD(HAHD) speed	- Ship's stopping capabilities from a speed which is relevant in harbour operation - Ship's dynamic response to throttle order when operating in transition from Quadrant 1→4 - Paddlewheel Effect/Stern Walk
Acceleration/Deceleration Combinations(start from & back to Dead In Water)	- Ship's dynamic response to throttle order when operating in transition from Quadrant 1→4→3 - Paddlewheel Effect/Stern Walk
Backing/Stopping Combinations (start from & back to DIW)	- Ship's dynamic response to throttle order when operating in transition from Quadrant 3→2→1 - Paddlewheel Effect/Stern Walk
35° Accelerating Turn Starting from DIW with SAHD bell	- Ship's ahead turning capability during acceleration at slow speed
35° Coasting Turn from SAHD speed	- Ship's ahead turning capability at slow speed during deceleration with propeller(s) wind milling or possibly stopped
20°/20° Overshoot Test with SAHD approaching speed	- Ship's yaw checking capability at a speed which is relevant in harbour operation
20°/20° Accelerating Overshoot Test Starting from DIW with SAHD bell	- Ship's yaw checking capability during acceleration ahead at slow speed
20°/20° Coasting Overshoot Test with SAHD or HAHED approaching speed	- Ship's yaw checking capability at slow speed during coasting ahead with propeller(s) wind milling or possibly stopped
Back & Fill with Fill First (for both Starboard Filling and Port Filling)	- Ship's maneuverability in tight space - Interactions between hull, propeller, and rudder when operating in transition from Quadrant 1→4→3
Back & Fill with Backl First (for both Starboard Filling and Port Filling)	- Ship's maneuverability in tight space - Interactions between hull, propeller, and rudder when operating in transition from Quadrant 3→2→1

Table 13 Suggested Additional Slow Speed Tests (Hwang et al, 2003)

NAME OF MANEUVER	TEST PURPOSES
Twist from DIW Stop from HALF (A Differential Thrust test with equal but opposite throttle orders for starboard and port)	- Twin-screw ship twisting capability using propellers only. If ship gains headway, one propeller in Quad 1, the other propeller in Quad 4. If ship gains sternway, one propeller in Quad 2, the other propeller in Quad 3.
Twist with Full Rudder from DIW	- Twin-screw ship twisting capability assisted by rudder
Bow Thruster Turn with Throttle at STOP	- Effectiveness of bow thrusters with no initial ship speed
Stern Thruster Turn with Throttle at STOP	- Effectiveness of stern thrusters with no initial ship speed
All Thruster Twist with Throttle at STOP	- Twisting capability using bow and stern thrusters with no initial ship speed
All Thruster Lift(Lateral Push) Maneuver with Throttle at STOP	- Lifting capability using bow and stern thrusters with no initial ship speed
Bow Thruster Accelerating Turn with SAST bell	- Effectiveness of bow thruster with accelerating sternway
Bow Thruster Accelerating Turn with SAHD bell	- Effectiveness of bow thruster with accelerating headway
Stern Thruster Accelerating Turn with SAHD bell	- Effectiveness of stern thruster with accelerating headway
Stern Thruster Accelerating Turn with SAST bell	- Effectiveness of stern thruster with accelerating sternway

The low speed manoeuvring performance is often required not for safety but for fulfilling a certain mission. Minimum wind speed at which ship can leave the quay is often used as a criterion (Quadvlieg and Coevorden, 2003). 20 knots wind is generally used for this criterion but for ferries and cruise liners 30 knots is used occasionally. Another criterion that is seen more and more is the ability to turn on the spot within a square area of 2 ship lengths within a certain time (Quadvlieg and Coevorden, 2003).

9.3 Other Standards

Criteria for certification of mathematical models for simulators. With increasing application of ship-handling simulators, there is a strong demand for the validation of the mathematical model in the ship-handling simulator.

IMSF (International Maritime Simulator Forum) has launched a research project on model documenting guidelines for ship-handling simulators (Hwang, 2004a & 2004b, Endo, 2006). IMSF have developed two guidelines for a ship model and a mathematical model. A ship model document includes enough manoeuvring information to handle a target vessel for the simulator users. A mathematical model document describes the outline of the mathematical modelling and the limitations of the valid model usage for the simulator users.

