27TH ITTC • Copenhagen

Manoeuvring Committee

Final Report and Recommendations to the 27th ITTC

1. INTRODUCTION

1.1 Membership

The 27th ITTC Manoeuvring Committee (MC) consisted of:

- Mr. Frans Quadvlieg (Chairman). MARIN, The Netherlands.
- Dr. Guillaume Delefortrie (Secretary). Flanders Hydraulics Research (FHR), Belgium.
- Dr. Jonathan Duffy. Australian Maritime College (AMC), Australia.
- Prof. dr. Yoshitaka Furukawa. Kyushu University, Japan.
- Dr. Pierre-Emmanuel Guillerm. Ecole Centrale de Nantes (ECN), France.
- Dr. Sun-Young Kim. KRISO, South-Korea.
- Dr. Claus Simonsen. FORCE Technology, Denmark.
- Prof. dr. Eduardo Tannuri. Escola Politécnica da Universidade de São Paulo, Brazil.
- Prof. dr. Xiao Fei Mao. Wuhan University of Technology (WHUT), China.

All members except Mr. Quadvlieg and Dr. Kim were new members in the committee.

In addition to the official members, the MC had significant aid from the representative of the QSQ committee in the area of uncertainty analysis:

- Dr. Michael Woodward. University of Newcastle upon Tyne, UK

1.2 Meetings

The committee has met four times during the course of their three years mandate:

- KORDI (now KRISO), Daejeon, South-Korea from March 12 to 14, 2012;
- ECN, Nantes, France from November 19 to 21, 2012;
- FHR, Antwerp, Belgium from June 5 to 7, 2013, in conjunction with the conference on manoeuvring in shallow and confined waters in Ghent;
- WHUT, Wuhan, People Republic of China, from March 3 to March 5, 2014, in conjunction with a seminar on manoeuvrability.

During all meetings, *all* members were present.

2. TASKS AND REPORT STRUCTURE

The following lists the tasks given to the 27th MC together with explanation on how the tasks have been executed.

Task 1. Update the state-of-the-art for predicting the manoeuvring behaviour of ships emphasising developments since the 2011 ITTC Conference. The committee report should include sections on:

a. the potential impact of new technological developments on the ITTC,

b. developments in manoeuvring and course keeping in waves,

c. new experiment techniques and extrapolation methods,

d. new benchmark data

e. the practical applications of computational methods to manoeuvring predictions and scaling.

f. the need for R&D for improving methods of model experiments, numerical modelling and full-scale measurements.

g. the effects of free surface, roll, sinkage, and trim in numerical simulation of manoeuvring.

This task has been achieved by an extensive discussion of the publications which were issued around the world. The particularly interesting technique is CFD, which received special attention in this report. The effects of free surface, roll, sinkage and trim have been discussed.

Manoeuvring and course keeping in waves has received special attention. The criteria proposed by IMO are followed and interpreted. Realising that the present day numerical methods are insufficient, this has also emerged as a separate section on manoeuvrability in waves in the report.

New benchmark data has been pro-actively pursued. These efforts are discussed in the benchmark section.

Task 2. Review ITTC Recommended Procedures relevant to manoeuvring and

a. Identify any requirements for changes in the light of current practice and, if approved by the Advisory Council, update them.

b. Identify the need for new procedures and outline the purpose and content of these.

The procedures have been reviewed and updated where needed, as discussed in the section on procedures.

Task 3. Complete the work on the Procedure 7.5-02-06-04, Uncertainty Analysis; Forces and Moment, Example for Planar Motion Mechanism Test, based on ISO approach. The present procedure 7.5-02-06-04 and the subsection on uncertainty analysis in the Procedure 7.5-02-06-02, Captive Model Test Procedure, prepared by the 23rd ITTC are based on the ASME approach. In view of the work already carried out for the Procedure 7.5-02-06-04, consider to keep the elaborated ASME example as one of the Appendices to the to-be-renewed 7.5-02-06-04.

The procedure for UA of captive tests has been significantly reviewed. This is discussed in the section on procedures.

Task 4. Based on results of the SIMMAN workshop held in 2008 and its next edition, continue the already initiated work to generate a guideline on verification and validation of RANS tools in the prediction of manoeuvring capabilities. Liaise with the QSG with respect to definitions of Verification and Validation.

A guideline for the use of CFD solutions for manoeuvring predictions is created. This is discussed in the section on procedures.

Task 5. Restricted waters:

a. Produce a guideline for experimental methods.

b. Complete the initiated one for numerical methods which may serve as a basis for recommended procedures for manoeuvring in restricted waters.

The guideline for experimental methods was integrated with the procedures for free running model tests and captive model tests.

Task 6. Free running model tests:

a. Update the Procedure 7.5-02-06-01, Free Running Model Test (FRMT) Procedure, in particular to include objective statements on the initial conditions of free manoeuvring model tests.

b. Elaborate the already initiated procedure on uncertainty analysis for free running manoeuvring model tests, including an example.

The procedure for FRMT is updated and a guideline on uncertainty for FRMT has been created. Details are provided in the section on procedures.

Task 7. Scale effects in manoeuvring:

a. Report on knowledge and collect, analyse and summarize data on scale effects for manoeuvring predictions.

The work conducted on scale effects is included in a separate section.

Task 8. Review developments in methods and draft a validation procedure of combined manoeuvring and seakeeping with respect to simulation. Liaise with the Seakeeping Committee and the Stability in Waves Committee.

The methods are reviewed. It is too early to create a validation procedure for simulations for combined manoeuvring and seakeeping. The Seakeeping Committee and the Stability in Waves Committee did not have tasks to address this.

Task 9. Support the organisation of a second SIMMAN workshop.

The members of the committee actively organise and support this workshop, which will now be held in December 2014.

Task 10. Manoeuvring criteria and relations to IMO:

a. Report on manoeuvring criteria for ships not directly covered by IMO like POD and waterjet driven vessels, naval ships, inland ships, HSMV, etc.

b. Study possible criteria for manoeuvring at low speed and in shallow waters and if warranted communicate findings to IMO.

A dedicated section is created on manoeuvring criteria and in particular a section is created to discuss non-IMO related criteria which are in use.

3. USING EXPERIMENTS AS A TOOL TO ADVANCE THE KNOWLEDGE IN MANOEUVRING

3.1 In Deep Unrestricted Water

Design Improvements. Recent studies have been undertaken to investigate the influence of ship design and operational aspects on manoeuvring characteristics.

Physical model scale experiments were conducted by Park et al. (2011) to measure the running trim of a high speed vessel at zero drift angle. Small drift angle tests were conducted to assess course keeping ability. For the zero drift angle tests vertical motions were measured to investigate the bow down trim at high speeds and how this can be reduced to move the lateral centre of pressure toward the stern to improve course keeping ability. The small drift angle tests were conducted for the naked hull and with a transom wedge. It was found that the addition of the transom wedge moved the lateral centre of pressure toward the stern and improved the course stability.

Hirata et al. (2012a, 2012b) presented results from full scale trials and model scale experiments to assess the effect that trim has on the manoeuvring performance of the training ship Toyoshio Maru, an azimuth propeller vessel. The full scale tests consisted of turning circle and zigzag manoeuvres for three load conditions, one even keel condition and two conditions trimmed by the stern. The model scale experiments consisted of oblique towing tests and circular motion tests in the even keel and the largest trimmed by the stern load conditions. The results showed that the vessel exhibited course instability for all load conditions, however trimming by the stern improved the course stability and remarkable improvement was seen in the Y'(β) and the N'(β) derivatives.

Free running physical scale model experiments were conducted by Miyazaki et al. (2013) to determine the manoeuvring characteristics of a KCS container ship model with a static heel angle. The yaw rate and drift angle during turns with a static heel angle were quantified and discussed.

Kang et al. (2011) investigated the manoeuvring and powering benefits of aligning twin rudders with the inflow of the propeller stream of a single propeller vessel. They conducted free running turning and zigzag physical scale model experiments at Osaka University. They showed that course keeping stability was increased by the non-zero rudder angle; however the turning ability was reduced.

Yasukawa et al. (2011) reported on captive model tests to measure the hydrodynamic force coefficients on a twin screw, twin rudder ferry hull form with a bow thruster. The force derivatives and coefficients were determined according to the MMG model procedure using the equivalent single rudder method to reduce complexity. The hydrodynamic force coefficients were presented for the hull, propeller and rudder together with the hull force characteristics due to bow thruster operation.

Yasukawa et al. (2012a) investigated the hydrodynamic force characteristics of a catamaran with asymmetrical demi-hulls. Physical scale model experiments were conducted with different demi-hull separations, rudder angles and propeller loads. The demi-hull separation was shown to have little effect on the rudder normal force and the smallest demi-hull separation provided the best course keeping performance. Numerical simulations of a turning circle manoeuvre were conducted and compared to trial results. The steady turning radius showed good correlation, while the advance and tactical diameter were over estimated.

In tight turning manoeuvres involving twin/multi screw vessels, the load in each propeller shaft can vary significantly, which can influence the manoeuvring behaviour of the ship. Coraddu et al. (2013) investigated the propeller loads on a twin screw vessel using free running model scale experiments and numerical simulations. They investigated the effect of constant propeller RPM, constant power and constant torque on propeller loads. They conducted zigzag, turning circle and Dieudonnée spiral tests and compared the experimental results to numerical manoeuvring simulations, which correlated well and showed the effect of the asymmetrical propeller loading.

Towed Stability. Towed stability receives more and more attention due to the many FPSO's which are nowadays towed over the oceans. Yang & Wada (2012) have been investigating both numerically and experimentally a better way to investigate the actual limits of towed stability. They concluded that there is quite a difference between towing in the traditional way and towing using an actual tug in the basin. The numerical model had the capabilities to quantify the effect of the environmental forces on the towed stability. Nakayama et al. (2011) investigated the towed stability in (head) waves. A mathematical model was proposed which was validated using model tests. They show a relationship between peak loads and surge and pitch motions. Zotti (2013) conducted a study to investigate the directional stability of a barge being towed by a tug. A physical scale model barge was towed at various angles of attack up to 6 degrees. Forces on the barge model were measured to perform a directional stability analysis applicable to only small perturbations from the equilibrium condition. The barge was tested in three configurations; without appendages, with a rudder and with two side skegs. The barge without appendages demonstrated directional instability, i.e. it had the tendency to move transversely and to rotate on itself when acted upon by an external force. The barge with the central rudder had little tendency to translate laterally, but a great tendency to rotate. The barge with skegs demonstrated little tendency to rotate and great tendency to translate laterally. Hong et al. (2013) present an overview of two different mathematical models that can be used for towed stability simulations: the MMG model for towed bodies by Fitriadhy & Yasukawa (2011a) and the cross flow drag model according to Wichers (1988). Coefficients for both models have been derived from captive model tests. Simulations were carried out using both models. By comparison of the simulated trajectories to model tests, the authors conclude that the cross flow drag model is easier to use, while giving practically the same results as the MMG model and model tests. Toxopeus et al. (2013b) show how CFD is used to perform virtual captive tests to predict the towed stability of a variety of skeg shapes, and as such CFD is able to balance the resistance and the towed stability in order to achieve good directional stability with minimum barge resistance.

3.2 In Shallow Water

General. It is necessary to validate ship-handling simulation models for use to approve new waterway designs. Böttner et al. (2013) presented experiments with two aims: to detect the influence of under keel clearance on turning and course keeping ability and to sound the limitations of the manoeuvring model implemented in a simulator when applied to manoeuvring in shallow waterways. A remotely controlled free sailing model was used to perform IMO standard zigzag manoeuvres in the wave basin of BAW in Hamburg at different initial speeds as well as at a range of water levels targeting a representative range of under keel clearances. Data from the manoeuvring trials were proven to be a good base for determination of coefficients. Another finding was the impossibility to find a suitable set of coefficients for a broad range of either water depths or speeds in shallow water.

False Bottom. The use of false bottoms to execute shallow water tests still demands validation and analysis. The flow field at the borders of the false bottom depends on the dimensions of the tank and on the size of the structure and the apparatus used to support the false bottom. If there is not enough space for the water above the false bottom to flow when the ship is passing, the pressure distribution can be disturbed and the shallow water effects will not be accurately measured. Only a few papers demonstrated such concern, presenting a validation of the false bottom dimensions and demonstrating that they are properly designed for the experiment. An example is the work by Yeo et al. (2013), which describes a false-bottom facility built at the KRISO towing tank. The tank dimensions are 200 m x 16 m x 7 m, and the false bottom is 54 m long and 10 m wide. Using this false-bottom facility, captive model tests were conducted with a 1:31 scale model of the KCS hull for three under keel clearances (h/T = 1.2, 1.5 and 2.0). The authors made a preliminary validation of the false bottom concept, aiming to verify the effects of the limited lateral size of the false-bottom. They compared static drift test results conducted along the mid-breadth line of the false-bottom and results from a static drift test conducted along the 1m biased-in-breadth line of the false-bottom. They concluded that the limit in the breadth of the false-bottom would not cause a significant effect on test results for cases in which the position bias in breadth (of the model) was within 1 m. Furthermore, based on this result, amplitudes of forced motion in dynamic tests of the benchmark PMM tests were selected to be within 1 m. This kind of verification must be carried out when using false-bottoms to perform shallow water experiments. The benchmark test results obtained in these experiments will be provided to participants of the SIMMAN 2014 conference to add to data for subsequent studies.

Béguin et al. (2013) presented the experimental database for three different models (Wigley Hull, Container Carrier and River Barge), with a combination of ship speed and water depth. It focused on additional hydrodynamic forces, as well as squat and vertical motions (trim and sinkage) of hulls sailing straight-ahead in shallow water, as a function of Froude number. The test facility is 138 m x 5 m. A double bottom made of 28 removable plates of 1 m width, firmly fixed to a scaffold structure was used to change the water depth on a 28 m length section of the towing tank. One problem addressed by the authors was related to the time window available to obtain the steady state results in the shallow water section. This is important for higher speeds and ship models with large inertia. The authors did not discuss the problems related to the flow at the lateral boundary of the false bottom. This may be a concern due to the small width of the tank, and may play some role in the shallow water effects.

3.3 In Restricted Water

Canal Navigation. Model scale experiments were conducted by Iseki & Kawamura (2011) to investigate the rudder angle required to counter ship-bank interaction. The experiments were conducted in a circulating water channel and involved adjusting the oblique angle of the ship model and the rudder angle close to a lateral bank to find the equilibrium point. The measured values for equilibrium were compared against the theoretical value of the Next Generation Fairway Design Standard, which showed some possibility of underestimation for the safety margins of the fairway.

Iseki & Takagi (2013) conducted experiments with a propelled scale model to determine the equilibrium position of a ship operating in the vicinity of a bank wall. The propeller RPM, oblique towing angle and rudder angle were varied for a range of water depth to draft ratios and distances off the bank. Ship speed was shown to have little influence on the required rudder angle.

Ibaragi et al. (2012) reported on physical scale model experiments to determine the effect that channel width, drift angle, under keel clearance and distance from a lateral bank has on the sway force and yaw moment of two different hull forms in restricted water. The captive model tests were conducted at the Seakeeping and Manoeuvring Basin at Kyushu University. A new empirical formula was presented to predict the sway force and yaw moment due to the drift angle, separation from the bank and under keel clearance. The formula represented the general trends but showed poor quantitative accuracy.

To investigate the behaviour of a ship in restricted water, Sano et al. (2012) conducted physical scale model experiments to quantify the sway force, yaw moment and rudder force acting on a vessel due to the effects of a bank, drift angle and rudder angle. The captive model experiments were conducted in a scale model channel of a Japanese port using a ship model fitted with a propeller operating at the self-propulsion point. The experiments were conducted at various water depth to draft ratios. The forces and moments induced by the rudder angle, bank effects and drift angle were exaggerated at low water depth to draft ratios. New equations were presented to determine whether a vessel is directionally stable when operating in restricted water.

Squat. Delefortrie et al. (2010) presented a mathematical model to predict squat of container carriers operating in muddy navigation areas. The new squat formulae are based on an extensive experimental research program carried out at the Flanders Hydraulics Research Towing Tank over the period 2001 to 2004 to investigate the manoeuvring behaviour of deep drafted vessels in muddy bottom areas. It was found that the sinkage over a muddy bottom is mostly less than a solid bottom, but the trim can be larger when manoeuvring in muddy areas.

An extensive captive model test program was undertaken by Lataire et al. (2012a) to investigate squat with a scale model of the KVLCC2. Tests were carried out for canals with rectangular cross section at different water depths, widths of the canal section, model lateral position in the canal and forward speeds (2-16 knots where possible). The measurements were used to validate a mathematical model, which takes into account the forward speed, propeller action, lateral position in the fairway, total width of the fairway and water depth.

