26th International Towing Tank Conference
Rio de Janeiro, Brazil, 28 August - 3 September, 2011

The Manoeuvring Committee

Final report and recommendations to the 26th ITTC

1. INTRODUCTION

1.1 Membership

The 26th ITTC Manoeuvring Committee consisted of:

- Prof. Dr. Andrés Cura Hochbaum (Chairman). Hamburg Ship Model Basin, Technical University of Berlin, Germany.
- Mr. Frans Quadvlieg (Secretary). MARIN, Netherlands.
- Mr. Kristian Agdrup. FORCE Technology, Denmark.
- Dr. Riccardo Broglia. CNR-INSEAN, Italy.
- Dr. Sun Young Kim. MOERI, Korea.
- Dr. Evgeni Milanov (until 2010). Bulgarian Ship Hydrodynamic Centre, Bulgaria.
- Prof. Dr. Kazuo Nishimoto. University of Sao Paulo, Brazil.
- Prof. Dr. Hironori Yasukawa. Hiroshima University, Japan.
- Prof. Dr. Zao-Jian Zou. Shanghai Jiao-Tong University, China.

1.2 Meetings

The committee met four times:

- INSEAN, Italy, January 2009
- Shanghai Jiao-Tong University, China, September 2009
- Technical University of Berlin, Germany, May 2010
- University of Sao Paulo, Brazil, January 2011

1.3 Tasks and Report Structure

The following lists the tasks given to the 26th Manoeuvring Committee (MC) together with explanation of how the tasks have been executed.

1. Update the state-of-the-art for predicting the manoeuvring behaviour of ships emphasising developments since the 2008 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.

The potential impact of new developments is discussed in sections 2 and 3. Manoeuvring and course keeping in waves is discussed in section 5. New experimental techniques are discussed in section 2, while extrapolation methods are discussed in a section on scale effects in section 8. The status of old and new benchmark data is discussed in section 4. Practical application of computational methods is discussed in section 3. The need for R&D is highlighted in every appropriate section and is summarised in the recommendations to the 26th ITTC. One particular need exists for mathematical models for low speeds. This is treated in a separate chapter, section 9.

2. Review ITTC Recommended Procedures relevant to manoeuvring (including procedures for uncertainty analysis).
   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.
   c) With the support of the Specialist Committee on Uncertainty Analysis, review and if necessary amend, Procedure 7.5-02-06-04, "Force and Moment Uncertainty Analysis Example for Planar Motion Tests" to bring it into line with the ISO approach adopted by the ITTC.

The review of the procedures is treated in section 10, whereas uncertainty analysis is treated in section 7.

3. Based on results of the SIMMAN workshop held in 2008:
   a) Evaluate capabilities and drawbacks of simulation tools.
   b) Update the procedure 7.5-02-06-03, "Validation of Manoeuvring Simulation Models".

The capabilities are evaluated extensively in section 4, and the guideline is provided, whereas the procedure has not been completed (see section 10).

4. Based on results of the SIMMAN workshop held in 2008:
   a) Evaluate the capabilities and discrepancies of time domain RANS based simulations,
   b) Produce a guideline on validation and verification of the RANS tools, and a guideline on the use of these tools in the prediction of manoeuvring capabilities.

The capabilities of time domain RANS tools are evaluated extensively in section 4, and a new guideline on the use of RANS tools for manoeuvring has been produced. However, although work has been done on a guideline for verification and validation of RANS tools, this guideline is not ready for adoption (see also section 10).

5. With the support of the Specialist Committee for Uncertainty Analysis write a procedure on Uncertainty Analysis for free running model tests.

The progress on the procedure on Uncertainty Analysis for free model tests is reported in section 7. Although progress has been made within the 26th MC, the procedure is not ready for adoption.

6. Review developments in ship manoeuvring in restricted waters (bank effects, muddy bottoms, ship-ship interaction, etc). Produce draft outlines of procedures for experimental and numerical methods that will serve as a basis for Recommended Procedures for manoeuvring in restricted waters.

Section 6 gives an extensive overview of the developments in shallow and confined waters. An overview was produced on the numerical techniques in shallow and restricted waters, however, this has not lead to an outline for a procedure. Experimental techniques have not been treated.

2. PROGRESS IN EXPERIMENTAL TECHNIQUES

The present section describes advances in experimental techniques, at model scale and at full scale. Model scale experimental techniques are divided into captive model tests, free model tests and special test techniques such as PIV measurements.

2.1 Captive model tests

Captive model tests can be subdivided in Planar Motion Mechanism (PMM) tests, rotating arm (RA) tests or circular motion tests (CMT) and computerised Planar Motion Carriage (CPMC) tests. In most of the applications, these tests are used to measure forces acting on the model(s). These are used to create mathematical models which are used to simulate manoeuvres, either fast time or real time. This is a well-established technique. The proceedings from the SIMMAN 2008 workshop on manoeuvring simulation models have shown that proper validation of these methods should be performed and every institute performing this, should be well suited for this job.

Testing methodology. Levi et al. (2007) describe the design of a test platform, to be mounted on a 35 meter long bridge in an ocean basin of 40 x 35 x 15 meter. This platform is able to force arbitrary motions to a model. The concept consists of a main carriage with a length of 35 meter and a sub-carriage to impose transverse motions and a yaw motion. In the trolley, mechanical devices can be mounted to impose harmonic oscillations in up to 3 degrees of freedom simultaneously. The paper treats structural design, mechanical design, the control design and the safety. Huang et al. (2010) describe a system in which the hydrodynamic forces on a vessel are measured in an underwater set-up. Two half bodies of the vessel are mounted on each other, and the ship is oscillated underwater as a virtual submarine in a "barbeque" set-up, see Figure 1. Only the lower half of the double body is measured. The authors do not make clear what the added value of the set-up is compared to a conventional PMM set-up, except that one may be able to perform tests at a higher Reynolds number, independent of Froude number. The technique seems complicated. Yongze et al. (2007) describe a PMM mechanism to measure the low frequent forces in waves (see Figure 2). Using the sketched set-up, the wave frequent forces will be absorbed by springs, while the low frequency forces or mean forces will be measured.