Lebeca et al. (2006) proposed a method for evaluating the adequacy of mathematical models for ship-handling simulators. They classified the mathematical model adequacy into three according to the problems to be dealt with in the simulator. They also proposed a method for evaluating modelling errors by introducing error regions.

Other criteria. Quadvlieg and Coevorden (2003) summarized criteria which are not covered by IMO standards but are considered in practice:

- The residual rate of turn ratio should below 0.3.
- The maximum heel angle due to steering should be below 13 degrees.
- The constant heel angle due to steering should be below 8 degrees.

- Necessary rudder angle in wind of 40 knots at 8 knots ship speed should be less than 20 degrees.
- The ship must be able to execute a 180 degrees course change with an initial speed of 40% of the maximum speed and at a rudder angle of 2/3 of the maximum rudder angle in waves of 6 metres height.

However, some of above criteria are dependent on ship size. So, they should be made ship-size-independent before they can be generalized.

10. PROCEDURES

10.1 Status of MC QM procedures

The MC reviewed QM procedures under its responsibility and made updates as following:

- 7.5-02-05-05 Maneuverability of HSMV: No necessary changes found.
- 7.5-02-06-01 Free Model Tests: Some improvements have been made, e.g. including limits and/or usual values of relevant parameters.
- 7.5-02-06-02 Captive Model Tests: Classification of different manoeuvring tests was changed to include other tests, especially for 4-DOF mathematical models. Distinction has been made between traditional PMM and CPMC (i.e. independent drives) systems. Section 4.2 was extracted because a proposal for a separate procedure on UA for captive model tests has been written.
- 7.5-02-06-03 Validation of Maneuvering Simulation Methods: Clearer distinction between *validation* and *documentation* of the simulation model. Introduce useful examples of documentation. Include mention of new benchmark data i.e. SIMMAN 2008
- 7.5-02-02-01 Full Scale Manoeuvring Trials: The procedure has been rewritten. Corrections and changes in its structure have been done and it has been made more consistent with the IMO recommendations. Outline and guidelines for GPS measuring techniques have been included. However, no procedure for MHSV and for podded driven vessels could be included because there is no common procedure at present. Research on limiting environmental conditions is still in progress so this has not been included yet.

Additionally the MC was given the task to prepare a new procedure for Uncertainty Analysis (UA) on Captive Model Tests. A proposal for a new procedure has been prepared and reviewed by the Quality System Group and Special Committee on UA. The methodology of the proposed procedure is described in Section 10. Further, UA results are compared between facilities followed by evaluations of conceptual biases such as asymmetry and facility biases. UA for free model tests was not covered by this MC.

10.2 UA Example for PMM Tests

An example of UA is provided for model scale towing tank Planar Motion Mechanism (PMM) tests following the 7.5-02-01-01 Rev 00, 'Uncertainty Analysis in EFD, Uncertainty Assessment Methodology' and 7.5-02-01-02 Rev 00, 'Uncertainty Analysis in EFD, Guidelines for Towing Tank Tests.' The approach follows errors/uncertainties definitions, systematic/random categorizations, and large sample size/normal distribution 95% level of confidence assumptions, as provided by the AIAA, AGARD, and ANSI/ASME standards.

The example is developed in collaboration between IIHR-Hydroscience & Engineering (IIHR), Force Technology (FORCE), Istituto Nazionale per Studi ed Esperienze di Architettura Navale (INSEAN), and the 24th – 25th MC, including overlapping tests using the same model geometry and identification of facility biases. The example does not provide UA for hydrodynamic derivatives or their effect on the full scale maneuvering simulations. Details of the results are presented in Yoon et al. (2008), Simonsen (2004), and Benedetti et al. (2006) for IIHR, FORCE, and INSEAN, respectively.