Full scale motion measurements of vessels transiting the Columbia River Bar have been obtained by Lesser & Jordan (2013). One of the aims was to quantify under keel clearance in moderate to high seas. Two methods were used to measure the vessel motion:

(1) high-precision Trimble GNSS (GPS) units mounted at the bow and bridge wings with an additional unit mounted to a pilot "chase" boat to measure the sea level;

(2) an iHeave unit in winter to measure the motions due to extreme weather.

Numerical simulations were also conducted using the Delft3/SWAN numerical model and DUKC software. No clear ‘rule of thumb’ was identified to eliminate risky transits; however several aspects affecting the transits were identified.

Briggs et al. (2013) compared full scale Differential Global Positioning System (DGPS) measurements of ship squat for four different vessels in the Panama Canal to predictions using a selection of empirical formulae and numerical techniques. They found that the prediction techniques provided reasonable results and can be used with confidence in deep draft channel design.

Crabbing. For cruise vessels and ferries, harbour manoeuvring is an important manoeuvring case. These ships are equipped with bow and stern thrusters, and the main propeller(s) are operating in push-pull model. Usually, berthing (going to the quay) and unberthing (leaving the quay) are investigated. Lee et al. (2011) investigated experimentally a twin screw vessel with bow and stern thrusters. Based on the experiments, a modular mathematical model was developed for the complex flow phenomena for different distances between the ship and quay and also for different water depths. The fine mesh of different distances to the quay at which captive tests were performed is particularly interesting.

Kwon et al. (2013) investigated the limiting operational conditions of a cruise vessel with 3 bow thrusters and 2 pods. Using experiments, the forces generated by the actuators were obtained. These were compared to the wind loads obtained by CFD. Model tests were carried out in deep and shallow water. For berthing, the results were similar in deep and shallow water, but for unberthing, there were significant differences measured.

Locks. During the last couple of years there has been a worldwide growing interest in the study of ship behaviour in locks, mainly due to the construction of new locks or the modernization of existing locks to cope with an ever increasing ship size. The most impressive example is the construction of the Third lane of the Panama Canal (2015) for which several experimental studies have been carried out. For that reason PIANC has started Working Group 155 (Thorenz, 2013) to study the ship behaviour in locks and approaches to locks. The ship behaviour in locks was also the main topic of the latest International Conference on Ship Manoeuvring Behaviour in Shallow and Confined Water (2013). An overview of significant locks and the challenges to enter them is described in a practical way by Eloot & al. (2013).

Ships are subject to forces during entry and exit manoeuvres, but also during the filling and emptying process while being in the lock chamber. The latter is however not considered to be a manoeuvring topic and is not treated in this report. During a lock entry a ship is subjected to an increased resistance, which is well predicted by the six-waves-model described by Vrijburcht (1988). His model proved to be useful for rectangular shapes such as barges, but needed improvement for slender ship's hulls (Vergote et al., 2013). The improved six-waves-model has been used to calculate the water level elevation at the end of the lock. The results have been compared with measurements for the ship models of a New Panamax container ship and a bulk carrier.

Locks can be divided into two categories depending on whether an approach structure is present or not. While the latter provides a useful aid for alignment, its induced asymmetry must be counteracted by the ship's available steering aids. A lateral force component and yawing moment also occur when a ship sails eccentrically in a symmetrical lock layout. Insight into these asymmetries is provided by experimental research, for instance the approach layout for the locks to the Panama canal (Delefortrie et al., 2009) or for the lock to IJmuiden (The Netherlands) (Kortlever & de Boer, 2013). In these two cases additional difficulties occur due to the exchange of fresh water with salt water during the levelling process and after the opening of the gates. Model tests and full scale trials for the West lock in Terneuzen (The Netherlands) were described by Verwilligen et al. (2012). The results of lock entry and exit tests can be implemented in a real-time manoeuvring simulator to evaluate the nautical qualities of the design of a new lock. An example of such an approach was discussed by Verwilligen et al. (2013).

The above mentioned model scale tests were all carried out at FHR (Figure 1), who provided benchmark data to the scientific community (Vantorre & Delefortrie (2013), see section 5.4). During the latest International Conference on Ship Manoeuvring Behaviour in Shallow and Confined Water (2013) several papers were presented focussing on the comparison between the benchmark data and numerical computations. Wang & Zou (2013) used an unsteady RANS solver with a dynamic mesh method, free undisturbed water level and user defined functions to define the ship motion in the lock. The lateral force and yaw moment were well predicted, while the longitudinal force was under predicted compared to the benchmark data. Lindberg et al. (2013) introduced a potential model for nearly real-time ship's hydrodynamics and linear water waves calculations. The model has been tested with the New Panamax container carrier sailing into the lock, but the interaction with vertical approach and lock walls is not yet well predicted by the model. De Loor et al. (2013) computed the effect of the exchange between fresh and salt water on a moored ship along a lock approach wall and compared the results with the benchmark data. It was concluded that although the application of CFD is not (yet) feasible to predict absolute values with sufficient accuracy, it can provide more insight in the physical processes.

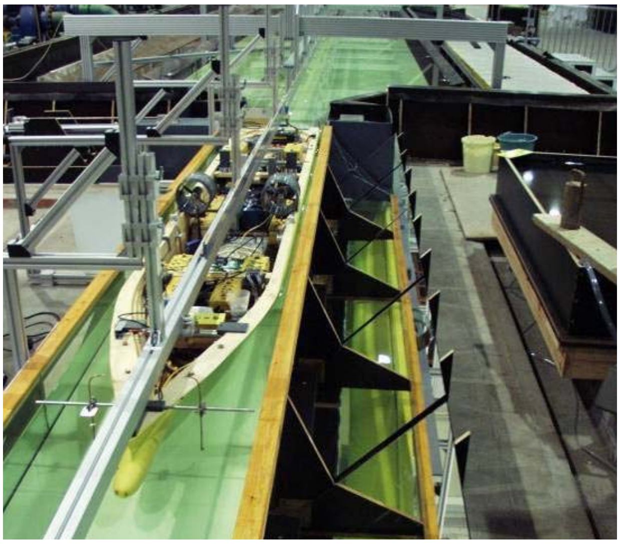


Figure 1. Lock entry model scale test at FHR.

Other authors also developed numerical or empirical codes, mainly focussing on lock entry speed and sinkage. Henn (2013) enhanced an existing code for inviscid flows to enable a real-time prediction of the ship's velocity and the squat during lock entry and exit manoeuvres. A coefficient was added to take account of the lock chamber frictional effects. The code was successfully compared with both experimental and full scale results. Spitzer & Soehngen (2013) gave a comprehensive overview of lock entry and exit manoeuvres. They evaluated existing semi-empirical formulae with model tests and full scale trials. The numerous uncertainties of such formulae call for the need of additional physical model tests and CFD research. A specific type of lock entry manoeuvres is an entry in a ship lift. Li et al. (2013) conducted experimental research focussing on the squat measurement and the derivation of a squat prediction formula for different ship lifts in China, such as the Three Gorges ship lift.

3.4 Ship-to-Ship Interaction

There has been a growing interest in ship to ship interaction issues, as evidenced by recent work on ship to ship transfer, tug – ship interaction and ship passing scenarios.

Ship to Ship Transfer. Physical model scale experiments were conducted by Arslan et al. (2011) to investigate the flow around the parallel midship sections of two ships in a side by side lightering operation using PIV and dye injection. The results from the experiments were used to validate CFD predictions. The numerical predictions generally showed good correlation with the experimental results.

Quasi-static and dynamic captive model tests were conducted by Lataire et al. (2012b) to simulate the interaction forces and moment due to a lightering operation of the KVLCC2 and a service ship. Different longitudinal and lateral positions of the service ship relative to the KVLCC2 model were tested. Both models were fitted with rudders and propellers (running at their open water model self-propulsion point). New formulae were presented to predict the forces and moments experienced by the service ship due to the KVLCC2. The formulae correlated well in surge, sway and yaw.

Yasukawa & Yoshida (2011) investigated a simplified lightering operation by conducting physical scale model experiments using two Wigley parabolic hulls. The lateral separation, drift angle and rudder angle were varied. The tests were conducted with no stagger between the two ships (i.e. midships adjacent). The sway force and yaw moment was measured on each of the models along with the normal force on the rudders. The results from the experiments were compared to numerical predictions based on nonlinear lifting surface theory. The numerical predictions correlated reasonably well with the experiments with a few exceptions.

Sano et al. (2013) reported on physical model scale experiments to investigate a ship to ship transfer manoeuvre. The hydrodynamic interaction surge force, sway force and yaw moment were measured on two Wigley parabolic hulls in close proximity with rudders. The rudder normal force was also measured on both models. The water depth to draught ratio, lateral clearance between the hulls, hull drift angle and rudder angle were varied during the test program. It was found that when a ship steered the interaction force acted not only on the own ship, but also induced an interaction force and moment on the ship alongside, which varied with water depth. The experimental results were used to validate numerical analyses using a nonlinear lifting body theory.

Tug-Ship Interaction. An investigation into tug-ship interaction was undertaken by Geerts et al. (2011). Physical model scale experiments were conducted to investigate the hydrodynamic interaction forces experienced by an azimuth stern drive tug sailing in the vicinity of the bow of a Panamax container vessel. The interaction forces on the tug model were measured for a range of relative positions and drift angles at multiple forward speeds. The forces were used as input to a fast-time simulation program to assess the required thrust and azimuth angle to keep the tug at a fixed station. An assessment was made on the most suitable position to pass the tug towline.

Passing Ship Scenarios. Delefortrie et al. (2012) investigated the hydrodynamic forces and moments acting on a berthed ship due to different ship traffic scenarios. Captive physical scale model experiments were undertaken to measure the forces and moments acting on a berthed ship due to a passing ship and due to multiple passing ship interaction, with different dock widths. The effect of a nearby swinging vessel was also investigated. The applicability of superposition theory was assessed for estimating the forces and moments experienced by a berthed ship due to multiple passing ships. It was concluded that while applicable in most cases, when under keel clearance or separation ratio is low, the superposition theory is less accurate. At low under keel clearances it was found that the forces due to a nearby swinging ship can be significant, even higher than realistic passing ship manoeuvres.

Duffy et al. (2011, 2013) and Denehy et al. (2012) reported on investigations into the influence of waterway geometry, around berth geometry, berthed ship size and berth occupancy arrangement on the hydrodynamic interaction forces and moments experienced by a berthed ship due to a passing ship. From captive physical model scale experiments it was found that the different scenarios significantly influenced both the form and magnitude of the interaction forces and moments.

Uliczka et al. (2013) conducted physical model scale experiments to measure the interaction sway force and yaw moment for two scenarios in a narrow fairway: a containership passing a moored containership and two containerships passing. Both head on and overtaking manoeuvres were investigated for both scenarios, however the overtaking case with both ships moving was conducted with each ship travelling at the same speed sailing parallel. The results were incorporated into ship-handling simulators for the simulation of containership manoeuvres in narrow fairways.

3.5 Special Experimental Techniques

This section focuses on some works that used special or non-conventional experimental techniques and arrangements to study ship manoeuvrability. Also, the application of new system identification (SI) techniques to derive models and coefficients from manoeuvring tests is presented.

Yoshimura et al. (2012) conducted a comprehensive set of measurements of open water rudder tests in several exposing conditions, using a large scale rudder model. The author's intention was to obtain a better prediction of rudder lift forces for ballast conditions, when a ship's rudder may be partially exposed on the water surface. They verified that the actual aspect ratio used for the prediction of rudder normal force must take into account the water surface at both sides of the rudder. Also, when only a small part of the rudder is above the water, the stall phenomenon does not appear and the maximum lift coefficient significantly increases. The influence of the ship's loading condition on the manoeuvring characteristics has also been investigated by Hirata et al. (2012a, 2012b). The authors used full scale trials of a training ship to verify the influence of trim angle on the manoeuvrability of the ship.

Blendermann et al. (2011) report the results of a combined numerical and experimental investigation of the wind loads on a scale model of a passenger / car ferry, as well as a full-scale computation. The ship model (scale 1:150) was tested in two wind tunnels. The deviations between the results in the two wind tunnels and the CFD computation were of the same order. Silva (2012) presented a comprehensive set of experimental tests for a supply boat for obtaining winds and current loads, in a wind tunnel and towing tank. The author also performed CFD calculations and obtained quite good agreement. The results indicated that CFD is a realistic and reliable alternative to wind tunnel model and towing tank tests for predicting static forces.

The manoeuvrability of an unusual vessel was studied by Ueno et al. (2011) using circular motion tests. The submersible surface ship (SSS) is a new concept ship that avoids rough seas by going underwater using downward lift of wings and keeping residual buoyancy for safety.

The System Identification (SI) technique of Extended Kalman Filter (EKF) has been used to estimate values of hydrodynamic coefficients for a submarine from its full-scale manoeuvring sea trials data in the paper of Ray & Sen (2012). Data from sea trials with two submarines were used to identify the hydrodynamic coefficients. The authors provide advice for problems related to the robustness of the SI techniques applied to the identification of hydrodynamic parameters from noisy full-scale data.

SI based on artificial intelligence was deeply investigated by Chinese researchers. They studied the Support Vector Estimation technique applied to AUV free-running tests (Xu et al. 2011), and obtained hydrodynamic derivatives similar to those obtained by traditional captive PMM experiments. Extended analysis concerning AUV application is presented by Xu et al. (2013). The technique was also used for ship model identification with good results, as shown by Zhang & Zou (2011c, 2013). More analysis and results for ship model identification is presented by Wang et al. (2013b). The authors also studied the influence of the noise in the estimation of the hydrodynamic parameters and applied a Wavelet Denoising technique to improve the results (Zhang & Zou, 2011b). The method was also applied to the estimation of a 4DOF mathematical model of ships using the roll planar motion mechanism (RPMM) test, adequate for the analysis of ship manoeuvring motion in waves (Wang et al., 2013b).

Neural Networks have also been applied to the SI of manoeuvring models, as presented by Zhang & Zou (2012) and Woo & Kim (2013).

Di Mascio et al. (2011) investigated prediction methods for the manoeuvrability of twin-screw naval vessels. Regression analysis, SI method, semi empirical corrections for the influence of appendage and RANSE calculations are applied for analysis of the manoeuvring behaviour of twin-screw ships. They concluded that the combination of the SI technique and RANSE calculations could be useful for reducing research costs.

Revestido & Velasco (2012) proposed an identification scheme for nonlinear manoeuvring models based on two steps with a gray box approach. On the first step, a suitable model structure is selected and initial parameters are estimated. Estimated parameters are refined using a nonlinear prediction error method on the second step.

Luo et al. (2011) applied support vector machines based SI to predict ship manoeuvring motion in the proximity of a pier. Manoeuvrability indices and the other parameters are identified taking group test results as the training sample.

Ahmed & Hasegawa (2013) conducted free running model tests of automatic ship berthing using an Artificial Neural Network (ANN) trained code. They found that the automatic berthing manoeuvre could be successfully implemented up to certain wind speeds once the appropriate teaching variables had been selected.

3.6 Improvements in Experimental Methods

Hexapods have become more common in hydrodynamic laboratories. In the past, these have been used as a tool in the investigation of sloshing and VIV (Vortex Induced Vibrations). The use of hexapods as a replacement of a traditional planar motion mechanism seems an easy step. Up to now, only the work of de Jong & Keuning (2005) was published. Added mass and sway and yaw damping were measured on a segmented model. The results show that the analysis of tests (oscillations tests in waves with a segmented model) is an elaborate job. Nevertheless, the use of a hexapod as a complete replacement of a PMM alone implies that the oscillations that can be made are so-called small stroke oscillations: the maximum transverse excursions are in the order of ±0.5 m. This would be an important restriction. A better approach is to mount the hexapod under a transverse carriage (with the transverse carriage mounted on the main carriage). As such, the hexapod can be used as part of a large stroke oscillator. Such a set-up is installed in the Marintek facilities (Berget, 2011).

A second observation is the use of false bottoms, which do not fit the whole basin, to investigate the behaviour in shallow water. The use of false bottoms has to be considered carefully. The shallow water PMM results for KVLCC1 and 2 that were obtained using a false bottom in the INSEAN basins were - after long discussion - rejected as benchmark data, as issues were raised concerning the accuracy of results obtained using the false bottom constructed of removable plates.

The increasing international attention towards manoeuvrability encourages several smaller basins to investigate manoeuvrability issues. Yoon & Kang (2013) are reporting the installation of a CPMC in a basin of 20 x 14 m. They performed tests at a scale of 1:223. It is very clear that such techniques should only be used qualitatively for educational purposes and that results obtained in this way are of use to demonstrate that there are indeed scale effects. But besides the considerable effects of blockage, the accuracy of transducers and bottom flatness are of a different level due to the very small forces that need to be measured. Obviously, the main concern with respect to scale effects is that the Reynolds numbers are so small that it is very likely that the flow around the hull is laminar which leads to a different flow pattern around the manoeuvring hull.

The desired increase of knowledge about the manoeuvrability in waves has led to using captive test techniques in waves with the objective to create mathematical models for manoeuvring prediction in waves. Sung et al. (2012) reported on the application of this technique to the KCS where PMM tests were performed in waves.