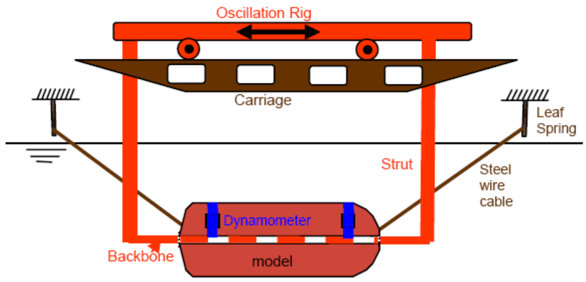

Figure 1: "Barbeque" set-up (Huang et al., 2010)

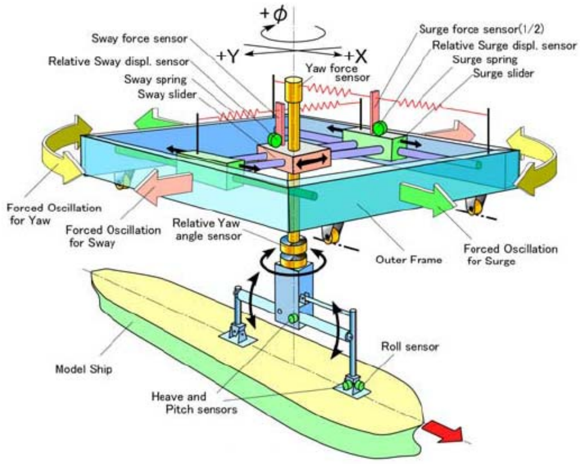

Figure 2: Measurement set-up to measure manoeuvring forces in waves (Yongze et al., 2007)

Katayama et al. (2009) demonstrate for two types of high speed craft the importance of not only heel to yaw coupling, but also the effect of dynamic trim and sinkage. He shows that for high speeds (Fn > 0.3), the effect cannot be neglected. This implies that for high speed craft, normal PMM tests are not sufficient, but that in addition to a heel coupling, considering trim and sinkage is necessary, and that hence a 6 DOF simulation model should be utilised. These conclusions were also drawn by Toxopeus et al. (1997).

Burgess et al. (2011) describe the new PMM mechanism, which is also used for creating mathematical models for manoeuvring in ice. Ueno et al. (2009) reported circular motion tests on KVLCC1, KVLCC2 and KCS with a description of the measurement uncertainty. The uncertainty is determined for the various forces and moments. This paper seems to be an important step forward in the understanding of the reliability of captive model tests.

An indispensable follow-up of captive model tests are simulations based on the results of the captive test. The logical step after captive tests is data analysis, derivation of a mathematical model and coefficients and simulations using this mathematical model. Sung et al. (2009) reported on PMM tests which were carried out at two conditions (model self propulsion point and ship self propulsion point) for a single screw vessel. Simulations were made using Abkowitz fits and MMG fits, and large differences are reported. However, looking at the obtained results some doubts arise so that no definite conclusions can be taken. This topic is discussed further in section 8.

Quasi stationary tests. Although this is a promising area, there are no further developments reported after Eloot (2006) and Hallmann (2008).

Typical applications. Armaoğlu et al. (2009) reports PMM tests on a tug. The PMM tests served to create a mathematical model for a highly unusual ship because the azimuthing thrusters are mounted asymmetrically. Free model tests and escort tests were used as validation for this model. The paper confirms that a standard mathematical model is often unable to cope with special ships.

Kim et al. (2007) have reported PMM tests carried out on a twin screw (twin gondola) and a single screw containership. Since container ships are sailing with very low GM-values, the use of a 4 DOF mathematical model is essential. To extend the mathematical model, the typical testing range is extended with pure drift with heel and pure yaw with heel. The apparent point of application of the side force while drifting was located at 0.54T below the waterline. The flow straightening coefficients for the ships are obviously different for the single screw vessel and the twin gondola vessel. Simulations were performed at a GM of 3 metres, which is relatively high for a loaded container vessel. This is the reason that the difference due to 3 and 4 DOF is not so large.

Nagarajan et al. (2008) report rudder open water tests on a fishtail rudder versus a Mariner rudder. The lift and drag coefficients of the fishtail rudder are presented up to rudder angles of 70 degrees. Oblique towing tests are carried out to determine the drift, propeller and rudder interaction coefficients. The yaw coefficients were determined using Kijima's empirical formulae. Free model tests were carried out in a pond to validate the model. Using the resulting mathematical model, simulations in various wind conditions were carried out, for which an autopilot needed to be designed. The description of the autopilot settings is useful. Koh et al. (2008a and 2008b) report an extensive series of captive tests carried out on pusher barges in various configurations, ranging from in-line configurations to more square configurations. Whereas Koh et al. (2008a) reports the conventional set-up, where the pusher is behind the barges, Koh et al. (2008b) reports more unconventional and asymmetric arrangements. The complete hydrodynamic coefficients derived from the CMT tests are reported as well as the used mathematical model. The results of the zigzag and turning circle simulations are compared to other published results. Kang et al. (2009) have extended the MMG model to a single screw–twin rudder set-up). This was applied on a VLCC with fishtail rudders. The variation of rudder coefficients was shown for this arrangement. Interesting is the effect that the working propeller has on the achieved lift and drag of the rudder. All tests are oblique towing tests. The derived formulations and mathematical model were validated with free model tests. Tanaka et al (2009) and Yasukawa (2009a) report captive model tests on a ship with azimuthing propellers (without nozzles). The results are compared to a twin screw twin rudder ship. The ship with azimuthing propellers turns easier, but the course keeping ability is worse. Comparing pushing and pulling azimuthing thrusters, it was observed that the pulling thruster performs better, both for turning ability and for course keeping ability. Yasukawa (2009b) demonstrates that the strut area of the azimuthing propeller is a very important parameter in the turning ability and course keeping ability. Ueno et al. (2010) presented captive manoeuvring test results of 3 different aft bodies for the same fore body: single screw – single propeller, twin gondola / twin propeller and a twin pod arrangement. Also several skegs were tested which were mounted to improve the directional stability of the podded variant. The results of the captive tests were compared to the 2nd order slender body theory of Nonaka (1993). Seo et al. (2010) report the development of a new rudder by using CFD and captive tests in a circulating water tunnel. Agdrup et al. (2009) describe how PMM tests on an articulated tug-barge are combined with CFD calculations to generate a mathematical model for full mission simulations. Tanake et al. (2009) describe captive tests on a chemical tanker with azimuthing thrusters. Fang et al. (2008b) have carried out PMM test on a ROV. The results are combined with a mathematical description of the umbilical to obtain a total mathematical model of the ROV on an umbilical. Chadwick and Khan (2011) report several challenges on performing PMM tests on slender underwater bodies. Focus is especially the on the longitudinal distribution of the side force.