PMM Test and UA Procedure. Static drift, pure sway, pure yaw, and yaw and drift tests are carried out at three towing tank facilities for ship models of same geometry but with different size. Facility dimensions L(m)×W(m)×D(m) are 100 ×3×3, 240×12×5.5, and 500×12.5×6.5, respectively, and model size L_{pp} (m) is 3.048, 4.002, and 5.720, respectively. The model geometry is DTMB model 5415 (5512) which is one of the 24th MC designated benchmark hull forms and used at the SIMMAN 2008 Workshop. The ship models are un-appended except for bilge keels, and mounted free to heave and pitch but fixed in roll.

Hydrodynamic forces and moment X, Y, N, are non-dimensionalized as per equations (1) – (3) denoted with a prime symbol.

$$X' = \frac{F_x + m(\dot{u} - vr - x_G r^2 - y_G \dot{r})}{1/2 \rho U^2 T_m L_{pp}} \quad (1)$$

$$Y' = \frac{F_y + m(\dot{v} + ur - y_G r^2 + x_G \dot{r})}{1/2 \rho U^2 T_m L_{pp}} \quad (2)$$

$$N' = \frac{M_z + I_z \dot{r} + m(x_G(\dot{v} + ur) - y_G(\dot{u} - rv))}{1/2 \rho U^2 L_{pp}^2} \quad (3)$$

where $U = \sqrt{u^2 + v^2}$. In general y_G = 0, but it is assumed to be non-zero for UA. For static drift tests the inertia terms in the numerator of (1) – (3) are zero and U is the towing speed U_C.

Carriage speed U_C, ship model motions (y, ψ), and forces and moments (F_x, F_y, M_z) are acquired as time histories through each carriage run. For the dynamic tests, the resultant time histories are reconstructed with a Fourier series (FS) equation to filter out possible electrical and/or mechanical noise.

Statistical convergence of F_x, F_y, M_z is estimated based on the convergence of running mean (RM) values with amplitude U_{SC}. As an alternative approach for dynamic test data, convergence of FS harmonic amplitude H is also estimated defining U_{HSC} from RM of H similarly for U_{SC}. Measurement uncertainty U_F is used as the convergence criteria. For static drift test, U_{SC} is smaller than U_F indicating statistical convergence. On the other hand, U_{SC} of dynamic test data is larger than U_F for the most of cases. However, U_{HSC} values are smaller than U_F for all dynamic test data indicating statistical convergence of FS harmonic amplitudes.

UA is applied to data reduction equations (1) – (3), which are rewritten in functional form

$$\mathrm{r}(x) = \mathrm{r}\begin{pmatrix} L_{pp}, T_m, x_G, y_G, m, I_z, \rho, \\ u, v, r, \dot{u}, \dot{v}, \dot{r}, F \end{pmatrix} \quad (4)$$

for dynamic tests, and

$$\mathrm{r}(x) = \mathrm{r}\left(L_{pp}, T_m, \rho, U_C, F\right) \quad (5)$$

for static drift tests, where r is X', Y', N', and F is F_x, F_y, M_z, respectively.

The total bias B_{r} can be determined as the root-sum-square (RSS) of the elemental biases B_x and their sensitivity coefficients θ_x.

$$B_{\mathrm{r}}^2 = \sum\nolimits_x \theta_x^2 B_x^2 \quad (6)$$

Sensitivity coefficients $\theta_x = \partial \mathrm{r} / \partial x$ are evaluated analytically. $B_{L_{pp}}$, B_{T_m}, B_{x_G}, B_{y_G} are estimated from errors in the model manufacturing and tank installation. B_m is the RSS of the mass scale reading errors including the model ship and ballast weights. B_{I_z} is derived from a series of independent I_z tests. B_ρ is taken from the ITTC 1963 density-temperature formula. As per B_{I_z}, B_{U_C} is derived from a series of independent U_C tests. B_u, B_v, B_r, $B_{\dot{u}}$, $B_{\dot{v}}$, $B_{\dot{r}}$ are biases derived from the specific equations of PMM motion. B_F is decomposed into elemental biases. $B_{F,\beta}$ and $B_{F,align}$ are model installation errors.