Some reported improvements in free sailing techniques are twofold: the correction of the longitudinal scale effect by adding an air-propeller on the free running model as proposed by Ueno & Tsukada (2013). Mauro (2013) reported how the propellers need to be controlled during free running model tests as a function of the instantaneous propeller load. The impact is considerable and it is indeed recommended to consider the effect of propeller load on the manoeuvrability of the ship.

A new basin to carry out free running model tests was reported by Sanada et al. (2012) and Sanada et al. (2013). The basin at IIHR measures 40x20x3m^3 and is equipped with wave makers and a xy carriage with a turntable. The carriage can follow a free manoeuvring model to perform free running manoeuvring tests in calm water or in waves. The carriage tracking system, the 6 DOF visual motion capture system and the model release and capture system were extensively described. The capability to perform local flow measurements through PIV besides a semi-captive model allows the measurement of local flow fields for comparison to CFD results.

An important improvement in the experimental techniques is the application of uncertainty analysis. Quadvlieg & Brouwer (2011) are applying this to free running model tests on KVLCC2. Woodward (2013) described how the uncertainty of the measurements of the forces and moments in captive model tests propagates to the manoeuvring derivatives. He applied this on KVLCC1.

4. USING SIMULATIONS AS A TOOL TO ADVANCE THE KNOWLEDGE IN MANOEUVRING

4.1 In Deep Unrestricted Water

Using Viscous CFD Methods. One of the main advantages of CFD is its ability to provide information about hydrodynamic loads and motions of the vessel together with detailed flow field information, which can help to understand the flow physics related to manoeuvring. Another advantage is that this type of simulation does not rely on model testing with physical scale models, which means that for instance the hull form or the rudder can be changed relatively easy. This is useful in the early design phase where CFD can help to investigate manoeuvring related issues and help to improve the design. Therefore, CFD is used ranging from detailed flow studies (to learn about the features of the flow field) for prediction of hydrodynamic forces and moments to direct simulation of manoeuvres. This applies to both surface ships and submarines. It seems that in addition to the traditional RANS approach, also Detached Eddy Simulation (DES) and Delayed Detached Eddy Simulation (DDES) have started to show up in practical applications.

In terms of flow field investigations Xing et al. (2012) made a very detailed RANS and DES based study of the bare hull of the KVLCC2 with different turbulence models in order to identify and study the generation and breakdown of the vortex structures around the hull in oblique flow at drift angles from 0 to 30 degrees. Comparison with model test results shows that many flow features are captured by the CFD solution. Amin & Hasegawa (2012) also study the flow around the KVLCC2 but find that unstructured grids make it difficult to accurately capture the flow features. Sakamoto et al. (2012a, 2012b) made a comprehensive flow field study covering vortex structures, velocities and free surface elevations for the 5415M in static and dynamic PMM conditions. The computed velocities in a number of cross planes along the hull were compared with results from SPIV measurements. Overall level flow features were captured, but vortex core properties were predicted to be too weak. Kim et al. (2012) studied the flow around the DARPA Suboff submarine to investigate the vortex structures from the hull and the fins in steady turn with drift. Comparison with experimental data in the studies above showed that many of the flow features can be captured, so CFD seems to be a promising tool for learning about the flow physics in manoeuvring.

When it comes to hydrodynamic forces and moments many different applications are covered to gain knowledge about loads on hulls, rudders and propellers. Silva (2012) calculated both hydro and aerodynamic loads on a supply vessel with RANS. Comparison with experimental tank and wind tunnel showed both close agreement and deviations depending on the flow angle relative to the heading of the vessel. Xing et al. (2012) computed hull forces and moments for the KVLCC2 and found a reasonably good agreement with measurements. Amin & Hasegawa (2012) also computed hull forces for the KVLCC2, but the applied unstructured mesh introduces deviations with the measurements. Arii et al. (2012) calculate rudder forces for an open water propeller-twin rudder configuration with reaction fins. The forces seem to be difficult to capture for larger rudder angles. In Miyazaki et al., (2011) the KVLCC2 was modified and used for a study of the influence of skeg configurations on the course stability. CFD is used to simulate the CMT test and the computed forces and moments were used to determine the hydrodynamic derivatives and evaluate the course stability index. Compared to experimental data, the results look promising. Shin et al. (2013) performed RANS based CFD computations for the KVLCC1 and KVLCC2 in pure turning and static drift conditions. The computed force and moment coefficients were compared with experimental PMM data. Fukui (2012) performs CFD computations of the forces and moments on a VLCC hull with rudder in order to estimate the rudder-hull interaction coefficients used in the MMG model. The overall forces are in reasonable agreement with measured data. Accurate representation of the rudder in the simulation seems to be important to capture the interaction effects. Simonsen et al. (2012) investigated forces and moments plus hydrodynamic derivatives for the appended KCS container ship with RANS and a body force propeller in a number of PMM conditions. Computed forces as well as moments plus hydrodynamic derivatives were compared with model test results. Further, simulations of the standard IMO manoeuvres were made based on both pure experimental PMM data and combinations of experimental dynamic PMM data and static computed PMM data. Results look promising on both force and manoeuvre levels; however, the simplified propeller model may introduce differences. Rajita Shenoi et al. (2013) made numerical simulations of the horizontal PMM conditions by means of RANS in order to determine the hydrodynamic derivatives and to perform 3 DOF manoeuvring simulations for the S175 container ship. A combination of measured and computed data is used as input for the simulator, similar to what was done by Simonsen et al. (2012). Computations covered the static drift and pure sway conditions. Other data came from empirical methods and measurements. The predicted turning circle compared reasonably well with measurements. Mauro et al. (2012) worked with the 5415M to investigate the asymmetric loading on a twin propeller configuration during turning. Sakamoto et al. (2012a, 2012b) performed static and dynamic PMM simulations for the 5415M based on RANS CFD. Thorough V&V was conducted and overall, the CFD solver seems to have the capability of handling static and dynamic PMM simulations, and the resultant forces and moment coefficients as well as hydrodynamic derivatives show reasonable agreement with measured data. Cheng et al. (2013) also performed RANS CFD computations for the 5415M in the pure yaw and pure sway conditions. When compared with measurements the quantitative accuracy of the above studies depends on properties like mesh size, turbulence modelling, propeller modelling and how extreme the flow condition is in terms of flow separation. Generally it seems that forces and moments plus trends are captured reasonably well. Finally, it is possible to use the computed forces and moments as input to system based simulators.

Drouet et al. (2011) cover the DARPA Suboff submarine to compute forces and moments in static drift condition. The results generally look good compared to measurements. Though, for a drift angle larger than 12° the configuration of the bare hull including the sail element deviates, possibly due to turbulence modelling. DARPA Suboff is also studied by Kim et al. (2012) to compute the loads in steady turn with drift. Zhang et al. (2013) computed the flow around the Series 58, Suboff and DRDC STR submarines with RANS in order to simulate steady turn with and without drift. Pan et al. (2012) used unsteady RANS simulation for captive simulations with the Suboff geometry, including steady oblique towing and dynamic pure heave and pure pitch PMM motion. The CFD method is able to provide estimates of the manoeuvring coefficients for the fully appended submarine model, but more studies on application of more advanced turbulence models, finer grid resolution and additional verifications and validations are recommended to improve comparison with data. Zaghi et al. (2012) studied the manoeuvring behaviour of a fully appended submarine in the vertical plane by using CFD based captive data as input for a manoeuvring model. There is no comparison with experimental data for validation. Polis et al. (2013) used CFD to compute the manoeuvring coefficients for the Suboff in steady conditions near the free surface to include the free surface effect in the coefficients. Different submergences and speeds were covered. Comparison with captive model test data shows reasonable agreement. In order to be able to include the coefficients in manoeuvring models, the computed results are approximated with exponentially fitted expressions.

The final application is direct simulations of the manoeuvres where the CFD tool is used to solve the flow field, compute the hydrodynamic forces and moments and find the trajectory of the ship during the manoeuvre. In Broglia et al. (2011) and Dubbioso et al. (2012) RANS simulations were performed for a free running twin screw tanker model performing turning circles and 20/20 zigzag. The propeller is modelled as a momentum disk approach where also side forces are accounted for. The results show that reasonable agreement can be obtained with measurements for speed, drift angle and yaw rate during the manoeuvre. In terms of overall manoeuvring characteristics a comparison between measured and computed transfer, advance, tactical and turning diameters looks promising. Sadat-Hosseini et al. (2013) performed RANSE based CFD simulations for the free running Delft Catamaran with water-jet propulsion during turning and zigzag manoeuvres. Simulations were conducted with two propulsion approaches:

1) bare hull with integral force models for water-jet;
2) bare hull with actual water-jet with body force impeller defined by pump curves.

The CFD results were compared with system-based predictions and both validated against experimental fluid dynamics (EFD) data. When compared to measured manoeuvres CFD with actual water jet model showed best agreement for turning. For the zigzag manoeuvre CFD with actual water-jet showed the largest errors, while good agreement was shown for CFD bare hull with the system based integral force water-jet model. The authors concluded that further works on water-jet characteristics and modelling are required.

In Carrica et al. (2013) URANS computations of standard manoeuvres were performed for a surface combatant at model and full scale. Two types of manoeuvres were simulated: steady turn at 35 degrees rudder deflection and 20/20 zigzag both with constant RPM approach and body-force propeller. Results are benchmarked against experimental time series of yaw, yaw rate and roll, and trajectories, and also compared against available integral variables. Comparison between CFD and experiments showed reasonable agreement for both manoeuvres, though issues regarding adequate modelling of propellers with side forces remain to be solved. The 20/20 zigzag manoeuvre was also simulated at full scale for one Froude number. The full scale case produces a thinner boundary layer profile compared to the model scale.

Araki et al. (2012a) performed free running CFD simulations for the ONR Tumblehome hull form in order to generate data for SI , which can be used to derive hydrodynamic coefficients for system-based simulators. The advantage of using free running CFD instead of model testing for this purpose is that both motions and forces on the hull and appendages can be generated in CFD. The results of the manoeuvring simulations obtained with coefficients from CFD SI look good when compared to measured standard turning circle and zigzag tests. This approach is an alternative to the one described above where a large set of CFD based PMM simulations are performed to determine the hydrodynamic coefficients for the mathematical manoeuvring model. Chase et al. (2012) have performed RANS, DES and DDES simulations for a free running submarine (DARPA Suboff) model performing a horizontal overshoot manoeuvre. The propeller was modelled with two different approaches:

- a body-force approach where the PUF-14 vortex-lattice potential flow code is coupled with the RANS solver;

- direct modelling of the propeller in the CFD model.

The horizontal overshoot manoeuvre was simulated with both propeller models. In terms of validation, the final free running manoeuvre was not compared with measurements, but both hull and propeller forces were compared with measurements for different conditions.

Using Potential Flow Techniques. Ommani et al. (2012) investigated the hydrodynamic forces on a semi-displacement vessel with a drift angle. The resulting flow asymmetry at the dry transom stern was investigated. The potential part was solved using the 3D Rankine source method and the viscous cross flow was calculated using a 2D+t theory. The agreement with experimental results is reasonable for the longitudinal and lateral force, but the neglected nonlinearities and 3D viscous flow are believed to hamper the prediction of the yawing moment.

Ommani & Faltinsen (2013) investigated the dynamic stability performance of an advancing mono-hull, semi-displacement vessel in sway-roll-yaw. A linear Rankine panel method was adopted and various Froude numbers were analysed. Compared with the experiments, the numerical analysis was able to predict the instability of system.

Ichinose & Furukawa (2011) presented an estimation method for hydrodynamic forces acting on a ship hull in oblique motion using a 3D vortex method. A vortex block model and a vortex sheet model were introduced to model the flow in the boundary layer, but the quantitative accuracy of the estimated forces is not sufficient.

Using Empirical Calculations. In order to predict the hydrodynamic forces acting on a hull, which is necessary to conduct ship manoeuvring simulation, Yoshimura & Masumoto (2012) made a database of manoeuvring hydrodynamic coefficients for medium speed merchant ships and fishing vessels. The database not only contains hydrodynamic derivatives but also interaction coefficients. The coefficients are arranged by the principal particulars of ships and regression formulae are presented. Sugisawa & Kobayashi (2012) proposed a correction method for hydrodynamic derivatives estimated by published empirical formulae. Correction factors for derivatives are defined to minimize the difference between simulated and measured turning trajectories. Viallon et al. (2012) investigated the reduction of the order and number of regressors of polynomial regression models for manoeuvring forces. A secondary regression which provides practically the same accuracy as the original higher order regression model for moderate manoeuvres is presented. Oh & Hasegawa (2013) evaluated four existing mathematical models for low speed ship manoeuvrability. Sway force and yaw moment predicted by the mathematical models were compared with experimental results. They also conducted a simulation study on turning motion and a zigzag manoeuvre to check the influence of each model.

In terms of propeller and rudder force, Shen & Hughes (2012) proposed a computation method for the effective inflow velocity of the rudder. They estimated the axial and tangential flow velocities at the rudder plane separately and the effective inflow velocity was determined based on the axial and transverse flow distributions and the rudder geometry encountered by the propeller slipstream. Hwang (2012) presented a pragmatic 4-quadrant propeller-rudder model based on the concept of Thulin (1974) and Chislett (1996). Dubbioso & Viviani (2012) analyzed the effect of stern appendage configurations comprising skegs, fins and rudders on the manoeuvrability of twin-screw ships. Based on extensive experiments for seven twin-screw models, an empirical correction method for appendages effect is proposed.

Fang et al. (2012) developed a real-time simulator based on a 6 DOF mathematical model including seakeeping and manoeuvring characteristics. Hydrodynamic coefficients were estimated with empirical formulae in published papers. The simulated turning motions of 8,200 TEU container vessels were compared with measured sea trial results for the validation of the simulator. Yuba & Tannuri (2013) investigated the manoeuvrability of pusher-barge systems which have an azimuth or a conventional propulsion system with/without an auxiliary bow azimuth thruster. The advantage of each system, depending on the manoeuvring situation, is shown.

Using Experimental Techniques. In order to evaluate the effect of roll motion on ship manoeuvrability, Yoshimura (2011) introduced a rudder to yaw response equation based on a linear mathematical model of hydrodynamic forces acting on a ship. He pointed out that the turning moment induced by roll motion is a key parameter which strongly affects the course-keeping and turning abilities. This tendency becomes remarkable when the roll angle becomes large. Yasukawa & Hirata (2013) conducted oblique towing and circular motion tests with changing heel angle to capture the characteristics of hydrodynamic forces acting on a ship hull. The effect of the heel angle on the course stability criterion was evaluated using hydrodynamic derivatives obtained by model experiments. Yasukawa & Yoshimura (2013) investigated the roll-coupling effect on ship manoeuvrability in the framework of linear motion theory. They proposed approximate formulae for the course stability criterion, steady turning index and time constant for steady turning. Simulation results of turning motion using hydrodynamic derivatives, including the effect of roll motion, are shown.

A mathematical model for a twin-propeller, twin-rudder ship was developed by Khanfir et al. (2011) based on captive model tests and free-running experiments. An experiment-based method for estimating rudder-hull interaction coefficients is proposed. Simulated results based on the proposed mathematical model are compared with free-running test results for validation.

The effect of static and dynamic azimuthing conditions on the propulsive characteristics of a puller podded unit were analyzed by Akinturk et al. (2012) based on model experiments in open water. They conducted a thorough uncertainty analysis to assess the uncertainty in their experiments and to identify the major factors influencing measured results. Amini & Steen (2012) also investigated the effect of a dynamically changing propeller revolution and azimuth angle on propeller shaft loads based on model experiments using a model of a pushing azimuth thruster. Song et al. (2013) investigated the thrust loss induced by the interaction between an azimuth thruster and a ship hull based on model tests using a model of a wind turbine installation vessel. Comparison between simulation results using a commercial CFD code and measured results is also shown.

Several publications relate to unconventional ships. Obreja et al. (2010) developed a simulation code for the manoeuvring characteristics of a Mediterranean fishing vessel. PMM experiments were used for evaluating the hydrodynamic derivatives. The simulation results for turning motion and zigzag manoeuvres were compared with the model test results. Zhan & Molyneux (2012) developed a simulation method for ship motion in packed ice, combining mathematical models for ship motion, ice motion and ship-ice interaction. The manoeuvring behaviour of an arctic drill ship with ice was simulated by the mathematical model and compared with experimental results.

Avila & Adamowski (2011) carried out forced oscillation and steady-state tests with an open-frame ROV. Analysing the variation of drag and inertia coefficients in Morison's equation as a function of Keulegan-Carpenter and Reynolds numbers, dependency or independency on the parameters is shown. De Barros & Dantas (2012) presented a comparative study of CFD and ASE (analytic and semi-empirical) methods for the prediction of the normal force and moment coefficients of an AUV with a duct propeller. The advantages of the symbiosis between CFD and ASE methods are suggested.