2.2 Free model tests

Testing methodology. Kimber et al. (2009) report the development of techniques to perform free model tests on submerged submarines. In this paper, it is stated that the way ahead for submarines is in free model tests, rather than captive tests. The development of techniques for underwater testing is challenging. A key aspect is the communication of the autonomous manoeuvring submarine with the controller. The paper describes which communications take place between AUV and shore and which components are in use at QinetiQ and at MARIN for submerged free model tests with submarines. Vankerkhove et al. (2009) describe how the towing tank of Flanders Hydraulics is prepared for shallow water tests. After a description of the captive techniques and how the basin's accuracy was brought into agreement with the required accuracies by flattening the bottom and rails, the techniques for unmanned testing are explained. The basin was recently modified to allow free model tests. The launch and recovery of the model by grippers is discussed. A smooth model release is essential for meaningful, repeatable and trustworthy test results. Deakin et al. (2010) elaborate on the testing techniques for light and fast models. The paper covers the selection of model, propulsors such as propellers and waterjets, engines and batteries. Apart from model manufacturing, the carrying out of the tests and the data logging is of prime interest. Speed control, GPS position measurement as well as radio control is discussed and 4 cases are treated. A third new development for free model tests is described by Kennedy et al. (2009). Also this paper reports that the developments in batteries and wireless communications were fundamental for the development of the new hardware. This paper describes how the same hardware is used for scaled model tests and for full scale tests. Kimber et al. (2009), Kennedy et al. (2009) and Deakin (2010) describe how some techniques (probably developed for hybrid applications in the automotive industry) have been extremely beneficial to develop new free model test hardware. Park et al. (2008) report on a new indoor GPS system, applied in the manoeuvring and seakeeping basin in Carderock. This shows promising data, but the authors indicate that some improvements are still necessary. Deng et al. (2011) report the set-up used for free model tests in Jiao Tong University. The onboard and onshore measurement systems are described, where the data is sent to shore through a WiFi connection.

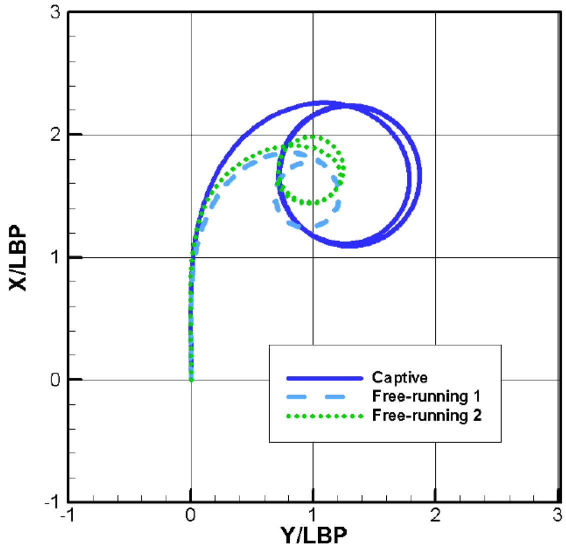

Figure 3: Comparison of TC trajectories from PMM and free tests (from Yang et al., 2009)

Yang et al. (2009) report differences between free model tests and captive model tests for a podded vessel. Full scale tests were carried out as well. There are significant differences between free model tests on one hand and the results of PMM on the other hand (see Figure 3). The full scale results in the paper contain some errors. Differences between PMM and free sailing may only be partly attributed to scale effects. There is a another aspect: for ships with pods, a constant RPM will yield different forces than a constant power strategy.

Son et al. (2010) developed a technique with an additional towing device with a servo motor which tows the model during free model tests. This is used to take into account the difference in frictional resistance between model scale and full scale. However, this force was constant, and was not adjusted based on the instantaneous speed, which would be a more correct approach. This topic will be discussed also in the section on scale effects.

Typical applications. Boudesteijn (2010) et al. demonstrate how the directional stability on tug with a very low L/B ratio is investigated using free running Dieudonné spiral tests. Free model tests showed to be a very effective way to investigate in an efficient way the effect of skegs on directional stability. Foeth et al. (2009) are showing free model test results on vessels with and without air lubrication. The effect of the air lubrication on the manoeuvring results is negligible for this vessel.

2.3 Full scale trials

New developments/techniques. La Gala and Gammaldi (2009) reported how a wireless inertial motion unit was designed for seakeeping experiments. This may in the future be used for manoeuvring tests, but it should be clarified how the low acceleration levels will be transferred to velocities and displacements without too large integration errors. New positioning systems such as Glonass or Galileo will yield new instruments to measure 6 DOF motions for ships on trials. However, there are no publications concerning these systems by the manoeuvring community yet. In the DP community, the vendors are taking up and are developing techniques for Glonass and Galileo.

Typical applications. Sutulo et al. (2009) reported a set of berthing and unberthing manoeuvres on high speed catamarans measured using a combination of DGPS and Octans. The objective was to get insight in the intuitive control actions of the operators to design an automatic berthing system. Altosolo et al. (2009) reported full scale measurements on a motor yacht equipped with triple water jets. The authors attempted to correlate these with a 6 DOF mathematical simulation model using system identification. The authors concluded that the best way to create a model was a hybrid testing program consisting of captive model tests, free model tests and full scale tests.

2.4 Other new techniques

In 2009, the AMT (Advanced Measuring Techniques) conference was held in Nantes, France. This conference, held as part of a European project, demonstrated various progresses in measurement techniques. Especially, the introduction of PIV as a standard for measuring flow fields is a very remarkable step for the validation of CFD. PIV has increased in number of tools and several model basins have purchased their own PIV systems.