$B_{F,acquis}$ and $B_{F,calib}$ are associated with the volt-force conversion and calibration standard weight inaccuracies, respectively. $B_{F,u}$, $B_{F,v}$, $B_{F,r}$, $B_{F,\dot{u}}$, $B_{F,\dot{v}}$, $B_{F,\dot{r}}$ are estimated errors incurred from modeling F as polynomial functions of related motion parameters. Finally, $B_{F,t}$ is the error associated with data sampling time scale.

The precision limits are determined end-to-end from 12 repeat tests. The datasets are spaced in time at least 12 minutes between tests to minimize flow disturbances from previous runs. The model is not dismounted and re-installed during the repeat tests. However, the PMM motion control parameters, such as drift angle, sway crank amplitude, or maximum heading angle settings are changed between tests. The precision limits are computed with the standard multiple-test equation

$$P_{\mathrm{r}} = \frac{\mathrm{t}\, S_{\mathrm{r}}}{\sqrt{M}} \tag{7}$$

where t = 2 is the coverage factor for 95% confidence level, and S_{r} is the standard deviation from the average of M repeat measurements.

The total uncertainty for the average result is the RSS of B_{r} and P_{r}.

$$U_{\mathrm{r}}^2 = B_{\mathrm{r}}^2 + P_{\mathrm{r}}^2 \tag{8}$$

A conceptual asymmetry bias B_{asym} is defined if data asymmetry is larger than U_{r} as:

$$U_{T1}^2 = U_{\mathrm{r}}^2 + B_{asym}^2 \tag{9}$$

Another conceptual facility bias B_{FB} is defined if the difference of each facility data from the facility mean is larger than U_{T1} as following:

$$U_{T2}^2 = U_{T1}^2 + B_{FB}^2 \tag{10}$$

For static drift test, B_{U_C} and B_F are the primary biases. $B_{L_{pp}}$, B_{T_m}, B_ρ are small or negligible. In general, B_{r} contributes over 90%, and P_{r} contributes less than 10% to U_{r} indicating results are highly repeatable. U_{r}'s are reasonably small, 2% ~ 4%, but relatively large compared with the resistance test uncertainty U_{C_T} = 0.67% reported in the 7.5-02-02-02 Rev01, 'Uncertainty Analysis, Example for Resistance Test'.

For dynamic tests, primary biases are B_F and B_u, B_v, B_r, $B_{\dot{u}}$, $B_{\dot{v}}$, $B_{\dot{r}}$, where for the latter their contributions vary according to test type. $B_{L_{pp}}$, B_{T_m}, B_{x_G}, B_{y_G}, B_m, B_{I_z} and B_ρ contribute small or negligibly. B_{r} dominates over P_{r} for Y' and N', but not for X'. U_{r} is 6% ~ 11%, 5% ~ 37%, and 3% ~ 5% of X', Y', and N', respectively.

UA Comparisons Between Facilities. UA comparisons at Fr = 0.280 are presented in Table 14. For static drift test, B_{r} is more dominant than P_{r} in most cases for IIHR and FORCE data, whereas B_{r} and P_{r} are comparable for INSEAN data. U_{r} is 2% ~ 3%, and observed to be smaller than those of the dynamic tests.

For dynamic tests, both B_{r} and P_{r} are significant for X' of IIHR and INSEAN data, but B_{r} is dominant for FORCE data. For Y' and N', B_{r} is dominant for IIHR and FORCE data, but P_{r} is also significant for INSEAN data. U_{r} is reasonably small < 8%, < 11% and < 5% of X', Y' and N', respectively, and tends to become smaller for bigger model and/or facility size.