Towed stability. Fitriadhy & Yasukawa (2011a, 2011b) developed a nonlinear numerical simulation tool to predict course stability and turning ability of a towing system in calm water. The motions of the towing and towed vessels were coupled by a towline. The towline was modelled using a 2D lumped mass method to take into account the dynamic motion of the towline. Linearized equations of motion were also derived to confirm the validity of the nonlinear analysis. The influences of several parameters such as towline length, towed vessel's dimension and tow points on course stability and turning ability of the towing system were investigated.

Fitriadhy et al. (2011) investigated the mechanism of slack towline motion and its influence on towing and towed vessels during manoeuvring. A linearized theory was applied to grasp the basic mechanism of dynamic interaction between towing and towed vessels. They proposed a formula which gives the appearance limit of slack towline during turning. Furthermore Yasukawa et al. (2012b) carried out nonlinear time domain simulations and tank tests to validate the formulae. It is concluded that the slack towline appearance limit qualitatively agreed with the results of simulations and tank tests.

Ren et al. (2012) proposed a mathematical model of a tug towage operation for an interactive tug simulator. Two kinds of towline tension models were used. The first one is a model with linear strain which can take account of the towline's own weight. The other one is a model with nonlinear strain which omits the towline's own weight. The appropriate model was selected in their simulation comparing the towline strain with the maximal towline strain given by the towline stress-strain diagram. Yoon & Kim (2012) modelled a towline with a finite element model in 5 DOF (roll excluded). The motion of the tow vessel was simulated in 6 DOF but the towed vessel was assumed to solely move in the horizontal plane. In the above papers, only the results of numerical simulations are presented.

4.2 In Shallow Water

Using Viscous CFD Methods. Toxopeus (2011b) performed a comprehensive study of the shallow water effect on the KVLCC2. Computations were performed with fixed sinkage and trim and free-surface effects were not taken into account. Results highlight the adverse influence of the water depth on the flow along the aft part of the ship. Kimura et al. (2011) applied CFD to study the manoeuvring forces on a VLCC in shallow water .

Using Potential Flow Techniques. Skejic et al. (2012) investigated the ship manoeuvring performance in calm water with variable finite water depth. A unified seakeeping and manoeuvring (MMG based) model was modified with the inclusion of shallow water effects. Simulated results of turning motion for variable sea bottom profile are shown.

Gourlay (2013) applied a modified slender body method to solve the ship‘s squat in a dredged channel and canal. The sinkage in a dredged channel is 20-30% larger than in open water, while in a canal, the squat can increase up to 100% compared to the value in open water.

A shallow water hydrodynamic coefficient prediction and MMG equation simulation of ship fleets manoeuvring in shallow water (Three Gorges Dam of China) was carried out by Cai, et al. (2012). The added mass was calculated by strip theory and empirically corrected with the shallow water effect. The simulation results showed good agreement with the experiments.

Using Empirical Calculations. A prediction method for linear derivatives in shallow water was proposed by Furukawa et al. (2011). The linear derivatives were obtained by adding correction factors to the deep water derivatives. The correction factors are provided as functions of parameters, which consist of principal ship dimensions and so on.

Quadvlieg (2013) presented a method to create mathematical manoeuvring models for the simulation of inland ships based on only the main particulars of hull, rudder and propeller without the need to execute model tests. A modular model is introduced based on slender body theory and cross flow drag theory for hull forces and a parameterised model for rudders of inland vessels based on systematic model tests.

Using Experimental Techniques. The inherent directional stability of a catamaran was investigated by Milanov et al. (2011) based on a linearized manoeuvring model and model experiments covering a wide range of Froude numbers and depth to draft ratios. Maimun et al. (2011) presented an experimental investigation of the manoeuvring characteristics of a pusher barge system for deep and shallow water conditions. Comparisons between simulated results using experimental or empirical coefficients with measured results are shown. Reichel (2012) developed a mathematical model based on the MMG approach for a twin-propeller, twin-rudder car-passenger ferry. PMM tests were conducted to determine the hydrodynamic derivatives and other parameters. Three modes of motion such as ahead, astern and pure drift were considered in the model tests to simulate port operations.

4.3 In Restricted Water

Using Viscous CFD Methods. Zou et al. (2011) compared results obtained with both potential and CFD codes with experiments for the KVLCC2 in a canal. Results show the influence of viscous effects on ship behaviour and flow field. The CFD results are in good agreement with the experiments for different UKC and lateral clearances. In Zou & Larsson (2012a) the research is extended to provide physical explanations of the flow field. Computations were performed for both 0 RPM and self-propulsion. Results show a strong influence of the bank on stern flow leading to high asymmetrical propeller loadings and yaw moments.

Lou & Zou (2012) performed CFD computations on a KVLCC hull in a canal. Computations were performed in pure sway for symmetrical and asymmetrical locations of the ship in the canal. Results showed strongly different behaviour of the sway forces and yaw moment for the two cases.

Using Potential Flow Techniques. With the first-order Rankine source panel method, Yao et al. (2011) studied the bank effects of a container ship sailing along vertical or sloping banks in shallow channels. The influences of the ship to bank distance , the speed and the water depth on the sway and yaw hydrodynamic forces were discussed.

Using Empirical Calculations. A statistical squat prediction model was proposed by Beaulieu et al. (2012) based on a stepwise regression tree algorithm. The prediction model was developed using a database containing 5,141 observations in the St. Lawrence River and produces a relationship between squat and ship speed. Om et al. (2013) evaluated the manoeuvrability of a shallow draft ore carrier with twin-propeller and twin-rudder, which is newly designed for inland waterways.

Muto et al. (2011) simulated the motion of a ship running in a non-uniform flow field, mimicking the flow field that a ship may encounter while sailing near the mouth of a river. Estimated hydrodynamic forces using empirical formula for large drift angles and simulated trajectories were compared with measured results. Hasegawa et al. (2013) investigated the ship manoeuvring behaviour in crossing current. They pointed out that a mathematical model for low speed should be considered even if the ship speed is not low because the crossing current causes a large drift angle.

Carreño et al. (2013) conducted full-scale trials of a riverine support patrol vessel which has a pump-jet propulsion system and a large beam-draft ratio. The standard parameters of turning tests were measured to compare with simulated results based on a mathematical empirical model.

Using Experimental Techniques. Yasukawa et al. (2012c) analysed the course stability and yaw motion of a ship running under steady wind conditions and proposed a course stability criterion including the effect of aerodynamic force derivatives. Then, Yasukawa et al. (2013) applied the course stability criterion for a ship running in a channel under steady wind and obtained the check helm angle required for course keeping by solving the steady motion equations.

4.4 Ship-to-Ship Interaction

Using Viscous CFD Methods. Mousaviraad et al. (2011) use CFDSHIP-IOWA to study interactions between passing ships. Replenishment and overtaking computations were performed in both calm water and waves. Influence of the spacing between ships and the sheltering effect of one ship was evaluated. Results are compared with experiments.

Fonfach et al. (2011) present a comparative study of potential and CFD computation on the flow past a tug boat close to a large tanker. Computations were performed using free-surface boundary conditions or double body conditions. Results highlighted the influence of the free-surface boundary condition to accurately predict the lateral force on the tug boat as the separation distance is reduced.

Simonsen et al. (2011) performed CFD computations on a tug boat next to a tanker for different tugboat drift angles and locations relative to the tanker. The CFD results are in good agreement with the experiments.

Benedict et al. (2011) developed a new and extended mathematical model to solve encountering and overtaking ship operations considering the surge and sway motion. A combined approach with finite volume discretisation and level-set free surface flow was adopted to simulate the hydrodynamic forces. The paper also introduced the safe passing distance based on a reference drift angle.

Sadat-Hosseini et al. (2011b) presented a study on investigating the interaction between two different tankers; Aframax and KVLCC2, free to heave and pitch, advancing in shallow-water with the same speed and with a fixed separation distance using CFDSHIP-IOWA V4.5 URANS simulation. The result was validated and shows good agreement. Several influences such as suction force and asymmetric ship wake on ship-ship interaction and longitudinal alignment on yaw moment were discussed. The same problem was investigated by Zou & Larsson (2012b). The paper applied the steady RANS to numerically simulate the hydrodynamic force between the Aframax and the KVLCC2. Both the RANS and URANS gave good results compared to the experiments.

Zhang & Zou (2011a) used the FLUENT software to calculate the hydrodynamic forces of encountering and passing ship-to-ship interaction. The influences of boundary conditions such as bank effect and water depth were presented.

Leong et al. (2013) focused on the interaction forces and moments acting on an AUV operating in close proximity to a moving submarine. The influences of longitudinal and lateral distances and a range of speeds were investigated through CFD and EFD and a safe path for the AUV to approach or depart from the submarine was suggested.

Zubova & Nikushchenko (2013) investigated ship to ship interaction using the Wigley hull form. Calculated forces and moments using commercial software (FLUENT, FINE/Marine and STAR-CCM+) were presented.

Yang et al. (2011) compared potential flow and CFD results for passing ships at low speed, of which one was the KVLCC2. Potential flow and CFD results are in good agreement.

Using Potential Flow Techniques. Potential theories are efficient in solving ship-to-ship interaction problems. With the manoeuvring model introduced by Skejic (2008) and a 3D boundary element method, Xiang & Faltinsen (2011) simulated the interacting hydrodynamic forces of two ships and carried out verification and validation in infinite water. In this research, a low Froude number and a rigid free surface was assumed. Xiang et al. (2011) also predicted the interacting loads of two tankers involved in a typical lightering operation with the 3D panel method. As for the ship to floating structure interaction, Skejic et al. (2011) used the STF strip theory and a two time scale manoeuvring model to simulate the process of manoeuvring a ship around a floating object with the assumption of low speed and uniform current.

Sutulo et al. (2012) applied the classic Hess and Smith method, combined with rigid free surface conditions, into the real time interacting forces of two ships. Compared with experiment results, the largest discrepancies were discovered for the sway force at a very small horizontal clearance. This effect could be analyzed with viscous flow theory and free-surface boundary condition, see Fonfach et al. (2011).

3D potential flow theories have been applied to the interactions between a moving ship and moored ship. Van der Molen et al. (2011) calculated the hydrodynamic forces of a moored ship in port due to passing ships by means of a 3D source method taking account of the free surface and the finite water depth . Pinkster (2011) gave 3D potential flow results of hydrodynamic forces on a moored vessel due to a passing vessel based on a double-body flow and free surface assumption. He also pointed out that the complexity of geometry, current or drifting angle would lead to inaccuracies. Based on Pinkster's double-body method, Bunnik & Toxopeus (2011) presented a RANS method to compute the effect of passing ships on moored ships. The discrepancy between RANS and the potential methods for large drift angles was analysed. The 3D potential flow method was also applied by Verdugo et al. (2013) who studied the methodology to analyse ship manoeuvres and passing ship effects on moored ships at different berths in the Port of Altamira (Mexico).

De Jong et al. (2013a) applied a newly-developed time-domain model based on the shallow-water flow formulations for continuity and momentum (Xbeach) to simulate the passing ship effect in waterways and ports. The non-linear effects such as shallow water waves, currents and an arbitrary bank condition could be taken into account.

Pinkster & Bhawsinka (2013) introduced a real-time simulation technique which links the program “Delpass” and MARIN’s real-time simulator. This might reflect more precise ship manoeuvring behaviour on the simulator since it uses the real-time force for ship-bank and ship-ship effects instead of the empirical hydrodynamics.

Ship-to-ship interaction research was carried out by Watai et al. (2013). The results based on strip theory, empirical regression and 3D Rankine source boundary element method were compared with the experiments. The 3D-BEM method gave the best agreement with the test on the passing ship effects.

Using Empirical Calculations. An artificial neural network method for predicting the sway force, surge force and yaw moment was studied by Xu et al. (2012). With this ANN technique, the influence of ship speed, water depth and ship dimensions could be immediately translated into ship-to-ship forces to help the pilot quickly judge the navigation environment and risks. Gronarz (2011) made a so-called hybrid regression to predict the transient behaviour related to forces and moments caused by passing ships.

4.5 Improvement in CFD methods

For the application of CFD for manoeuvring, simulation of the captive conditions is the most commonly used approach today. It seems that reasonable results can be obtained, Simonsen et al. (2012), but the downside of the approach is that many CFD simulations must be performed to give enough data to provide the required derivatives for simulator models. On the other hand, part of the test matrix can be computed and combined with input from other sources. The CFD based SI approach from Araki et al. (2012a) is currently not used much, but if the CFD code is capable of simulating the free sailing manoeuvres it can be done. The simulations required are complex, but fewer runs are required compared to the captive approach. It should be mentioned that if the free sailing capability is available in the CFD code and one is only looking for the standard IMO manoeuvres they could be directly simulated without going through the system-based model. If more general manoeuvres are to be performed the CFD based SI method could be a better option.

Recent works using unsteady Navier-Stokes equations to simulate free-running manoeuvres have been published. Simulations are usually performed using propeller models in order to reduce computational effort. One of the weak points that are currently experienced by many of the CFD applications is the propeller modelling. It would be good to run the CFD simulations with spinning propeller geometry, but this is very time consuming due to the different time scale between propeller physics and manoeuvring forces variations. Therefore, many users apply simplified propeller models which are missing some of the rudder-propeller-hull interaction effects and in some cases also the side force from the propeller. This influences of course the loads on the individual components and will influence the predicted manoeuvre.

4.6 Autopilots and other control applications

This section presents the developments related to the application of control systems to the manoeuvring problem. Besides autopilots' new technologies, there are some improvements related to automatic berthing, optimal route finding, etc.

Bhattacharyya et al. (2012) developed a fuzzy autopilot algorithm for manoeuvring of surface ships and verified the performance using time-domain simulations of a Mariner class vessel. However, this can be considered an introductory work, since the analysis assumed an undisturbed environment without any waves, current or wind. Mucha & Moctar (2013) tested different control approaches to design and tune the autopilot applied to a vessel navigation close to a bank.

Luo et al. (2013) proposed a hybrid architecture for the autopilot, with real time identification of ship dynamics based on support vector machines and robust techniques applied for the controller design. Numerical simulations were used for the performance analysis.

Do (2010) derived a general control algorithm for underactuated ships, with no independent actuator in the sway axis. The trajectory control using the rudder is an example of such a problem. The algorithm is based on nonlinear control theory and numerical simulations illustrated its effectiveness.

The concept of multi-controller structure was applied to autopilot design by Saari & Djemai (2012). The ship speed is used to select between different PID control gains, and a simple switching law is adopted. The authors showed that the non-linear behaviour of the system due to the speed can be adequately compensated by the proper switching of PID control gains.

Mizuno & Matsumoto (2013) derived an automatic ship's manoeuvring system using a sliding mode controller. They demonstrated the advantages of the proposed controller by means of computer simulations and actual sea tests carried out using the small training ship Shioji-Maru under various conditions. The authors emphasized that the control scheme can be easily implemented in the autopilot for small size ships.

The automatic berthing is a marine control related problem, in which the model describing the vessel motion is highly non-linear, especially in the case of low speed and large manoeuvring motion. Also, the number of inputs used to control the vessel position and heading may be large, due to the utilization of thrusters and tugboats. Due to the previous characteristics of the problem, the definition of the minimum-time approaching control for automatic berthing requires a large computer processing capacity. Mizuno et al. (2012) developed an automatic berthing system using GPU, which is able to cope with external disturbances. The method uses the prediction of the future position of the vessel in order to define the next set of inputs. Numerical simulations and full-scale tests were used to verify the system. Tran & Im (2012) presented an automatic berthing system with an artificial neural network (ANN) controller. The controller is designed to use assistant devices such as bow thruster and tugboat.

The online prediction of ship roll motion during manoeuvring plays an important role in navigation safety and ship control applications. Yin et al. (2013) derived a method for this task, using neural networks. The results of full-scale sea trials were used to validate the method.

A method for automatic route finding and collision avoidance was presented by Xue et al. (2011). This paper presents an effective and practical method for finding safe passage for ships in possible collision situations, based on the potential field method. Simulations of complex navigation situations demonstrated the effectiveness of the method.

Nakano & Hasegawa (2012) proposed a prediction method for manoeuvring indices K and T in Nomoto's model by analysing AIS (Automatic Identification System) data with an optimisation method.

5. BENCHMARK DATA

5.1 SIMMAN 2014

Goal. In continuation of the Workshop on Verification and Validation of Ship Manoeuvring Simulation Methods, SIMMAN 2008, a new workshop SIMMAN 2014 will be held in December 2014. Since SIMMAN 2008 some of the deep water data sets used for the workshop has been replaced by new measurements based on the learning from 2008. Further, the scope of SIMMAN 2014 has been extended compared to 2008, so shallow water is also a part of the workshop. This has necessitated measurements in shallow water.