PIV. The AMT conference created several sections on the challenges related to PIV measurements. Hallmann et al. (2009) reports on the new PIV system at MARIN in a fixed set-up. The paper summarises the challenges that are encountered before the PIV system gives answers that can be used to validate CFD calculations. Molyneux (2007) and Molyneux et al. (2009) present PIV measurements on an escort tug, operating under a drift angle of 45 degrees. The paper focuses largely on the challenges of the PIV measurements, including a discussion of test set-up and related challenges. The results are compared to CFD calculations by Molyneux and Bose (2008). The flow around an escort tug at such angles is very unsteady, which makes the measurements a challenge. However, the insight in the vortices generated along the hull is very useful for the understanding of the hydrodynamic forces generated by the hull and skegs of escort tugs. Atsavapranee et al. (2010) report results on stereo PIV measurements carried out during rotating arm tests. The tests are carried out on a geosim of the benchmark vessel 5415. The results focus on the aft part of the vessel.

System identification. Viviane et al. have made several publications on system identification as a new technique including (2007). In Viviane et al. (2009) this method is extended to twin screw vessels. Luo and Zou (2009, 2010) apply an artificial intelligence technique called “support vector machines” to determine a mathematical model based on free model tests.

3. PROGRESS IN SIMULATION TECHNIQUES

3.1 Introduction

The development and use of numerical methods for manoeuvring prediction continued at high level over the past three years. Most publications appeared in this period refer to RANS methods but also inviscid techniques are still object of development. No substantial progress has been found on new empirical methods. Some improved or adapted empirical methods can be seen in the proceedings of the workshop SIMMAN 2008.

3.2 Inviscid Numerical Methods

Inviscid methods are still used for certain manoeuvring tasks like close-proximity problems or for high-speed crafts. This subsection reviews papers on manoeuvring prediction methods using numerical simulation tools based on inviscid flow models, i.e. potential flow theory or Euler equations.

Sutulo and Guedes Soares (2009) present the application of a potential flow method for the simulation of close-proximity manoeuvres, applied for a ship being overtaken by a faster one. Both fixed rudder and autopilot simulations are included, being specially suited for online application, e.g. for manoeuvring simulators. In Yasukawa and Nakayama (2009c) a potential flow method for manoeuvring simulations in waves is described, deriving different motion equations for low frequency manoeuvring motions and high frequency wave-induced motions. With this approach, rough agreement with free model tests is achieved.

Several potential flow computational methods are especially in use for investigating restricted water issues. These papers are discussed in section 6.

3.3 Viscous Numerical Methods

Simulation of Forced Motions The simulation of forced motions plays a crucial role for the validation and verification of numerical techniques for manoeuvring purposes. Some examples of this for pure drift motions can be found in Stern et al. (2009), Toxopeus and Vaz (2009) and Lungu and Pacuraru (2009), among others. In Stern et al. (2008) this is undertaken with special care on the validation of vortical structures, making use of both DES and RANS methods and different convection schemes, leading to practical recommendations for such calculations. To give an example, in Figure 4 the vortical structures obtained using the second order upwind scheme coupled with algebraic Reynolds stress detached eddy simulation (FD2-ARS) and the second order TVD scheme with Superbee limiter (TVD2S-ARS) for the KVLCC2 in steady drift are shown. It is clear that, the TVD2S-ARS is the least dissipative scheme, preserving the fore-body bilge vortex (FBV), fore-body side vortex (FSV) and aft-body bilge vortex (ABV) at much longer distances compared to FD2 (and also FD4h).

LES and LES-based simulations were performed also by Sakamoto (2009) for the analysis of manoeuvring characteristics of a surface combatant model. This paper was focused on captive (both static and dynamic) tests. Of special interest is the verification and validation assessment of the static and the dynamic forces and moments.

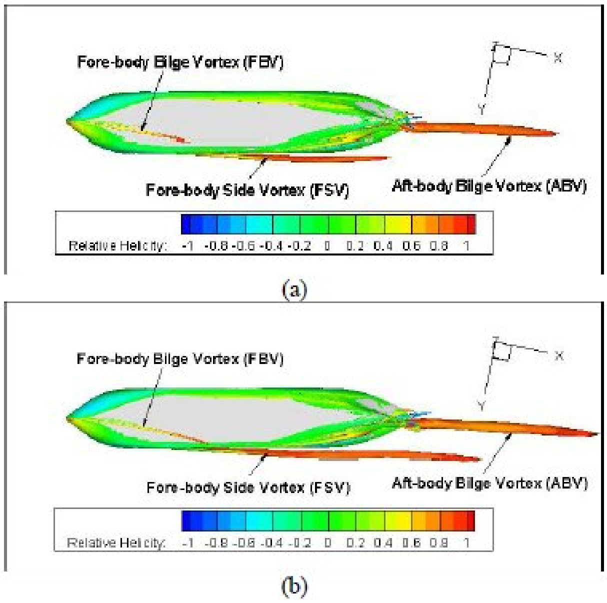

Figure 4: Vortical structures (iso-surface of Q=100 coloured by helicity) at 12° drift angle computed with (a) FD2-ARS and (b) TVD2S-ARS. (from Stern et al., 2008)

An interesting overview of the use of LES in ship hydrodynamics has been given by Fureby (2008). Different topics were illustrated and several applications have been shown, ranging from simple academic problems up to surface ship and submarine hydrodynamics, propeller applications and steady drift motion of a submarine.

The still conventional practice of neglecting the free surface and modelling it as a symmetry plane can be observed in many of the mentioned publications. Vorhoelter and Krueger (2008) studied the influence of drift in the wake distribution, including the comparison of two different codes and experimental results. In Wang et al. (2009a) pure yaw motions for different water depths are investigated and a validation for the deep water case is made.

In a further step, the derivation of mathematical manoeuvring models from RANS computations was observed. In Toxopeus (2009) and Toxopeus (2011), empirical methods are supplemented with data from viscous flow computations leading to considerable improvements when compared with empirical methods alone, usually applied in an early design stage. In a recent paper, Sadat-Hosseini et al. (2011), data from viscous and potential CFD computations have been used as input for manoeuvring simulations.

In Roddy et al. (2008) CFD has been used to support PMM tests. Straight ahead and pure drift tests have been performed in order to estimate the loads on the body prior to testing. In this paper an analytical and experimental study of the manoeuvring characteristics, as well as stability and control properties of non-body-of-revolution submersibles has been performed. A non-linear modelling technique has been used to predict the manoeuvring performance of a NBOR submersible model.