Table 14 Comparisons of UA between facilities

Test	Facility	X' (%) B_{r}	X' (%) P_{r}	X' (%) U_{r}	Y' (%) B_{r}	Y' (%) P_{r}	Y' (%) U_{r}	N' (%) B_{r}	N' (%) P_{r}	N' (%) U_{r}
Static drift	IIHR†	97	3	1.9	95	5	3.4	95	5	2.8
	FORCE‡	78	22	3.4	74	26	2.1	21	79	2.4
	INSEAN‡	47	53	1.4	52	48	3.3	48	52	3.1
Pure sway[1)]	IIHR	35	65	5.8	73	27	5.5	98	2	4.2
	FORCE	98	2	3.1	98	2	1.8	93	7	1.5
	INSEAN	47	53	1.3	66	34	2.1	73	27	1.8
Pure yaw[2)]	IIHR	24	76	7.6	88	12	10.8	90	10	2.9
	FORCE	99	1	3.4	93	7	5.5	94	6	3.3
	INSEAN	53	47	1.7	86	15	4.6	60	40	1.4
Yaw And drift[2)]	IIHR	32	68	6.8	80	20	4.7	93	7	4.9
	FORCE	99	1	5.8	89	11	2.1	98	2	2.7
	INSEAN	68	32	1.3	74	26	3.5	64	36	4.4

† at β = -10°; ‡ at β = 10°; 1) at $v' = v'_{max}$; 2) at $r' = r'_{max}$

Evaluation of Asymmetry Bias. Test results show fairly large asymmetry between positive and negative β, particularly for X'. With $B_{F,\beta}$ and $B_{F,align}$ accounted above, other factors such as the model fabrication error and/or the initial heel of model due in part to imperfect weight ballasting maybe the possible reasons. Due to lack of solid explanations, the average result r_m is taken as the representing data and the asymmetry is added to the total uncertainty as asymmetry bias B_{asym} defined as

$$B_{asym}^2 = D_{asym}^2 - U_{\mathrm{r}}^2 \tag{11}$$

if $\left|D_{sym}\right| > U_{\mathrm{r}}$, where $D_{asym} = \mathrm{r} - \mathrm{r}_m$, otherwise B_{asym} = 0. The total uncertainty U_{T1} is estimated as per equation (9). UA results for static drift test are recalculated in Table 15 by including B_{asym}.

For pure sway test as an example, odd order harmonics for symmetric variable X' and even order harmonics for anti-symmetric variables Y', N' are not expected from their FS expansions since the PMM motions are symmetric with respect to towing tank centerline i.e., towing direction. Accordingly, D_{asym} for dynamic tests are redefined for pure sway and pure yaw test data as $D_{asym} = \mathrm{r} - \mathrm{r}_{FS}$ where r_{FS} is FS reconstructed data with proper odd or even order FS harmonics, and B_{asym} and U_{T1} are estimated as per (11) and (9), respectively. These symmetry considerations are also true for pure yaw test data, but are not appropriate for yaw and drift test data due to its asymmetry PMM motions. UA results are recalculated by including B_{asym} in Table 15.

Table 15 UA including B_{asym}

Fr = 0.280		X' (%)			Y' (%)			N' (%)		
Test	Facility	B_T	P_T	U_{T_1}	B_T	P_T	U_{T_1}	B_T	P_T	U_{T_1}
Static	IIHR	100	0	10.5	95	5	3.3	95	5	2.8
Drift[1)]	FORCE	78	22	3.3	74	26	2.1	46	54	3.0
	INSEAN	99	1	11.5	52	48	3.4	48	52	3.3
Pure	IIHR	38	62	6.3	94	6	10.1	98	2	4.1
Sway[2)]	FORCE	98	2	3.1	98	2	1.8	93	7	1.6
	INSEAN	100	0	16.8	66	34	2.1	73	27	1.8
Pure	IIHR	74	26	15.0	88	12	10.2	93	7	3.3
Yaw[3)]	FORCE	99	1	3.4	93	7	5.5	96	4	3.8
	INSEAN	98	2	6.9	88	12	5.3	60	40	1.4

[1)] at β = 10° [2)] at $v' = v'_{max}$; [3)] at $r' = r'_{max}$

10.3 Evaluation of Facility Biases

The facility biases or certification intervals of facilities are estimated using an $M \times N$ - order testing method as per Stern et al. (2005). The method is a statistical approach for assessing probabilistic confidence intervals with the mean facility data as reference values for M facilities with N repeat tests under the assumptions of normal distribution for the sample population X_i, 95% confidence level, $M \geq$ 10, and $N \geq$ 10. For present example M = 3 and N = 12 are used. Although number of facilities M = 3 is minimal, the results show usefulness of the approach as discussed in Stern et al. (2005).