At the SIMMAN 2008 workshop the focus was placed on four hull forms selected by the ITTC for benchmark, i.e. the KVLCC1 and KVLCC2 tankers, the KCS container ship and the 5415M. However, the results from the 2008 workshop showed that there were only minor differences in manoeuvring characteristics between the KVLCC1 and KVLCC2. Therefore, to limit the number of test cases and focus the effort on fewer ships it was decided to only focus on KVLCC2, KCS and 5415M in SIMMAN 2014. A discussion of the 2008 data is given in Stern et al. (2011).

The main focus of the workshop is on appended hull tests in deep and shallow water to provide data for simulation of free manoeuvres. Though, bare hull tests for validation of CFD-based methods are also available. Ship, rudder and propeller geometries plus the captive part of the data from the model tests is already available to the public via request from the workshop website www.simman2014.dk. Free running test results will be made available after the workshop, since the free running test cases are blind. An overview of the model test data available for the workshop is given in Table **1**. Some test data has not yet been received.

Captive Model Test Data. All test conditions for the workshop are specified in model scale, i.e. appended captive tests are made at model self-propulsion point using constant RPM throughout the manoeuvre. Typical output are X- and Y-forces plus yaw and heel moments (4 DOF). In some cases rudder and propeller loads are also measured.

For KVLCC2, new PMM data is available for both deep and shallow water in both appended and bare hull configurations. Hyundai Maritime Research Institute (HMRI) has provided data for a 3 DOF test in deep water with a model at a scale of 1:46.426. INSEAN is planning on making the same test in deep water, but with a smaller model at a scale of 1:100. This data will be available in the second half of 2014. The Bulgarian Ship Hydrodynamics Centre (BSHC) has contributed with 3DOF

PMM data in shallow water for an appended model at a scale of 1:45.714. Water depths ranging from very shallow to moderate shallow were covered with h/T_m ratios of 1.20, 1.50 and 2.00. In addition to this a number of bare hull conditions were also covered for h/T_m=1.20. Flanders Hydraulics Research (FHR) also executed shallow water 3 DOF PMM tests for the KVLCC2. In this case the scale was 1:75 and h/T_m ratios of 1.20, 1.50 and 1.80 were covered. A subset of bare hull conditions are also available from FHR. Concerning circular motion tests (CMT) with the KVLCC2, the 3 DOF data set for the appended hull used for SIMMAN 2008 is still used and available. The scale of the model was 1:110.

For KCS in deep water PMM tests were performed at FORCE with the appended hull. Since heel plays an important role for the container ship the test was performed as a 4 DOF test, which means that heel variation is included in the test. A limited set of conditions with the bare hull is also covered. The scale of the model is 1:52.667. In shallow water two data sets have been made. One set is made by FHR who considered water depths with h/T_m ratios of 1.20, 1.50 and 2.00. The model used in this case is the same as the one FORCE used, i.e. model scale of 1:52.667. The other data set is made by MOERI. The test was made with a model at a scale of 1:31.6. Data from this test has not yet been released by MOERI.

With respect to CMT tests two data sets are available. The first is from NMRI who made 3 DOF CMT for SIMMAN2008 with a model at a scale of 1:75.5. The other set is made by China Ship Scientific Research Centre (CSSRC). To account for heel, the test was made as a 4 DOF test with the appended hull. The scale of the applied model is 1:52.667.

Table 1. Available data for the SIMMAN 2014 workshop.

	Hull	KVLCC2			KCS			5415M		
Captive	PMM app. deep	INSEAN (2014) missing	HMRI (2012)		FORCE (2009)			MARIN (2007)		
	PMM app. shallow	BSHC (2013)	FHR (2012)		FHR (2012)	MOERI (2013)				
	PMM bare deep	INSEAN (2014) missing			FORCE (2009)			FORCE (2004)	IIHR (2005)	INSEAN (2005)
	PMM bare shallow	BSHC (2013)	FHR (2012)							
	CMT app. deep	NMRI (2006)			NMRI (2005) 3DOF	CSSRC (2013) 4DOF	IHI (2012)	MARIN (2007)		
	CMT bare deep									
Free	Free app. deep	HSVA (2006)	MARIN (2007)	CTO (2007)	MARIN (2009)			MARIN (2007)		
	Free app. shallow	FHR (2012)	MARIN (2013)		BSHC (2008/ 2011)	FHR (2012)				

A third set of CMT tests in 4DOF is made available by JMU and Hokkaido University based on measurements in 2012 at a scale of 1:105.

For the 5415M the PMM test results are available for both bare and appended hulls. For the bare hull three data sets were made by FORCE, INSEAN and IIHR. The three institutes used different model scales: 1:35.480, 1:24.830 and 1:46.588, respectively. These data sets were also available for SIMMAN2008. For the appended 5415M MARIN has provided a set of PMM data for the model with a twin screw-twin rudder arrangement, a centre line skeg, bilge keels and stabiliser fins. The PMM test was conducted as a 4 DOF test and in addition to the traditional overall forces and moments acting on the ship, local force measurements on rudders and stabilizers were also performed. Concerning CMT test results, MARIN performed this test with the same 5415M model that was used for the PMM test. Both appended 5415M data sets are new compared to the sets used for the workshop in 2008.

Free Model Test Data. The nominal conditions for the free model tests comprised constant RPM at the model self-propulsion point as well as a certain speed, rudder rate and GMT for each ship. The typical measurements cover turning circles (full or partial) plus 10/10 and 20/20 zigzag tests.

For the KVLCC2 tanker in deep water free model tests were performed with the same model (1:45.714) at the nominal conditions at three facilities: HSVA, MARIN and CTO for SIMMAN 2008. It can be noted that KVLCC1 was also tested and it was from these results that it was found that the difference in manoeuvring characteristics between the two versions of the tanker was quite small. It was decided to skip KVLCC1 for SIMMAN2014. In shallow water two new data sets have been measured. One was made by FHR with the same model (1:75) that they used for the PMM tests. Another data set was measured by MARIN with the FHR model (1:75). The considered water depths covered h/T_m ratios of 1.20, 1.50 and 1.80.

For the KCS container ship in deep water a new set of free model tests has been performed by MARIN with a model at a scale of 1:37.890. It can be noted that this is a somewhat larger model compared to the one used for deep water PMM at FORCE. In shallow water three new data sets have been measured. Two were made by BSHC and one was made by FHR, but they were all made with a model at a scale of 1:52.667. Both BSHC and FHR considered h/T_m ratios of 1.20, 1.50 and 2.00. It can be noted that at BSHC the full turning circles were measured, while the FHR data only contains partial turning circles due to limited width of the towing tank.

During SIMMAN2008, the free model tests from MARIN for the 5415M showed a surprising asymmetry between the port and starboard turning circle manoeuvres, but this has subsequently been checked and corrected, so data should be ready for SIMMAN2014.

As a final comment to the shallow water captive and free running test results in shallow water, it should be noted that towing tank blockage may influence the results as indicated in Toxopeus et al. (2013a). In deep water the width of the applied towing tanks does not influence the results significantly. But, when testing for instance at h/T_m of 1.20 with very small under keel clearance, the width of the tank has an influence. So, when using the shallow water data for validation of simulation tools this has to be kept in mind.

5.2 Submarine

The DARPA SUBOFF is a recommended submarine hull form for benchmark tests. This is described by Groves et al. (1989). Very detailed flow measurements were published by Huang et al. (1992) based on measurements in a wind tunnel. Towing tank experimental results were presented by Roddy (1990). The latter one concerns rotating arm experiments carried out in the Carderock Model basin of NSWC.

The DARPA SUBOFF comes in various configurations having different arrangements of aft planes and stern arrangements: it is recommended to work with one of the following configurations. Configuration AFF-1 is an axisymmetric body without sail, propeller and planes. Measurements are carried out until drift angles of 18°. This is often taken as the base case for many research programs. Configuration AFF8 is the fully appended hull with a sail and aft planes. In addition to the results of captive manoeuvring experiments, this set of data also includes the flow field at several locations and the pressures at several locations on the hull measured during the captive manoeuvring experiments.

Many researchers over the world are using this hull form as the study object: A collaborative exercise to calculate the manoeuvring forces for DARPA SUBOFF by CFD is reported by Toxopeus et al. (2012). Zhang et al. (2013) simulated the flow over the AFF-1 form. Kogishi et al. (2013) have also performed calculations on this hull form, but unfortunately performed experiments on a different submarine hull. Ray (2010) used RANS to determine the hydrodynamic coefficients of the DARPA SUBOFF. Vaz et al. (2010) compared the results of two different viscous flow solvers for DARPA SUBOFF.

5.3 Hamburg Test Case

The Hamburg Test Case (HTC) is a 1:24 scale model of a 153.7m container ship built by Bremer Vulkan in 1986. Captive deep water model testing was conducted with the HTC within the VIRtual Tank Utility in Europe (VIRTUE) project by Hamburgische Schibau-Versuchanstalt (HSVA) in order to provide data for CFD validation. The tests covered force measurements for the bare hull, the hull with rudder and the hull with propeller and rudder. In addition, PIV measurements were conducted with the bare hull model while sailing in steady turning motion. The experiments were reported in VIRTUE deliverable D3.1.3, Vogt et al. (2007). Further, free running model tests were performed by MARIN to determine the manoeuvring characteristics in connection with measured turning circles and pull out plus 10/10 and 20/20 zigzag manoeuvres. The results are reported in Toxopeus (2011a).

5.4 Restricted Water Cases

Bank Effects. To investigate bank effects and make a public data set to be used for validation of mathematical models and CFD computations a comprehensive research project covering captive model testing has been carried out at Flanders Hydraulics Research in Belgium in cooperation with the Maritime Technology division of Ghent University, Lataire et al. (2009b). In this study two types of banks were investigated: one covers surface piercing banks, characterised by a constant slope from the bottom up through the free surface and the other covers banks with platform submergence composed of a sloped part from the bottom up to a certain level where it transitions into a horizontal, submerged platform. Further, three different under keel clearances were considered. Three ship models were used during this test: a 8000 TEU container carrier, a LNG-carrier and a small tanker. Only a limited set of model test results from the study are made available for the container carrier model at different loading conditions. The data covers measured hull forces and moments, rudder forces, propeller thrust and torque, dynamic sinkage and trim plus free surface elevations.

Ship to Ship Interaction. In relation to ship-to-ship interaction captive model test results for lightering conditions are presented in Lataire et. al. (2009a). The service ship (SS) is an AFRAMAX and the ship to be lightered (STBL) is the KVLCC2 tanker. Both ships are at a scale of 1:75 and are equipped with rudder and running propeller. Speeds of 2, 4 and 6 knots were covered in shallow water corresponding to h/T=1.87 for the STBL. During the static tests the transverse and longitudinal position of the SS relative to the STBL were varied. Further, different drift angles of the SS were also covered. During dynamic tests both harmonic pure yaw and pure sway conditions were covered. The results of the tests cover propeller thrust and torque, rudder torque and forces plus hull forces and moments for both ships. Further, the wave elevation at three positions in the basin were recorded to track the wave making of the passing ships.

Lock Effects. The last benchmark data set for restricted water covers model test data for ships approaching and leaving locks. In Vantorre & Delefortrie (2013) model tests with a free running self-propelled 12000 TEU containership at a scale of 1:80 were conducted in model of the new locks in the Panama Canal. Both lock entry and lock exit conditions were covered for under keel clearances of 20% and 10%. In terms of published results the ship's position, the set speed and the actual speed, the longitudinal forces (propeller thrust and tug force), the propeller rate the lateral force and yawing moment, the absolute running sinkage of the ship's bow and stern, the height of bow wave and the water level elevation at the closed lock door were measured. In addition to this data, results for a limited number of captive tests with a bulk carrier at a scale of 1:75 sailing in the approach channel to another lock are also provided in Vantorre & Delefortrie (2013).

5.5 Manoeuvring in Waves

Yasukawa (2006) provides benchmark data for manoeuvring in waves. Free running turning circles with a container ship (S-175) at a scale of 1:50 were carried out in regular waves. The ship model always started at $F_r = 0.15$. The regular waves were tested in both beam and head seas of varying wave length ($\lambda/L = 0.5$-1.2, $H/L = 0.02$). Course keeping tests in regular waves were performed for wave directions 0, 30, 90, 150 and 180 and varying wave length ($\lambda/L = 0.5$-1.5, $H/L = 0.02$).

6. MANOEUVRING AND COURSE KEEPING IN WAVES

6.1 Overview

Manoeuvrability in waves is a common name but it gathers many different applications like course keeping in following waves, broaching and "pure manoeuvrability".

Course keeping in head waves is dealing mainly with forces at wave frequency and small heading deviation. Consequently it is more a seakeeping concern than a manoeuvring issue. In following seas, the encounter frequency is significantly lower and ship motions are studied like low-frequency motion. Moreover, waves may be jeopardizing ship stability in the horizontal and vertical planes which may result in large heading deviations. Tools to analyse course keeping in following seas are therefore derived from manoeuvring tools.

Broaching concerns the loss of stability in the horizontal plane in following seas. Once broaching occurs, kinematic energy along the velocity axis transfers in the roll motion (Wu et al., 2010) which leads to strong heel angles and loss of heading. Usually models are developed to study broaching inception (early stage corresponding to the loss of stability in the horizontal plane) since once the ship is broaching, it can hardly be controlled. Small ships are mainly concerned by broaching since sailing speed and ship length have to be close to wave speed and wave length.

Pure manoeuvrability (i.e. turning ability) in waves is concerned with the influence of waves on the manoeuvring criteria of a ship. Turning capability in waves is linked to the IMO “manoeuvring in adverse conditions“.

Ship manoeuvring and course keeping in waves are studied using experimental methods, numerical simulation based on specific numerical models and CFD.

6.2 IMO criteria

In the past few years, some new IMO regulations of Energy Efficiency Design Index (EEDI) were carried out in which the ship’s manoeuvrability and course keeping ability in adverse wind and waves are added. It means that the techniques of prediction of manoeuvring in waves need to be developed urgently.

In May 2011, MEPC 62/5/19 was issued in which a minimum propulsion power line criterion is stated and the adverse weather condition is defined. In June 2012, MEPC 64/4/13 and MEPC 64/INF.7 were issued. The approach consists of three levels of assessment: minimum power line method, simplified method and comprehensive method. In May 2013 it resulted in an interim guideline, MEPC.65/22, in which the comprehensive approach was dropped. MEPC 66 added in April 2014 EEDI calculations for ships that were not considered in 2012 (LNG carriers, RORO carriers and cruise ships with alternative propulsion). No changes were made to the 2013 interim guidelines for determining the minimum propulsion power.

The first level of assessment in these guidelines is an empirical and statistical method to set a minimum power value for the installed power, which correspondent to different ship types (bulk carriers and others) and deadweights, see for example Figure 2.

The second level of assessment is to evaluate the manoeuvrability empirically based on not only the ship’s size but also the other factors such as windage area and rudder area.

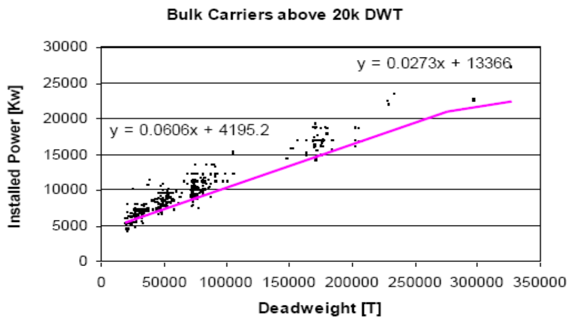


Figure 2. Statistics of minimum propulsion power line of a bulk carrier above 20k DWT.

Table 2. MEPC weather conditions and indices.

Environment and indices	MEPC 62/5/19	MEPC 64/4/13	MEPC 65/22
Sig. wave height (m)	<9.8	<8	<5.5
Mean wind speed (m/s)	<21.4	<25	<19
Course deviation (°)	5-10	10	10
Min advance speed (kn)	2-4	4	4

The third level of assessment, which was dropped in 2013, was to make a comprehensive assessment under specified adverse weather conditions. A ship needed to show the capability to maintain a minimum speed with a maximum course deviation of 10° in any wind and wave direction. It is clear that more research and tool development is needed before being able to set the limits for the third level approach.

At the same time the weather conditions and criteria for the key indices were lowered from MEPC 62 to 65, see Table 2.

6.3 Overview of methods

There are 4 classes of methods used to consider manoeuvring in waves: experimental methods, unified methods, two-time-scale methods and direct calculations by CFD.

Experimental methods. Using a combination of physical model tests and numerical tools, Otzen & Simonsen (2012) developed a mathematical model of a high speed catamaran ferry manoeuvring in waves. The model is able to simulate broaching, as demonstrated by validation against model test results. The aim is to include the mathematical model in a full mission bridge simulator.

Unified methods. Matusiak & Stigler (2012) presented experiments and simulations of a steady turning manoeuvre in irregular waves. Results show a very unsteady behaviour of the roll angle. The simulations are based on an unsteady manoeuvring model based of infinite added mass and Cumming integrals for radiation forces.