The combination of boundary element and RANS methods has demonstrated to be a straightforward approach, especially for the inclusion of the propeller effect with a comparatively low computational effort. In Phillips et al. (2009) a self-propelled ship is studied considering both pure drift and rudder forces in straight ahead condition for different rudder angles. Same authors applied this approach for the analysis of straight ahead and steady nose down manoeuvres of a submarine and compared the results with sea trial tests, Phillips et al. (2008). In Broglia et al. (2008) the presence of the propeller is modelled by means of body forces derived from the propeller loading calculated by a BEM code. In order to take into account for the effective wake inflow to the propeller and for the complete hull/propeller interaction, the RANS and the BEM codes run iteratively. Forced motions have been also used for the study of berthing motions. In Wang et al. (2009c) transient berthing motions for a Wigley hull are studied with different turbulence models and results validated with experiments.

Simulations submitted at SIMMAN 2008 for two tankers (KVLCC1 and 2), a container (KCS) and a naval vessel (5415) demonstrated the capability of RANS methods in the evaluation of forces and moments when a forced motion is accomplished (both in static and dynamic case). Broglia et al. (2008) investigated the manoeuvring qualities of the appended KVLCC1 and KVLCC2 by means of prescribed oscillatory motions in pure drift and pure yaw motion. Due to the relatively low Froude Number investigated, the free surface effects have been neglected.

However, as reported in Cura Hochbaum et al. (2008) free surface effects could be important in the stern region due to the high angle of drift reached during the enforced motion. The analysis of the flow field has shown a strong correlation between vortical structures shed from the edge of the hull, surface pressure, cross flows and the time histories of the hydrodynamic forces and moments. In this paper captive manoeuvres were performed using suitable amplitudes and frequencies for system identification; hydro-dynamic coefficients were determined in order to simulate standard rudder manoeuvres based on a manoeuvring mathematical model of wholeship (Abkowitz) type. The results were in good agreement with the experiments. Simulated turning circle (see Figure 5 and Figure 6) and spiral tests showed that the KVLCC1 has a slightly broader hysteresis loop than KVLCC2. This case seems to confirm the reliability of CFD in capturing the effects of different stern section shapes on the manoeuvrability of the vessel.

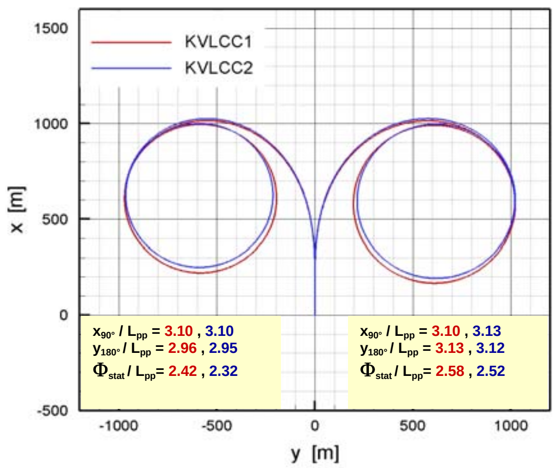

Figure 5: Turning circle tests (□=*35°*) for KVLCC1 and 2 (from Cura Hochbaum et al., 2008)

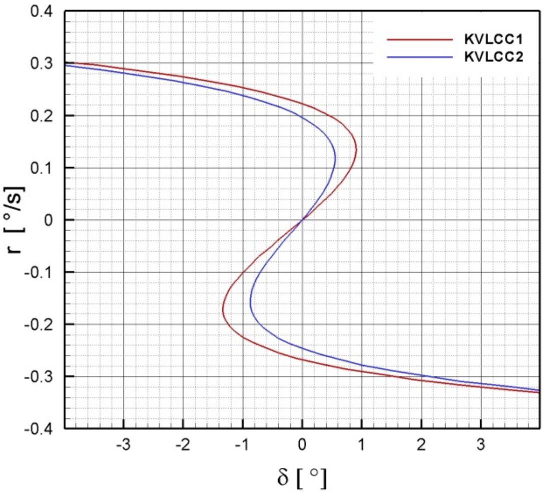

Figure 6: Reverse spiral tests for KVLCC1 and 2 (from Cura Hochbaum et al., 2008)

Simonsen and Stern (2008) studied the loads and the hydrodynamics of the fully appended KCS in performing a pure yaw prescribed motion. Computations have shown that the rudder plays a significant role for the overall Y-force and the yaw moment acting on the ship and that the propeller introduces a certain degree of asymmetry between the forces and the moment in the cardinal points. With respect to the field quantities, the overall flow field looks promising, at least qualitatively. The propeller seems to play an important role for the flow field in the stern region, where the combination of yaw driven cross flow and propeller induced rotation strongly influences the rudder inflow. Guilmineau et al. (2008) investigated static drift and pure sway motions for the 5415 at model scale with and without appendages. Effects of drift angle on vortex generation and wave field are carefully analysed and discrepancies among the two configurations are discussed. In particular discrepancies in terms of wave field are caused by the different trim of the bare hull with respect to the fully appended one. The computed flow pattern evidenced that the position and size of the bilge vortex detaching from the bow is similar for both hulls and that it moves towards the free surface. This is not the case for the fore body keel vortex which is fragmented by the stern appendages. Miller (2008) simulated a large set of static and oscillatory motions for the case of 5415 for both bare hull and appended hull (with bilge keel only). Discrepancies between simulated and experimental data are higher in the fully appended case.

CFD tools have been also applied for studying the manoeuvrability of multihull vessels. Broglia and Di Mascio (2008) applied an in-house CFD code for investigating interference effects for a catamaran. The study focused on the analysis of scale effects. The manoeuvring characteristics and the inherent course stability of a high speed catamaran have been analysed combining experimental and numerical activities by Zlatev et al. (2009) and Milanov et al. (2010). In the first paper steady drift, pure sway and pure yaw motion tests have been performed experimentally and numerically for the DELF-372 catamaran. The analysis focused on shallow water effects. This was also the main topic of the second paper, which concentrated on the course stability of the catamaran and the influence of the Froude number on it. In both papers, the reliability of CFD tools for the study of different topics has been demonstrated. Especially valuable is the combined use of experiments and numerical simulations. The main result of this research work was to detect inherent yaw instability of the catamaran at the whole range of depths and Froude numbers, with a tendency of an instability reduction at higher depth Froude numbers.