For the mean facility data $\bar{X}$, where X is X', Y', N' of individual facility, the uncertainty $U_{\bar{X}}$ in $\bar{X}$ is the RSS of the bias limit $B_{\bar{X}}$ and the precision limit $P_{\bar{X}}$, which are the average RSS's of the M bias limits B_i and M precision limits P_i, respectively. By comparing the difference $D_i = X_i - \bar{X}$ with its uncertainty $U_{D_i} = (U_{X_i}^2 + U_{\bar{X}}^2)^{1/2}$ if $\left|D_i\right| \leq U_{D_i}$, then the individual facility is certified at interval U_{D_i}, whereas if $\left|D_i\right| > U_{D_i}$ the facility bias B_{FB_i} is defined as

$$B_{FB_i}^2 = D_i^2 - U_{D_i}^2 \tag{12}$$

with U_{T2} as per equation (10).

For static drift test data, in general, X' is certified but with large certification interval U_D about 10%, Y' and N' are uncertified but with fairly small facility bias B_{FB} about 1 ~ 2% in averages. Pure sway test results X', Y', and N' are all uncertified with B_{FB} about 3 ~ 8%. X' and Y' of pure yaw test are certified but again with large U_D 11 ~ 14%, and N' is uncertified with U_{FB} about 3%. Yaw and drift test data are all certified with U_D about 4 ~ 6%. Consequently, reduction of certification interval U_D of X' and Y' for dynamic tests and for the former also for static drift test is largely required by reducing of individual facility bias.

11. CONCLUSIONS

11.1 Overview of Manoeuvring Prediction Methods (Section 2)

The amount of methods for manoeuvring predictions has significantly grown over the last decades. This opens the possibility for the naval architect to compare and select from multiple methods. Each method has its advantages and disadvantages of which the consensus is written down in this section.

Despite all knowledge & experience it is difficult to quantify the relative accuracy of each method. Therefore the selection of the most appropriate method is difficult. The experience of the experts remains necessary.

11.2 Progress in System Based Simulations (Section 3)

For conventional vessels the manoeuvring prediction methods seem well established for standard manoeuvres. Some developments are reported on the fine tuning of empirical models. The SIMMAN 2008 Workshop provided a first step on the relative performance of these methods and their validation.

For less conventional vessels other procedures are developed resulting in new types of manoeuvring prediction methods dedicated to these types of ships. However these mathematical models require further development and validation for more robust application.

Unfortunately, not much research is reported on scale effects for predictions which are based on model scale results.

Validation and documentation is needed for mathematical models used in ship-handling simulators, especially regarding non standard manoeuvres, e.g. at slow speed and in shallow waters.

11.3 Progress in CFD Based Simulations (Section 4)

The rapid development and application of RANS for manoeuvring applications has continued during the last years. New techniques, e.g. for free surface capturing and non-matching/dynamic-overset grids enable simulations for practical relevant manoeuvring problems, including simulations of static and dynamic captive model tests and even of free model tests.

Prediction based on virtual captive model tests has reached a state which allows practical applications and can be regarded as an intermediate step towards the direct prediction of manoeuvres by RANS simulations.

Further development is needed for accurate predictions for manoeuvres involving large sway and yaw motions. Required resources, lack of trained users, user-friendly codes, and need for V&V are pace setting issues for more widespread use of CFD in practice, as also concluded by the 24th MC.

Used codes have still to become much more faster to make CFD-based predictions more useful for industry, thus speed-up and scalability for parallel computing are required for reducing wall clock time and enabling larger scale industrial applications.