Two-time scale methods. Skejic & Faltinsen (2013) applied their two-time scale model to irregular sea states. The effect of varying significant wave heights and varying phase angles was applied to the turning circles of the S-175 container ship. Seo & Kim (2011) coupled a potential seakeeping tool with a manoeuvring model. Both models have a different time-scale and coupling is performed at each time step of the manoeuvring model. The coupling consisted of adding the drift forces coming from the seakeeping tool to the manoeuvring model while, position and heading coming from the manoeuvring tool were used to update the seakeeping computations. Rankine panels were used with linearized boundary conditions in the seakeeping tool. The manoeuvring model coefficients were derived from empirical formulae or from the experimental data in waves (Yasukawa, 2006). Nemzer et al. (2012) presented analytical and experimental procedures to assess ship manoeuvrability in wind and waves. The procedures were used to find the minimum speed at which test vessels can maintain course in waves and to determine the range of wave encountering angles where the ship can manoeuvre at low speeds. Kim & Sung (2012) validated their two-time scale method with PMM-tests in waves on the KCS.

Direct calculations by CFD. Mousaviraad et al. (2012) used CFD simulation software to conduct free running simulations of ships manoeuvring in deep and shallow water in quartering waves. The influence of waves on turning circle and zigzag manoeuvres was quantified. De Jong et al. (2013b) performed simulations based on a potential method using a transient diffraction-radiation Green function. Resistance, seakeeping, forced motion and free-running tests with hydrojet were performed. Extensive simulations were carried out to study broaching and surfriding conditions depending on speed, wave steepness and heading. Araki et al. (2012b) derived improved coefficients for a 6 DOF simulation model from free running CFD simulations. The original 6 DOF simulation model was based on captive tests augmented with linear FK forces. Sadat-Hosseini et al. (2011a) used CFD-ship IOWA to simulate 6 DOF ship motions in following seas and to study the broaching instability limits. The CFD results were compared with model tests. Greeley & Willemann (2012) used a weak scattered potential flow theory combined with lifting line theory with vortex shedding to derive manoeuvring forces in calm water and waves. Simulations of a the 5415M with bilge keels in following and quartering seas were performed and a comparison of relative importance of Froude Krylov (FK) and hydrostatic forces relatively to lift forces. The main results show that the lift forces are of the same order as the FK forces and in phase. Concerning the yaw moment, the results show that the lifting forces are higher than the FK yaw moment.

6.4 Judgement and analysis

Manoeuvring in waves raised new challenges for both experimental and numerical modelling:

Numerical modelling of ship motion and ship stability in steep following waves with low encounter frequency requires the development of new models, different from traditional seakeeping and manoeuvring models, with specific models for flow-propeller-rudder interactions. More and more teams are assessing this problem using CFD. Nevertheless such computations require a tremendous implementation effort and numerical resources. A solver dealing with manoeuvring in waves has to include URANS equations with free-surface effects, ship motions, propeller modelling and wave modelling and propagation.

Manoeuvring experiments in waves also require some new background research to address arising questions, such as: what are the relevant parameters to be measured to study course keeping in stern waves or turning in waves? What methodology (experimental set-up, initial conditions, number of repetitions, analysis procedure, ...) should be used to get converged mean values and standard deviations of the chosen parameters?

For a ship manoeuvring simulator that takes account of wave action, a force based mathematical model is needed. If EFD is used this means that captive model tests are needed in waves. Performing PMM tests in waves can be cumbersome because it leads to an exploding test program: each variation of PMM or wave frequency can lead to a different encounter position between the ship and the wave, which can possibly have an effect on the measured forces.

It is clear that numerical methods for the prediction of the IMO third level assessment are not fully developed yet. An experimental verification of the comprehensive approach is so elaborative that it becomes unaffordable. There are many methods used and every ‘problem’ mentioned in 6.1 cannot be dealt with using the same methods. Regarding the complexity of the problem, a workshop on manoeuvring in waves should be organized. Possible topics are:

- Give input to the IMO MEPC;
- Propose dedicated guidelines, both for experimental and numerical methods to verify and validate possible tools;
- Define the need for further research on manoeuvring in waves;
- Stimulate therefore the creation of benchmark data on manoeuvring in waves.
- Define a common understanding of “the result” and if warranted, define a way of analysing time domain results to reach converged final results.

7. SCALE EFFECTS

7.1 Correlation data

Effect of model size. At the SIMMAN2008 workshop, PMM and CMT data for KVLCC1 and KVLCC2 with three different size models were submitted. MOERI and INSEAN carried out PMM tests with a 5.5 m model and a 7.0 m model respectively and NMRI carried out CMT tests with a 2.9 m model. INSEAN and NMRI set the propeller rpm to model self-propulsion, but MOERI set the propeller rpm to ship self-propulsion. Bare hull test data are also available for static drift and pure yaw tests.

Figure 3 shows the comparison of side forces and yaw moments with drift angle for the bare hull of the KVLCC2. They show good agreements generally except in the region of large drift angles where the NMRI data have a larger value than the other data. This can be explained by the effects of Reynolds number on the cross flow drag component which becomes larger as the drift angle increases. This shows that a 3 m model at scale 1:110 is not large enough to avoid scale effects. Whether the difference is due to the scale, the model size or the Reynolds number achieved during the measurements is unknown.

Similar conclusions can be drawn for the KVLCC1 equipped with rudder and propeller: the NMRI data deviates from other data as drift angle and yaw rate increase.

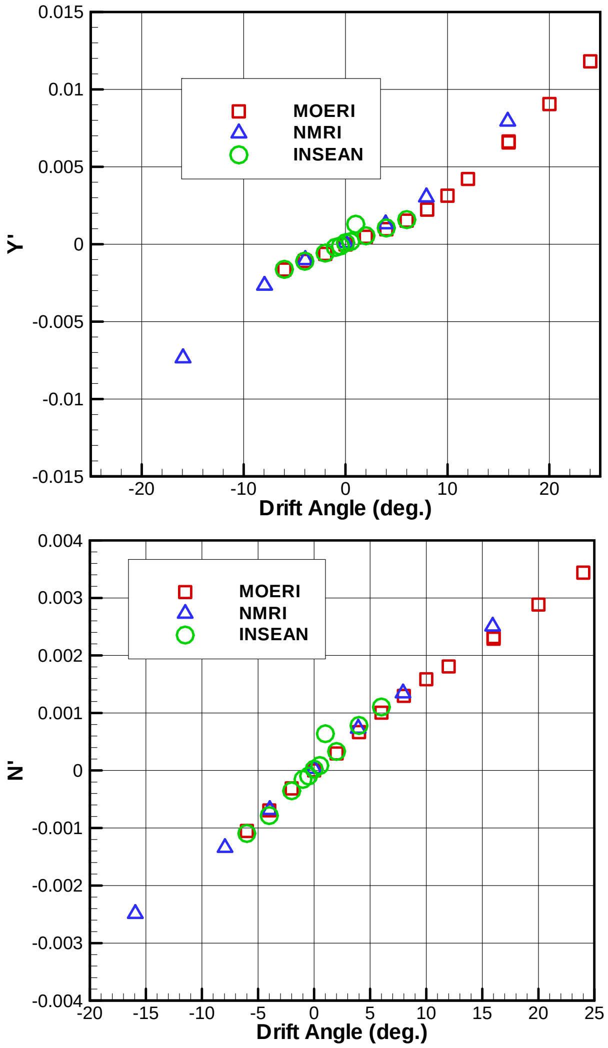


Figure 3. Comparison of static drift test data for KVLCC2 (Bare Hull)

Scale effects for podded vessels. Specifically because during the last ITTC period, the correlation between FRMT and full scale trials were questioned, during the course of the ITTC working period, interviews were held with 5 shipyards building podded vessels. These shipyards indicated that the free running model tests used for the prediction of the manoeuvrability were satisfactory. The typical model sizes for FRMT were in the range of 4.5-6.5m and the RPM was power controlled (and hence load dependent).

7.2 Recent studies on scale effects

As observed at the SIMMMAN 2008 workshop, the application of different self-propulsion points during manoeuvring model tests significantly affects the prediction results. Shin et al. (2012) investigated the effects of the choice of the self-propulsion point on the hydrodynamic coefficients and the predicted manoeuvring performance for KVLCC1 and KVLCC2 by PMM tests and simulations. They carried out PMM tests at both ship self-propulsion point (SSPP) and model self-propulsion point (MSPP) and carried out simulations with both a whole-ship model and a modular model. When the whole-ship model is used, the hydrodynamic coefficients obtained at the MSPP give a more stable manoeuvring performance than those obtained at the SSPP. Furthermore, the difference of manoeuvring performance between KVLCC1 and KVLCC2 becomes smaller when the hydrodynamic coefficients obtained at MSPP are used. In the modular model, the propeller slip stream effect with different propeller loading conditions is taken into account by the rudder inflow model. The manoeuvring performance predicted by hydrodynamic coefficients obtained at MSPP and SSPP is not significantly different. However, the propeller-rudder-hull interaction coefficients obtained from tests at MSPP and SSPP show some difference, although they are assumed to be independent of the propeller loading condition. This means that the selection of the self-propulsion point also could affect the manoeuvring results even when a modular model is used. Although the modular model can principally consider the effect of the changing propeller loading on the rudder forces, more careful examination on the effects of propeller loading on the propeller-rudder-hull interaction coefficients is required to assure that the predicted results by a modular model can be completely free from the effects of self-propulsion point.

To apply a self-propulsion point different from MSPP in free running model tests, it is necessary to equip the ship model with an auxiliary device to apply a towing force. Tsukada et al. (2013) developed a prototype of an auxiliary thruster that assists free-running model ships' propellers. The auxiliary thruster can control its forward force and adjusts the model ship propeller load to arbitrarily time varying target values. Free-running tests of a ship were used to study the effect of propeller load on manoeuvrability. The skin friction correction applied to the container ship model demonstrates the auxiliary thruster works well and the effect on manoeuvrability is clear. Theoretical simulation calculation also confirmed the effect. It was observed that the effect on the overshoot angles is marginal, but the effect on the overshoot time is larger.

The optimal self-propulsion point, which makes the ship model's rudder inflow dynamically similar to the full scale ship's rudder inflow, lies between MSPP and SSPP, but there has not been a concrete proposal yet on how to determine the optimal self-propulsion point. Ueno & Tsukada (2013) determined the optimal self-propulsion point (REC) as the point at which the rudder force of a model is equivalent to the force of a full-scale ship. They carried out free running tests using an auxiliary thruster and performed simulations at MSPP, SSPP and REC. However, the comparisons of free running model test data and simulation results are not satisfactory, mainly because of the dependency of the rudder force model.

Sun et al. (2012) presented research on the influence of the Reynolds number on the hydrodynamic coefficients in submarine model tests. A virtual fluid viscosity was introduced and the mesh motion technology based on mesh deformation was used to calculate the hydrodynamic coefficients of a submarine in different orders of Reynolds numbers. They also examined the influence of Reynolds numbers in submarine manoeuvring hydrodynamic calculation.

7.3 Recommendations for the study of scale effects

Systematic Method. Since there are many contributors to scale effects, it is not easy to establish a standard full-scale extrapolation method from manoeuvring tests in the near future, like a full-scale powering prediction method. In this section a systematic method to identify possible scale effects prior to model test is presented.

In the 26th ITTC manoeuvring committee's report (ITTC, 2011), several correlation methods to minimize scale effects were reviewed and categorized in-to pre-test methods, post-test methods and during-test methods. Figure 4 and Figure 5 represent a flow chart for free model and captive model tests respectively together with correlation methods applicable at each stage. Each method, however, requires knowledge on scale effects and some tools to be developed.

The first decision in model tests is the size of the model, which is so critical to scale effects that it must be reviewed with available model-ship correlation data and/or some tool to be able to roughly estimate scale effects. CFD can be used to estimate possible scale effects. The model size is restricted by the dimension of the facility and stock propellers. In this case, the attachment of a flow stabilizer or turbulence stimulator can be considered to minimize the scale effects due to a too small model size. A flow analysis in CFD can assist to find a proper size and position of the flow control devices.

The determination of the self-propulsion point is also critical in accurate full-scale prediction, especially for free model tests, see for instance the method proposed by Ueno & Tsukada (2013). The magnitude of the rudder angle can also be adjusted to apply a dynamically equivalent rudder force. It requires information on the effects of the Reynolds number on the rudder force and on the inflow to the rudder.

Post-test methods to correct the test results require an abundant sea-trial database and reliable mathematical models to describe the ship dynamics.

Before these diagrams and methods can be matured, much effort will be needed: robust estimation of hydrodynamic coefficients using SI, established methods to correct hydrodynamic derivatives to full scale and methods to control boundary layer.

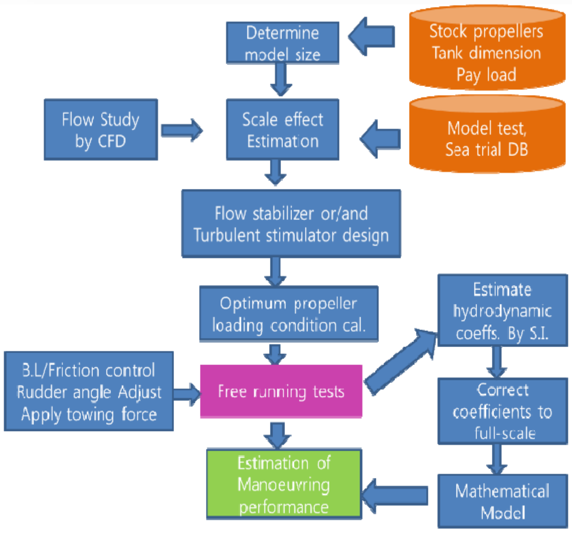


Figure 4. Flow diagram for free model test and model-ship correlation method applicable at each stage.

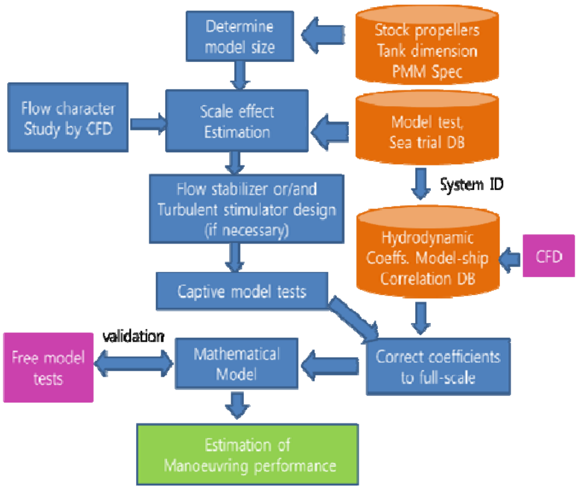


Figure 5. Flow diagram for captive model test and simulation method and model-ship correlation method applicable at each stage

<u>Necessity of CFD research</u>. Knowledge on scale effects is still limited due to the scarce information on full-scale data. CFD could allow computations to be performed to investigate the similarities (Froude, Strouhal, cavitation) and more specifically the viscous (Reynolds) effects. Comparison of full scale and model scale CFD computations may then appear as a good candidate to study such effects. However, to study scale effects using CFD, many issues have to be overcome:

- At full scale, the grid size in the direction normal to the hull has to be adjusted to full scale boundary layer characteristics which leads to a large mesh size.
- Full scale computation of ship manoeuvring requires a huge computational effort and validation data including local flow characteristics (boundary layer flow for example), which is scarce, especially for manoeuvring.

There is a strong need for research on scale effects for knowledge and identification of the limits of present day experimental procedures. CFD is mature enough to be used for specific studies on the different origin of scale effects, such as: influence of the scale on non-linear coefficients, influence of the scale on the wake fraction and propeller loading, influence of the scale on rudder inflow and rudder forces.

For the research on scale effects, more knowledge on propeller-hull-rudder interaction is required. Fukui (2012) has investigated the interaction coefficients between hull and rudder in the MMG model using CFD. This kind of approach is very promising to understand the physics of flow into the rudder during manoeuvring motion and can easily be extended to understand the mechanism of scale effects.

8. MANOEUVRING CRITERIA

This section gives an overview of criteria that are in use, including those that are commonly and less commonly used. Apart from the commonly known IMO criteria for ship manoeuvrability, the heel angles, the guidelines for naval vessel ship manoeuvrability, the SOLAS rudder tests, criteria for inland ships, fast ships and dedicated low speed manoeuvres are studied.