Steady turning manoeuvres of a rotationally symmetric submarine have been studied by means of a commercial RANS based tool by Maxwell et al. (2010). Several turning radii and submarine shapes have been considered. The agreement between computed results and experiments is rather good.

Atsvanapranee et al. (2010) measured the flow field characteristics by means of PIV techniques and the lateral forces acting on the main body and on the appendages (propeller, rudders and bilge keels) for a twin screw naval vessel (5415). RANS computations have been carried out for the fully appended hull at the same conditions. In this case the propeller is modelled by means of an actuator disk approach. However, body forces modelling the propeller itself are directly obtained from the experimental thrust and torque. Numerical simulations have been capable of capturing the complex asymmetric flow in the stern region mainly characterized by pronounced vortex structures (see Figure 7). The quantification of the side force generated by the hull and its various components, including the rudder and propellers, is valuable benchmark data for the validation of numerical codes and, moreover, it provides a basis to investigate the propeller asymmetric behaviour during a tight turn and relate it with the stern wake field.

In Shen et al. (2010a) scale effects on the prediction of manoeuvring qualities of ships, have been systematically investigated numerically and experimentally for a naval twin screw twin rudder vessel (DTMB-5617, a larger geosim of the 5415). In this study scale effects experienced by the ship model in a turning manoeuvre are attributed to rudder scale effects. Rudder effectiveness can be influenced by many physical variables such as boundary layer thickness, propeller loading, rudder stall and rudder cavitation (at full scale) whose effects vary with speed and propeller load. The numerical calculations were limited to pure rudder angle tests (i.e. the ship advancing straight and deflecting the rudder) with propelled and unpropelled ship. The CFD results are in agreement with the experimental results. But this does not quantify the scale effects as a whole on manoeuvring. This is also discussed in section 8.

Figure 7: Computed streamlines for baseline (fully appended) configuration with 9.8-degree drift angle at 30-knot approach speed (from Atsvanapranee et al., 2010)

Simulation of Free Manoeuvres. Direct prediction of ship manoeuvres with RANS tools has become possible and is increasingly being applied, mostly in a research context. Muscari et al. (2008) and Muscari (2008) present encouraging turning circle results for a self-propelled ship (KVLCC2) in three degrees of freedom using an overset grid. In Bhushan et al. (2009), simulations of a 20°/20° zigzag test for a fully appended ship (5415) are shown. Model- and full-scale simulations are compared, remarking the use of a two-point multilayer wall-function for this purpose. In this study, the propeller is modelled by body forces and the free surface effect is included. In Figure 8 the time histories of the heading and rudder angles at model and full scale are compared during a 20°/20° zigzag test of the 5415. It seems that in full scale the rudder check point is reached faster than in model scale, indicating a slightly more efficient rudder action in full scale.

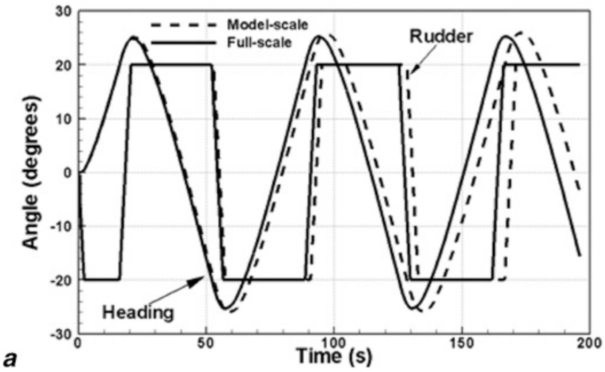

Figure 8: Time histories of a heading and rudder angles, 20°/20° zigzag test for self-propelled 5415 (from Bhushan et al., 2009)

In this paper it has also been shown that, even if there is no significant scale effect on the free-surface elevation, the transom rooster tail shows slightly higher elevation in the full-scale computations compared with model scale. On the other hand, Reynolds effects are evident on the velocity field. In order to give an explanation about the differences between model and full scale the authors state that, since the propeller is modelled with body forces, the velocities at the propeller plane and around the rudder are higher at full scale.

Drouet et al. (2008) show the ample perspectives of numerical methods for the prediction of free manoeuvres, presenting a newly developed 6-DOF approach for the simulation of a free turning motion in calm water and in regular waves. The turning circle simulations in calm waters are made also within a systematic hull form variation, presenting an optimisation of manoeuvring characteristics by different bulbous bow geometries. The inclusion of regular waves is undertaken by a SWENSE approach (Spectral Wave Explicit Navier-Stokes Equations), as described in Luquet et al. (2004). The potential of this technique for future applications is shown, making further validation data from experiments necessary.

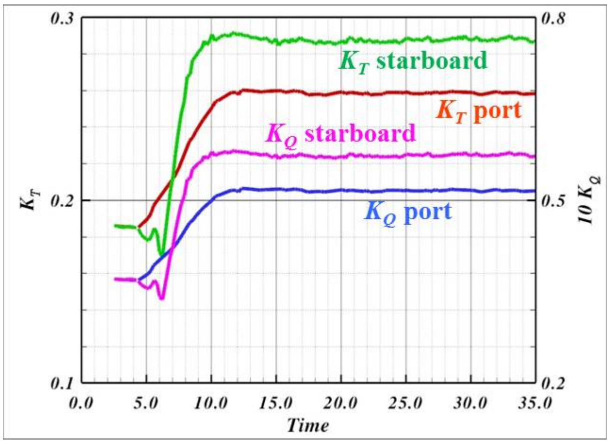

Figure 9: Propeller loads during a turning circle manoeuvre (from Durante et al., 2010)

A numerical simulation of the 35° port side turning circle manoeuvre for a tanker-like ship has been also presented by Durante et al. (2010). In this paper a simplified actuator disk body force approach has been used to model the effect of the propeller. The simple non interactive Hough and Ordway (1965) model has been modified in order to take into account the axial flow reduction at the propeller disk and the side force developed by the propeller. It has been shown that, at least for this particular ship, which is unstable in yaw in its single rudder-twin screw configuration, both the load unbalance between the two propellers (see Figure 9) and the lateral force exercised by the propellers themselves, should be taken into account for the correct prediction of the manoeuvre. A simplified model based on an empirical parameter for the estimation of the side force has been proposed.