11.4 Validation of Simulations & Benchmark Data (Section 5)

The SIMMAN 2008 Workshop was the first of its kind for several reasons. System and CFD-based manoeuvring simulation methods have been benchmarked for their prediction capabilities through systematic quantitative validation against EFD. The simulations were blind for all test cases. The international collaboration for captive and free model EFD validation data was noteworthy, as it involved thirteen ITTC institutions and ten countries from Europe, Asia, and America. Benchmark cases, KVLCC, KCS, and DTMB 5415, following the recommendations of the 24th MC, have been used. For the KVLCC test case two stern shape variants named KVLCC1 and KVLCC2 with different yaw stability were included.

Valuable insight into the performance of the different participating methods was obtained during the workshop. Since the workshop was held just before the deadline for the MC report, the analysis and the comparisons between the methods are not completed yet, but will be addressed at the 25th ITTC.

11.5 Manoeuvring and Course Keeping in Waves (Section 6)

More attention has been paid to the investigation of ship manoeuvring and course-keeping in waves during the last years. The trend is that ship manoeuvrability in waves is investigated by unified manoeuvring and seakeeping theories. Experimental studies are performed to investigate ship manoeuvring and course-keeping in waves. System based simulation methods are commonly used for prediction of ship manoeuvring and course-keeping in waves. However, CFD based methods are becoming available and expected to play a more prominent role.

11.6 New Experimental Techniques (Section 7)

Many efforts in manoeuvrability experimental works over the past years have been devoted to CFD validation. Stereo-PIV has become a mature technique enabling to measure the three components of the velocity field surrounding a manoeuvring ship or submarine.

DGPS in its kinematics mode provides a useful tool for accurately measuring the position in both horizontal and vertical plane. The measurement of vertical position will be useful for full scale squat measurements.

No significant experimental studies were reported regarding the extrapolation methods for manoeuvrability predictions.

11.7 Shallow and Confined Waters and Ship-Ship Interactions (Section 8)

Many papers on shallow and confined waters and ship-ship interactions have been published over the past three years. Extensions have been made for complicated problems such as muddy bottoms and ship-ship interaction in waves.

More effort is needed both, experimentally and numerically for better understanding of the ship manoeuvrability in the confined waters. Only few significant studies about bank effect have been reported.

11.8 Standards and Safety (Section 9)

IMO standards for ship manoeuvrability MSC.137(76) have been generally accepted as a criteria for a conventional ship to guarantee minimum safety. However, there have been some views that it is necessary to improve the standards further to keep safe navigation in restricted waters and to develop rated criteria for achieving better manoeuvring performance.

For some special ships, e.g. Pod-driven ships or high speed ships, there have been some arguments on the validity of the IMO standards. Further investigation is needed to clarify whether a revision of the IMO standards for these ships is required. In addition, it would be relevant to extend these investigations to those types of ships not covered in the current IMO standards.

Regarding the IMO Explanatory notes (MSC Circ.1053), some research has been carried out on corrections for environmental effects such as wind, current, wave during sea trials. Further research is required to develop a standard method for the correction of sea-trial data obtained at non-standard trial conditions.

The necessity of low speed manoeuvring criteria has been constantly raised and some low-speed manoeuvres and indices have been proposed. However, there was no proposal on criteria including specific limits. For practical and meaningful low-speed manoeuvring criteria, it is required to obtain more information on that from both pilots and ship designers and to collect full scale manoeuvring data in the harbour and waterways.

11.9 Procedures (Section 10)

Significant progress on UA for captive model tests including facility biases and model size has been made, which hopefully will be utilized by the ITTC members.

12. RECOMMENDATIONS TO THE ITTC

Adopt the improved procedure 7.5-02-06-01, "Testing and Extrapolation Methods, Manoeuvrability, Free Model Test Procedure"

Adopt the improved procedure 7.5-02-06-02, "Testing and Extrapolation Methods, Manoeuvrability, Captive Model Test Procedure"

Adopt the improved procedure 7.5-02-06-03, "Testing and Extrapolation Methods, Manoeuvrability, Validation of Manoeuvring Simulation Models"

Adopt the improved procedure 7.5-04-02-01, "Full Scale Manoeuvring Trials"

Adopt the procedure on UA in captive model tests "Forces and Moments UA example for PMM tests"

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