8.1 Overview of Existing Manoeuvring Criteria

<u>IMO Criteria for Manoeuvrability</u>. At the 25th ITTC (2005), a review was given based on the experience with the (at that time new) IMO criteria MSC.137(76). The 2005 ITTC-MC report describes the history of the development of the IMO manoeuvring criteria. Turning ability, initial turning, course keeping and stopping ability were at that time considered the manoeuvring criteria that were to be encompassed. This was the first ITTC conference taking place after the IMO criteria for ship manoeuvrability had become mandatory in 2003. In 2005, it was discussed how many institutes were considering the code as mandatory and how they assured compliance with the criteria. The interpretation was quite diverse. The MC believes at present that the manoeuvring criteria are less ambivalent, and considered more widely accepted by the shipbuilding community. Moreover, currently many researchers know the actions to be undertaken to assure that the ships are able to meet the requirements of IMO MSC 137(76).

<u>Criteria for Heel Angles during Turn for Passenger Vessels</u>. In the international code on intact stability IS2008, issued by the IMO, it is stated that for passenger vessels, the angle of heel on account of turning shall not exceed 10° when calculated using the following formula as heeling moment due to turning:

$$M_R = 0.2\frac{V_0^2}{L_{WL}}\Delta\left(\overline{KG}-\frac{T}{2}\right) \qquad (1)$$

The RINA has proposed amendments on the code, amongst others because it was not clear whether this code was related to the constant heel angle during a turn, or related to the more critical and larger outward initial heel angle in a turn. RINA proposed 15° as criterion for the maximum outward heel angle in a manoeuvre and 10° as criterion for the maximum constant heel angle in a turn. The objective of the criterion is not to prevent capsizing, but to ensure passenger safety. RINA recommends to use simulations or model tests or full scale measurements to demonstrate compliance with these criteria.

It is not the mandate of the ITTC-MC to come up with a level value for the maximum heel angle, it is the mandate to have an opinion on the applicability and realism of the procedures to achieve the level. The MC has investigated the applicability of the rule and compared the actual measured heeling angle due to turning with the IMO rule. The opinion of the MC is that it may be the maximum angle which is more representative for the passengers' safety than the constant heel angle. Furthermore, the formula originally proposed by IMO is not representative for the maximum heel angle.

<u>SOLAS Test</u>. A SOLAS test is often used (considered mandatory) to demonstrate at full scale that the rudder engine has enough capability. The aspect to prove is that at full speed, the rudder should be able to move from 0° to +30° to -35° and back to zero. The objective of the manoeuvre is to verify that the rudder movement from +30° to -35° should take place in 28 seconds or less. Care should be taken that the heel angle during such test does not become critical.

8.2 Inland Ships

<u>Europe</u>. In Europe the inland ships are assigned to a class based on their length and beam. The classes vary from I (38.5 m x 5.05

m) to VII (285 m x 34.2 m). While the fist consist of a small self-propelled barge, the latter represents a push convoy of one pusher and 6 barges in 3 by 2 or 2 by 3 configuration. The inland waterways receive the same classification, for instance a ship of class III can sail on waterways of class III and higher.

The Central Commission for Navigation on the Rhine (CCNR) has issued manoeuvring criteria for vessels sailing on the river Rhine. These criteria concern speed, stopping and turning abilities and evasive capabilities. The trials have to be carried out with a minimal loading condition of 70% in calm water in a channel of sufficient width and minimum 2 km straight. The minimal under keel clearance is 20% of the draft, but never lower than 0.5 m.

Every inland ship, including convoys needs to be able to reach a speed of 13 km/h ahead and 6.5 km/h astern. Any ship needs to be able to reach 6.5 km/h with its installed emergency power (e.g. a bow thruster). Ships that are up to 110 m x 11.45 m need to be able to stop from 13 km/h within 305 m. Larger ships have to stop within 350 m.

A specific kind of test for inland ships is the so-called evasive manoeuvre, also performed at 13 km/h, that is comparable to a zigzag manoeuvre, but the rudder checking is performed based on the yaw rate instead of the heading deviation. The yaw rate to be checked depends on the ship's size and the rudder angle, which depends on the under keel clearance. The criterion depends only on the period of the evasive manoeuvre, which is a function of ship size and under keel clearance, see Table 3.

Table 3. Evasive manoeuvre: maximal period.

UKC (% of draft)	>40	≤40	≤40	>40	>100
Used rudder angle (°)	20	45	45	20	20
Size (LxB m²)	Yaw rate checking (°/min)		Maximal period (s)		
≤110x11.45	20	28	150	110	110
≤193x11.45 110x22.9	12	18	180	130	110
≤193x22.9	8	12	180	130	110
≤270x22.9 193x33.35	6	8	Expert judgement		

China. Manoeuvring standards were issued for the Yangtze river because both the dimension and the speed of the vessels increase and the fact that hazardous goods are being transported along the river.

The maximum length of the vessels or convoys is 150 m. According to hydrological conditions the river is divided in several navigation areas, namely, in increasing order of difficulty, A, B, C and J (J1: very turbulent, J2: turbulent). Like in Europe each ship (type) can be assigned to a limit class. Sometimes due to changing hydrological conditions (which can also be a consequence of operational decisions) a section of the river can have a more restricted class, for example near the Three Gorges Dam the class can be restricted to J2. Typical ships are:

- A: large dimension (> 130 m);
- B: large B/D ratio: B > 20 m, T: 3 to 5 m;
- C: twin propeller.

The following manoeuvring indices are regulated (JT/T 258-2004):

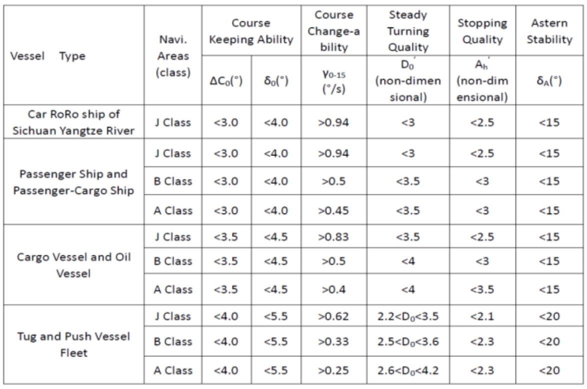
- Stability;
- Turning;
- Stopping;
- Astern stability.

Table 4 shows the requirements to be met for each manoeuvre and each navigation class. In this table the following variables are used:

- ΔC_0: the allowable course variation at $\delta = 0°$, measured over 3 min.
- δ_0: the allowable rudder variation to keep a prescribed course during 5 min.
- $y_{0\text{-}15}$: the minimal allowable yaw rate when moving towards 15°/min with a rudder angle of 15°
- D_0 and A_h represent the dimensionless tactical diameter and track reach;
- δ_A: the allowable rudder variation to keep a prescribed course astern during 3 min.

The manoeuvres have to be carried out at a steady speed, the value of which is not specified. Due to water level variations in the Three Gorges dam, the navigation conditions can vary significantly. In deep conditions navigation needs to occur in the vicinity of flooded banks, while in shallow conditions 180° turning is impossible. The strong current (~3m/s) of the river challenges both downstream navigation (less rudder efficiency) and upstream navigation (power lacking).

Table 4. Yangtze river manoeuvring requirements (Standard Ship Type Index System of Inland Transportation Vessel).



Vessel Type	Navi. Areas (class)	Course Keeping Ability		Course Change-ability	Steady Turning Quality	Stopping Quality	Astern Stability
		ΔC_0(°)	δ_0(°)	$\gamma_{0\text{-}15}$ (°/s)	D_0' (non-dimensional)	A_h' (non-dimensional)	δ_A(°)
Car RoRo ship of Sichuan Yangtze River	J Class	<3.0	<4.0	>0.94	<3	<2.5	<15
Passenger Ship and Passenger-Cargo Ship	J Class	<3.0	<4.0	>0.94	<3	<2.5	<15
	B Class	<3.0	<4.0	>0.5	<3.5	<3	<15
	A Class	<3.0	<4.0	>0.45	<3.5	<3	<15
Cargo Vessel and Oil Vessel	J Class	<3.5	<4.5	>0.83	<3.5	<2.5	<15
	B Class	<3.5	<4.5	>0.5	<4	<3	<15
	A Class	<3.5	<4.5	>0.4	<4	<3.5	<15
Tug and Push Vessel Fleet	J Class	<4.0	<5.5	>0.62	$2.2<D_0<3.5$	<2.1	<20
	B Class	<4.0	<5.5	>0.33	$2.5<D_0<3.6$	<2.3	<20
	A Class	<4.0	<5.5	>0.25	$2.6<D_0<4.2$	<2.3	<20

Applicability of the criteria. In practice modern inland ships do not have significant problems to comply with the CCNR criteria. On the other hand there is a tendency to increase the class of the European waterways. A lot of research is going on to investigate whether an inland waterway can accept a larger class inland vessel. This research consists of analysing a wide range of scenarios and is typically performed on a ship manoeuvring simulator, Eloot & Delefortrie (2012), which of course requires the availability of realistic manoeuvring models in restricted waters. Hasegawa (2013) also sums up the difficulties and challenges of river transportation in Asia.

8.3 Waterjet/Fast Ships

Whereas the manoeuvring characteristics and criteria of displacement vessels are well understood and documented, the same information regarding high speed craft is not so readily available. Some seminal works discussing specific manoeuvring criteria for high speed vessels (HSVs) are presented in this section.

The stopping manoeuvre for HSV was investigated by Varyani & Krishnankutty (2009). The stopping abilities of vessels ranging from medium speed containership to high-speed vessels have been estimated using analytical models, verified with known results and checked for the actual stopping criteria. The authors verified that the stopping ability of high-speed vessels with waterjet propulsion has been found to be far better than the IMO manoeuvring criteria, which are based on stopping tests performed on conventional vessels. This result is coherent with the fact that a HSV must stop in a smaller distance for safety reasons, since if there is traffic around, the other vessels do not have sufficient time to avoid collision with HSVs. This paper is an indication that a more stringent stopping criterion must be defined for HSVs.

The turning capability of HSVs was studied by Lewandowski (2004), who derived a regression equation based on full-scale data. The work of Bowles (2012) examined various aspects of the turning capabilities of a high speed monohull craft and based on the previous studies, tried to define a set of criteria adequate for the turning ability of HSVs. The first criterion defined by Bowles (2012) is that a high speed monohull should be capable of a predictable, controllable hard over turn at maximum speed while rolling inboard to the turn. The author demonstrated several problems associated with outboard rolling angles related to safety and comfort. Furthermore, a high speed monohull should be able to manoeuvre within a turning circle diameter not larger than 110% of the predicted diameter based on the regression equation developed by Lewandowski (2004). Finally, a high speed monohull (recreational craft passenger vessel) should not be able to execute turning manoeuvres if the horizontal accelerations developed exceed 0.35g to avoid being hazardous to occupants. A method for calculating the minimum recommended turning circle diameter is also derived in that work.

8.4 Naval ships

An initiative of several NATO countries has led to the development of proposed manoeuvring standards for naval vessels. This process is described by Örnfelt (2009). Since about 2002, the specialist team on seagoing mobility formed under NATO Maritime Capability Group 6 on Naval ship design has been progressing significantly in the development of new mission-oriented criteria, which include a large envelope of operational requirements. This work has resulted in several Allied Engineering Publications (ANEP) like NATO ANEP 70 (2003), ANEP 78 (2007) and ANEP 79 (2007). Based on the experience obtained from these ANEPs, definitive criteria in the format of a NATO STANAG have been developed, and is at present under ratification (NATO STANAG 4721). Justification for the need of a common naval manoeuvrability standard is given by Örnfelt (2009). Examples to get experience on how to apply the manoeuvring criteria to naval vessels are described by Armaoglu et al. (2010) and Quadvlieg et al. (2010). Armaoglu et al. (2010) explain the draft criteria, Quadvlieg et al. (2010) explain an update of the criteria and a practical application on the 5415M (the ITTC benchmark vessel). The main objective was not to judge if the 5415M would meet the criteria, but to judge if the tools that are available have the capabilities to predict whether the performance could be met or not.

The key of these developments is that the manoeuvring criteria are related to the general profile of a naval ship (the safety) and to mission abilities (for example, for mine hunting, different manoeuvrability may be required than for replenishment at sea).

To quantify the “safety”, the following basic capabilities are distinguished.

- Transit and patrol;
- Harbour manoeuvring.

To quantify the “mission ability”, the following missions are distinguished:

- Anti-submarine warfare (pro-active);
- Anti-submarine warfare (re-active);
- Mine warfare (hunting);
- Mine warfare (sweeping);
- Mine warfare (avoiding);
- Anti-air warfare (pro-active);
- Anti-air warfare (re-active);
- Vehicle interaction (replenishment at sea);

- Vehicle interaction (air vehicle);
- Vehicle interaction (sea vehicle);
- Vehicle interaction (sea vehicle LPD/ Dock).

A minimum amount of manoeuvring abilities are required to fulfil the missions. The following are the manoeuvring abilities:

- Course keeping (where the maximum allowed course deviation (95% probability) in a sea state has to remain below a criterion level);
- Track keeping (where the maximum allowed track deviation (95% probability) in a sea state has to remain below a criterion level);
- Turning (quantified by the tactical diameter);
- Initial turning (quantified by the time it takes to reach 20 degrees heading change after setting the rudder to 20 degrees. This can be obtained from a 20/20 zigzag test.);
- Yaw checking (quantified by the first overshoot time in a 20/20 zigzag test);
- Turning from rest (quantified by the time needed to turn to 90 degrees from rest);
- Stopping (quantified by the track reach from a stopping test);
- Acceleration (measured by the maximum acceleration during a manoeuvre from 0 to maximum speed);
- Astern course keeping (where the maximum allowed course deviation (95% probability) in a sea state has to remain below a criterion level while sailing astern);
- Station keeping (showing the ability to maintain a position with environmental disturbances, quantified by a heading/position deviation that the ship is not to supersede during 95% of the time);
- Lateral transfer (quantified by the crabbing velocity);
- Turning from rest (quantified by the time needed to turn to 90 degrees at rest using all manoeuvring aids);
- SDNE (standard deviation of navigational error), this involves not only the hydrodynamic capabilities of the ship, but also the accuracy of navigational aids, including navigational sensors and autopilot. This is quantified by the standard deviation from a predefined earth fixed track).

For every mission or for safety, a different speed is to be selected at which the manoeuvring ability needs to be demonstrated. Furthermore, for the requirements of course keeping, track keeping, astern course keeping and station keeping, a target sea state needs to be selected.

The required levels for every manoeuvring ability, (for example a minimum tactical diameter of 3.5 ship lengths) have a minimum level (i.e. the level that at least needs to be met) and a target level (the vessel that meets that level shows superior performance).

Apart from the NATO development, the Korean Navy also employed a similar structure to quantify the manoeuvring performance of their naval vessels together with the IMO criteria. Rhee et al. (2013) established the relationship among ship types, missions and manoeuvring tests based on naval experts' opinions, and finally proposed manoeuvring criteria for Korean naval ships with respect to ship types, referring to the criteria of NATO, Lloyd register (2006) and Korean naval ship's trial data.

8.5 Pod-Driven Ships

A question that is often raised is whether the manoeuvring criteria of IMO would be valid for pod-driven ships of over 100 m length as well. IMO manoeuvring criteria were developed for conventionally propelled and steered ships. This is augmented by a discussion about the large heel angles that podded vessels may encounter when sailing at full speed and applying 35 degrees of helm. Also the crash stop test was under discussion as the loads on the bearings during the full scale crash stop test are not desired.

To answer these questions it is important to address each manoeuvre separately. The MC made a couple of mini-interviews with shipyards regularly building podded vessels and institutes having experience with the podded vessels.

To demonstrate adequate turning ability, the turning circle test is used. On full scale trials a common approach among the interviewed shipyards is that it is considered acceptable to carry out the turning circle test with a lower pod angle than 35 degrees, as long as with this lower pod angle, it is also demonstrated that the criteria of advance and tactical diameter can be met.

For course keeping, yaw checking and initial turning, the zigzag test is used. Investigations of Woodward et al. (2009) have revealed that the application of the same criteria for the overshoot angle of the 10/10 zigzag test and the 20/20 zigzag test are realistic and valid. The zigzag test is still a measure for directional stability and also a measure for the steering difficulty. So, for course keeping, yaw checking and initial turning, the 10/10 and 20/20 zigzag tests are to be carried out and the results judged in the same way as for the conventionally propelled ships. Kobyliński (2012) warns that the overshoot angles of ships with podded propulsion may be larger than for ships with conventional twin screw twin propeller arrangements.

For crash stop tests, it is considered acceptable to perform the crash stop test in such a way that it can be demonstrated that the ship can stop within 15 ship lengths.

8.6 Manoeuvres in Restricted Conditions

Initiatives to develop criteria in restricted conditions. The restrictions can have different sources, namely speed limitations, shallow or restricted water or harsh weather conditions.

SNAME Panel H-10 performed a study of the issues of characterising 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.