The occurrence of a relevant propeller side force arising during a manoeuvre has also been shown by Atsavapranee et al. (2010). Results are extremely encouraging; a rather good prediction of the turning diameter (the error being less than 2.5%) is achieved. Disagreement has been observed in the transient phase, perhaps due to some weaknesses of the propeller model. In this paper an analysis of the flow field during the turning circle manoeuvre has also been done. The large vortical structures and their mutual interaction (see Figure 10) reveal the complexity of the flow field and the importance of using a flow solver based on the RANS equations.

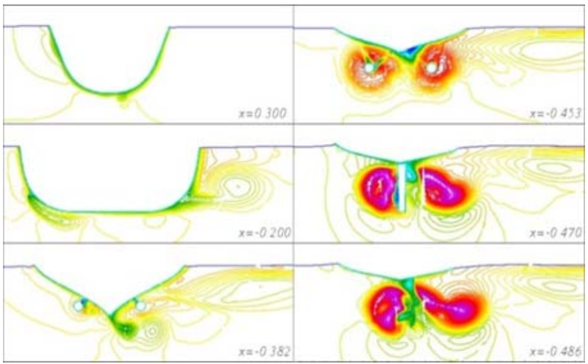

Figure 10: Axial velocity contours at different cross sections (from Durante et al. (2010))

In Carrica et al. (2008a) computations of standard manoeuvres for a surface combatant at model and full scale have been performed. Steady turn manoeuvres in calm water and in regular waves are presented at model scale for two rudder deflections at two different Froude numbers, Figure 11. Zigzag tests are performed for model and full scale, Figure 12. Scale effects in the stern region (rudders and propellers) due to the thicker boundary layer leading to different manoeuvring characteristics of the ship are qualitatively captured.

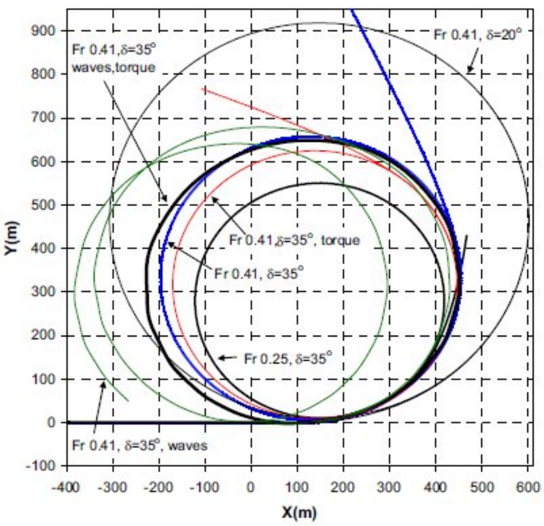

Figure 11: Trajectory predictions for a surface combatant during turning circle manoeuvres (from Carrica et al., 2008a)

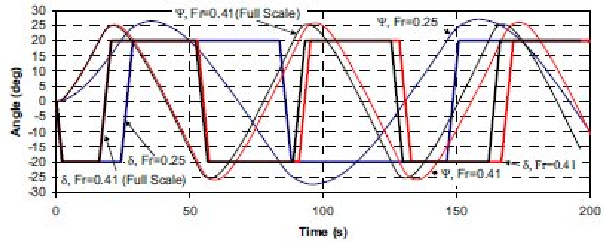

Figure 12: Heading and rudder angles for a 20°/20° zigzag test of a surface combatant (from Carrica et al., 2008a)

In order to resolve the complex flow field due to propeller-rudder interaction in a wake field during a general manoeuvre, Carrica and Stern (2008b) included the discretised rotating propeller in a grid being fine enough to capture the main vortical structures produced by the propeller blades and hub, as well as the interaction between the propeller and the incoming flow. The highly turbulent flow behind the propeller has been captured with a DES model, greatly improving the turbulence representation and the pressure fluctuations on the rudder and the free surface, Figure 13. In particular, turning and zigzag tests for the KVLCC1 have been simulated. The amount of data generated by these runs is very large and includes information allowing for analysing turbulence quantities, wake noise, vortex-induced stresses and vibrations and propeller optimisation. The computations are still extremely time consuming, taking months of CPU and wall clock time.

Dreyer and Boger (2010) presented an interesting paper on the validation of a URANS simulation tool for a guided multibody in free sink and trim condition.. The capability to simulate the interaction between multiple bodies, guided and free running (prediction of 6DOF motion and control) has been included in an existing URANS solver (UNCLE). A simple body forces approach is used for both the propeller and the fins. Numerical simulations of a large ship that overtakes a submarine have been performed. In one test the motion of the ship and the submarine was prescribed. In another test the trajectory of the submarine (with fixed control fins) was predicted. In a last series of tests the fins have been used to control the attitude and the depth of the submarine. Results were in fairly good agreement for the locked fins case, whereas large discrepancies have been observed in those cases with moving fins.

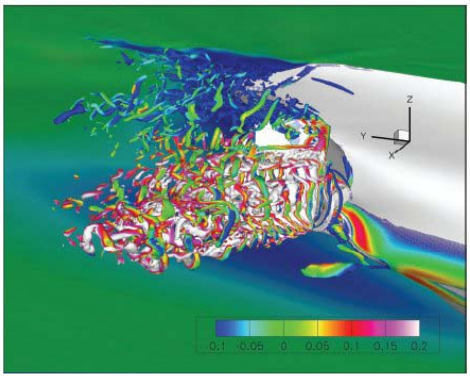

Figure 13: Vortical structures: isosurface of Q=2500 coloured with dimensionless total velocity (from Carrica and Stern, 2008b)

In Mousaviraad et al. (2008) the effects of waves and wind on ship forces, moments, motions, manoeuvrability and controllability were investigated for the ONR Tumblehome. The air/water flow computations are carried out using a semi-coupled approach in which the water flow is not affected by air flow, but the air flow is computed assuming the free surface as a moving immersed boundary. Ship computations are performed to investigate the effects of different wind speeds and directions on static drift and dynamic PMM tests in calm water, pitch and heave in regular head waves, and 6DOF motions in irregular waves simulating the scenario of the hurricane CAMILLE. Results have shown that the wind has strong effects on ship forces and motions.

3.4 New techniques

In the last years novel numerical models have been developed to describe phenomena characterized by a complex evolution of the free surface. In this context, specific care has been devoted to the modelling of the air/water interface, wave breaking and air entrapment. Among these, the Smoothed Particle Hydrodynamics (SPH) Monaghan (1988) and the Constrained Interpolation Profile (CIP) rouse a special interest. Some papers on these methods are reported here, since they could be interesting for manoeuvring tasks.