Abramowicz-Gerigk (2005) evaluated the manoeuvres proposed to characterize the ship performance in constrained waters previously proposed by Hwang et al. (2003). The investigations used full mission simulators and a training vessel of Gdynia Maritime University, and considered the back & fill - fill first to starboard manoeuvre. The slow speed manoeuvres involve rather complex hydrodynamic phenomena, large drift angles, big propeller loadings, strong interaction between ship hull and control devices. There are frequent piloting commands and the vessels are mainly in transitory motion (not steady state), and the operation involves different combinations of vessel moving and propeller thrust directions (four quadrant operation). Due to this complexity, the investigations have concluded the necessity of full scale trials since the accuracy of mathematical models in such cases are not always satisfactory. The author also concluded that it was still too early to define standards for slow speed manoeuvrability.

In Europe several joint-industry projects have started that focus on the validation of manoeuvring models, including scale effects and manoeuvring in waves.

An on-going R&D project sponsored by Research Council of Norway, Norwegian and international partners named "Sea Trials and Model Tests for Validation of Ship-handling Simulation Models" aims to continue this effort to define standards for slow speed manoeuvrability (2013 to 2016). The main objective is to develop and apply a method for validation of numerical ship models used in engineering tools for studies of ships' manoeuvring performance in deep and restricted waters and ship handling training simulators. This will be done by comparing outcomes of numerical simulation models to measured responses from sea trials of selected case vessels. It also aims to establish benchmark datasets for validation of simulation models. Some preliminary information can be found at Marintek, (2014).

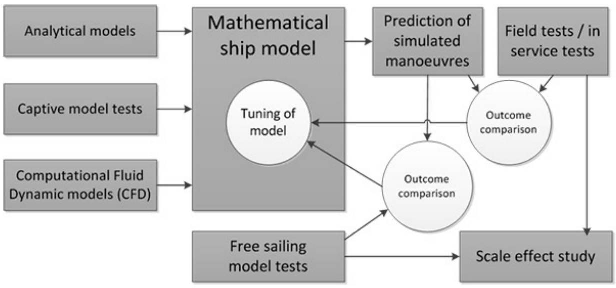


Figure 6. Project layout of MAROFF KPN.

The project SHOPERA "Energy Efficient Safe Ship Operation" also runs from 2013 to 2016 and started from the concerns on sufficient propulsion and steering power in harsh weather conditions due to the EEDI. The aims of the project are:

- Further development and refinement of existing hydrodynamic simulation software tools for the efficient analysis of the seakeeping and manoeuvring performance;
- Performing seakeeping/ manoeuvring model tests in combined seaway/wind environment by use of a series of prototypes of different ship types to validate the numerical tools. Full scale trials will also be used as a validation tool.
- Develop new guidelines for the required minimum propulsion power and steering performance to maintain manoeuvrability in adverse conditions.

Development of criteria. In a general point of view, to select manoeuvring criteria, the following sequence is to be followed:

1. The selection of an important characteristic (for example turning ability)
2. The selection of a representative measure (for example turning radius)
3. The selection of a limiting value (for example 5 ship lengths)

Regarding the first item, the MC considers that, just as in deep water, there could be requirements for turning ability and yaw checking. A minimum amount of turning should be considered, related to the turning radii that a ship has to make in shallow water as well, when approaching a harbour. A minimum level of course keeping and initial turning is required as well, such that the ship should be able to not turn too drastically so that the rate of turn can be sufficiently counteracted.

Regarding the second point, it is essential to define the speed at which the manoeuvres are to be carried out. It needs to be representative for the ship. It is considered to be the speed at which ships are approaching the harbour, but at which the ships are not yet under tug/bow thrusters assistance. Considering that this slow-ahead will have different speeds for all ships, this means that there is some variability of the speed allowable for this.

The turning ability could be typically expressed by a turning circle test or a test at which maximum rudder is given and a constant rate of turn is achieved. In shallow water, this rate of turn converges much quicker to a constant value than in deep water, so perhaps already only a partial turning circle could be sufficient. The course keeping ability is in shallow (and/or restricted) water often evaluated in an evasive type of manoeuvre like applied to inland ships (see section 8.2). The rudder is applied to an angle (maximum angle). A rate of turn builds up, and at a certain value, the rudder is swung over to the opposite side. This is similar to a classical zigzag test, but now with the rate of turn as lead signal.

The international guidelines and rules for port and navigation channels design such as PIANC (MarCom Working Group 121, 2014) and ROM (2000) are intrinsically related to the definition of standards for slow-speed manoeuvres. Those guidelines take into account “average” vessels navigating to or from the berth, and design the port/channels dimensions accordingly. A more accurate definition of the requirements for the vessels during the port manoeuvres will directly result in a more accurate definition for the dimensions of the ports and channels.

9. PROCEDURES

9.1 Overview

The MC reviewed the procedures and guidelines under its responsibility and made updates as follows:

7.5-02-06-01 Free Running Model Tests: descriptions on the parts of the procedures which are common in captive model tests and free running model tests were unified. A section on restricted water was added. The definition of deep, shallow and restricted water was included. Specific test types in shallow and restricted water have been added for free running model tests, e.g. evasive (avoidance) tests are different in shallow and deep water. The aspects which require special considerations when performing manoeuvring tests in shallow and restricted water were specifically outlined.

7.5-02-06-02 Captive Model Tests: descriptions on the parts of the procedures which are common in captive model tests and free running model tests were unified. The SIMMAN 2008 tests were added to the benchmark list. The definition of deep, shallow and restricted water was included. The explanation of multi-modal tests was added. Special considerations for shallow and restricted water were added. Because there is now a section related to uncertainty analysis for captive model tests, a large part of UA was deleted from this procedure, and reference is given to the procedure for uncertainty analysis of captive model tests, which received a very significant update.

7.5-02-06-03 Validation of Manoeuvring Simulation Methods: more precise definitions of deep, shallow and restricted water are included. References for benchmark data for shallow and restricted water manoeuvres have been added. A general revision on the nomenclature was also carried out.

7.5-02-06-04 Force and Moment Uncertainty Analysis on Captive Model Tests: the procedure has been very significantly updated. The text was adapted to ISO GUM and the example was rewritten for clarity. Furthermore, as the previous procedure provided just an example of an uncertainly analysis towards the measured force during captive tests, the present procedure describes how the uncertainty in the measured force can be used to determine the uncertainty of a characteristic derived from a manoeuvre based on simulations which are based on captive tests. The description of how this 'from-begin-to-end' uncertainty chain is working is fully elaborated. An example from beginning to end is not yet included.

7.5-02-05-05 Manoeuvrability of HSMV: the year of the sources has been updated and minor English corrections have been applied. The procedure reflects that the worldwide experience to HSMV is limited and that the ITTC recommends to perform free running tests or CMT tests in 6 DOF, not in 3 or 4 DOF.

The MC also developed two new guidelines, with the following topics:

7.5-03-04-02 - A new guideline named "Validation and Verification of CFD Solutions in the Prediction of Manoeuvring Capabilities" has been made. The guideline describes how Validation and Verification (V&V) can be performed for CFD based simulation of captive and free-running conditions. The verification covers the assessment of the numerical uncertainty and hereby gives an indication of the uncertainty related to the simulated results. The validation concerns the comparison between computation and measurements in order to quantify how well the computation agrees with the measurement, taking both numerical and experimental uncertainty into account. More details about this new guideline are given in Section 9.2.

7.5-02-06-05 Guideline on Uncertainty Analysis on Free Model Tests. The purpose of the guideline is to provide guidance for ITTC members to perform uncertainty analysis (UA) of a model scale free-running model test following the ITTC Procedures 7.5-02-06-01, 'Free Running Model Tests'. It is a guideline until it has proved itself for at least one 3-year period of the ITTC so that more institutes can elaborate this and become familiar with the concept of uncertainty analysis for free running model tests. More details about this new guideline are given in the Section 9.3

9.2 New guideline on V&V of CFD Solutions in the Prediction of Manoeuvring Capabilities

Captive PMM type CFD simulations are becoming more widely used, therefore a V&V guideline for this type of simulation has been created. The captive part of the guideline covers stationary straight-line motions (static drift, static rudder etc.), dynamic harmonic motions (pure sway, pure yaw etc.) and stationary circular motions.

Static simulations are typically treated as steady computations and the hydrodynamic forces and moments will in this case be constant. Dynamic simulations are treated as transient computations, since the flow is not steady due to the dynamic motion of the ship and the hydrodynamic forces and moments will be represented as time series. V&V in the guideline is therefore focused on single value forces or moments for the static conditions, while for the dynamic simulations the focus is put on time series for forces and moments, either in the time domain or in the frequency domain (Fourier coefficients).

In the guideline the numerical error covers contributions from the iterative solution procedure and the grid for all kinds of simulations. The time step size is also concerned for dynamic simulations.

The free running part of the guideline covers V&V of free running simulations, where the trajectory of the manoeuvring ship is predicted directly by CFD. The focus is on classical IMO manoeuvres like ±35° turning circle and 10/10 or 20/20 zigzag tests and the goal is to make V&V representative for the trajectory instead of the force level.

In reality it is quite difficult to make a formal V&V on time level for the trajectories, so a more practical approach is to consider the global parameters representing the trajectory. This means that for turning circles it is recommended to consider the following global parameters for V&V: tactical diameter, advance, transfer, yaw rate once steady in turn, peak yaw rate, drift angle once steady in turn, speed loss and heel angle (4 DOF). For zigzag tests, relevant parameters are: first and second overshoot angles, first and second overshoot time, peak yaw rate and period.

For these global parameters the guideline suggests that the numerical error estimate covers contributions from the iterative solution procedure, the grid and the time step size.

Assuming that the numerical uncertainties are estimated during the verification procedure described in the guideline and that model test data with experimental uncertainties is available the guideline finally gives a procedure on how the validation should be made in order to check how well the CFD simulation captures the manoeuvre of interest.

9.3 New guideline on UA in free running manoeuvring tests

This newly developed guideline is based on ideas proposed by Quadvlieg & Brouwer (2011). The ideas were sparked by discussions during the SIMMAN2008 workshop, because it was deemed that the initial conditions at the start of a manoeuvre were significantly determining the outcome of a manoeuvre such as the first overshoot angle. A methodology is described that takes into account these effects, and is based on the uncertainty propagation technique. The methodology uses the sensitivity of the final outcome to the initial condition. It is important to note that this sensitivity coefficient may be determined based on simulations, as long as the simulations are adequate enough to capture the desired effect. The guideline comes with an example. In the light of the comparison between the manoeuvring predictions made by different prediction methods in the frame of the SIMMAN2014 manoeuvring workshop, the determination of the uncertainties of free running manoeuvring tests will gain importance.

10. CONCLUSIONS

10.1 Using Experiments as a Tool to advance the Knowledge in Manoeuvring

As in previous years, work has been conducted to investigate standard manoeuvres in deep unrestricted water. However, there is a growing trend towards research in shallow and restricted water. For example, a significant amount of research into vessel behaviour in locks, ship-ship interaction and ship-bank interaction can be observed. Experiments have been carried out with false bottoms in towing tanks and basins to study the behaviour of ships in shallow water. Further work is required to establish the length of the false bottom needed to ensure the flow around the model is not adversely influenced by the ends of the false bottom. The rigidity of the false bottoms is also a large concern.

There is a trend towards more detailed specialized manoeuvring research, such as investigating propulsion system operation settings, asymmetrical propeller loading effects, appendage configurations and the effect of static trim and heel angles. Also, a significant quantity of work has been conducted on SI, including the use of artificial intelligence.

10.2 Using Simulations as a Tool to advance the Knowledge in Manoeuvring

The viscous CFD methods have not evolved that much over the last three years, but have become more widely used. The most used approach is the simulation of captive deep water conditions to provide input for manoeuvring simulations. The propeller modelling however remains a weak point.

In restricted water the use of CFD is mainly focussing at ship-bank interaction or ship-ship interaction. The latter has been tackled thoroughly, also with potential flow models. In any case more emphasis should be put on verification and validation of the simulation models.

10.3 Benchmark Data

Concerning generation of new benchmark data most work has been performed with surface ships. The upcoming SIMMAN2014 workshop on manoeuvring has facilitated much new deep and shallow water data for both KCS and KVLCC2. Further, it seems that both of these ships plus the naval combatant 5415M have been adopted by the community as benchmark ships. In addition, HTC, S175 and DARPA SUBOFF became benchmark cases. Also data for more complex restricted water cases are made available. So, it appears that there is focus on benchmark data generation in the community and that people are using it. This is positive and valuable in order to support the validation of the numerical simulation methods, which are being used widely.

10.4 Manoeuvring and Course Keeping in Waves

Concerning manoeuvring in waves, the IMO criteria are currently defined, which has been discussed in the report. The title “manoeuvring in waves” may cover very different topics (broaching, course-keeping, manoeuvres at sea). For each of these topics, different methodologies are used. The MC grouped the methodologies that are in use in logical groups. FRMT are still giving the most complete picture of reality including events like for example propeller ventilation. Simulations are however strived at for obvious reasons. There is no consensus yet on the preferred simulation method per topic.

10.5 Scale Effects

Some researches were carried out to investigate the effect of the self-propulsion point on the manoeuvrability. However, research on scale effects is hampered by the absence of good quality open full scale data that can serve as benchmark. As an alternative CFD can be used as a tool to assess geosim conditions.

10.6 Manoeuvring Criteria

An overview is given for criteria for ship manoeuvrability.

The IMO criteria for ship manoeuvrability are in place and well established and used. They are valid for podded vessels and ships with flap rudders as well.

The criteria for heel angles initiated by turning are not very well established and lack some realism. They need further improvement.

For naval vessels and inland vessels, manoeuvring standards are in place. For planing vessels and manoeuvres at slow speed and shallow water, proposals for criteria are made and summarised in this section.

It is not the mandate of the ITTC-MC to generate criteria, but the ITTC-MC will have an opinion about the realism, practicality and applicability and can, as such, contribute to the development of criteria.

10.7 Procedures

The MC reviewed the procedures and guidelines under its responsibility. Major updates and improvements were done in 7.5-02-06-04 Force and Moment Uncertainty Analysis on Captive Model Tests. Additional restricted water recommendations have been added to captive and free running procedures.

The MC also developed two new guidelines. The guideline "Validation and Verification of CFD Solutions in the Prediction of Manoeuvring Capabilities" (7.5-03-04-02) describes how Validation and Verification (V&V) can be performed for CFD based simulation of captive and free-running conditions. The verification covers the assessment of the numerical uncertainty and hereby gives an indication of the uncertainty related to the simulated results. The validation concerns the comparison between computation and measurements in order to quantify how well the computation agrees with the measurement, taking into account both numerical and experimental uncertainty.

The Guideline on Uncertainty Analysis on Free Running Model Tests (7.5-02-06-05) provides guidance for ITTC members to perform uncertainty analysis (UA) of a model scale free-running model test following the ITTC Procedures 7.5-02-06-01, ‘Free Running Model Tests’. Amongst others, this guideline uses the uncertainty propagation techniques to quantify the effect of the initial conditions on the final result.

11. RECOMMENDATIONS

Continue work in order to have a full set of benchmark data for each of the benchmark hulls (KVLCC2, KCS, 5415M, HTC, SUBOFF and S175 – manoeuvring in waves). Ideally add real vessels to the benchmark set.

Capitalize the momentum created by SIMMAN2014 and the conference on shallow and confined water to continue the development of V&V of ship manoeuvring simulation methods, including CFD.

Extend the UA for captive model tests from measurements towards the mathematical models and the predicted manoeuvres. Elaborate with an example.

Issue a new questionnaire concerning the procedure of captive tests (7.5-02-06-02), with particular attention to the use of PMM and hexapod, and have the procedure of captive test (7.5-02-06-02) revised, including 6 DOF considerations.

Revisit the full scale manoeuvring trials procedure (7.5-04-02-01). Monitor the full scale measurement campaigns starting up in the joint industry projects to use this as a starting point for scale effects research, supported by CFD.

Investigate the effect of movable bottoms to study the behaviour of ships in shallow water.

Stimulate the use of proposed low speed manoeuvres (full scale, free running, simulation model). Share the results and build up a database to identify possible manoeuvring criteria.

Manoeuvring in waves needs specialist knowledge from various fields and has a variety of applications and goals. It is therefore recommended to work either with a specialist committee on manoeuvring in waves or to organize a workshop on manoeuvring in waves or to have a dedicated member both in the seakeeping and the manoeuvring committee to address the topic. Liaise with IMO or IACS to address manoeuvring in waves in the future.

The Manoeuvring Committee recommends to the Full Conference to:

- Adopt the revised procedure 7.5-02-06-01 Free running model tests
- Adopt the revised procedure 7.5-02-06-02 Captive model tests
- Adopt the revised procedure 7.5-02-06-03 Validation of manoeuvring simulations models
- Adopt the revised procedure 7.5-02-06-04 Uncertainty analysis on captive model tests
- Adopt the revised procedure 7.5-02-05-05 Manoeuvrability of HSMV
- Adopt the new guideline 7.5-03-04-02 Verification and validation of CFD solutions in the prediction of manoeuvring capabilities
- Adopt the new guideline 7.5-02-06-05 Uncertainty analysis on free model tests

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