The SPH belongs to the class of meshless schemes, that is, those models that do not require any computational grid. This feature, along with its Lagrangian formulation, allows the SPH scheme to describe the evolution of the interfaces between two (or more) fluids or phases in a straightforward way. More in detail, the fluid domain is represented through a set of fluid particles which move according to the flow velocity and carry all physical quantities.

Notwithstanding the ongoing research aimed at improving this model, the SPH still presents weak points which limit its applicability to ship hydrodynamics, especially to manoeuvrability. This is mainly due to its difficulty in representing complex solid geometries and in correctly simulate the fluid field close to them, and in particular the turbulence of the flow.

Among the numerous models proposed in the SPH literature some have been specifically developed to get an accurate prediction of the pressure field and of the related local loads against structures, see for example Antuono et al. (2010), Ferrari et al. (2009) and Marrone et al. (2011). Numerical simulations of hydrodynamics problems are provided in Marsh et al. (2010).

Regarding CIP models, they have been developed to avoid the use of complex grids subject to large deformations. Similarly to the well-known VOF and Level Set schemes, CIP models can accurately describe the motion of the interface between fluids. Their main advantage is that they can describe advection problems with extreme accuracy in time and space and with moderate computational effort (Hu and Kashiwagi (2009)). Generally, CIP models are robust and can be easily implemented on parallel computer machines.

Some applications of these schemes to hydrodynamics problems are proposed in Zhu (2006).

Carrica et al. (2008c) presented some results obtained with the overset curvilinear grid based, single-phase level set code CFDShip-Iowa version 4 on very large grids (from 7 million to 70 million grid points). This paper is focused on the analysis of the performance of the parallel code. A demonstration of the improvement in the solutions achieved with high resolution grids has been presented as well for the forward speed diffraction and the pitch and heave problems in head waves of the surface combatant model DTMB-5512.

Oberai et al. (2010) presented a novel sub grid air entrainment model for the simulation of multiphase air/water bubbly flows around a ship. The methodology has been validated with model problems, namely a plunging liquid jet and a hydraulic jump. The agreement with experimental data was rather satisfactory. The sub-grid air entrainment model has been applied to the simulation of the flow around the Athena vessel in straight ahead and steady turn manoeuvres and around the 5415 in straight ahead motion. The simulated results matched physical observations and available void fraction data reasonably well.

De Barros et al. (2008) investigated the use of analytical and semi-empirical (ASE) methods to estimate the hydrodynamic derivatives of an AUV. A comparison is done with the results obtained by using computational fluid dynamics to evaluate the bare hull lift force distribution around a fully submerged body. An application is made to the estimation of the hydrodynamic derivatives of the MAYA AUV. The estimates obtained were used to predict the turning diameter of the vehicle during sea trials.

In Maki et al. (2010) a procedure for studying the motions of a vessel during a manoeuvre in a seaway is proposed. In particular, potential flow solvers fail in providing non-zero damping coefficients for sway and yaw motions at very low frequencies, viscous effects not being taken into account. In order to improve the capability of such a simplified tool for the reliable evaluation of ship motions during a manoeuvre in a seaway, a viscous frequency dependent correction is proposed on the basis of previous work of Clarke et al. (1983), Bailey et al. (1998) and Fossen and Smogeli (2004). Comparisons with viscous flow computations for oscillating motions in the horizontal plane demonstrate the reliability of the viscous flow correction in the lowest frequency range. In particular the viscous correction improves the direct damping coefficients (i.e. sway force due to sway motion and yaw moment due to yaw motion), whereas the predictions for the coupled modes are worsened. As stated by the authors, a broad set of vessels at a range of forward speed should be investigated in order to further improve this approach.

3.5 Concluding remarks

The papers reviewed in this section show a strong further development of the RANS tools applied for manoeuvring prediction. On the other hand, the transfer of CFD developments into commercial application is happening somewhat slower than expected. Probable reasons are the lack of validation and that the acceptance has not increased enough yet, together with the required effort and expertise.

4. BENCHMARK DATA AND CAPABILITIES OF PREDICTION TOOLS

4.1 Introduction

The main development in the field of benchmark data for manoeuvring prediction in the recent years has been connected to the Workshop on Verification and Validation of

Ship Manoeuvring Simulation Methods, SIMMAN 2008. An overview of this workshop including a description of the used hull forms, the performed model tests as well as a few preliminary results and conclusions were given in the Report of the 25th ITTC Manoeuvring Committee, which was published before termination of the workshop proceedings, Stern and Agdrup (2009).

The following section provides a description of the benchmark data available today, both from SIMMAN 2008 and from other sources, as well as an overview of the supplementary model tests that either have been performed or are planned for joining the already extensive list of benchmark data in connection with a coming second SIMMAN workshop. This section also provides further evaluation results from the analysis made after SIMMAN 2008 giving additional insight into the performance of different types of manoeuvring prediction methods including CFD based methods.

4.2 Status of benchmark data available after SIMMAN 2008

One of the main accomplishments of the SIMMAN 2008 workshop was the completion of an extensive amount of model tests for four hull forms selected by the ITTC for benchmark, i.e. the KVLCC1 and KVLCC2 tankers, the KCS container ship and the 5415 naval combatant. The main focus of the workshop was on appended hull tests in deep water to provide data for simulation of free manoeuvres, but included also bare hull tests for validation of CFD-based methods as well as shallow water tests, which were not used at the workshop. The raw data from these test series is available to the public via the workshop web site. An overview of the model test data available after the workshop is given in Table 1, where also the tests performed in preparation for the second workshop have been added.

Captive model test data. The simulation test cases for the workshop were specified in model scale, i.e. captive tests at model self-propulsion point, and using constant RPM throughout the manoeuvre.

For KVLCC1 and KVLCC2, the CMT tests at NMRI were done at these nominal conditions. However, the PMM tests at MOERI had been done at ship self-propulsion point and the tests at INSEAN were done using a constant torque strategy and with unresolved issues for the static rudder tests. A new set of appended hull PMM tests for the KVLCC2 is being carried out at BSHC this year.

Table 1: Overview of model tests series from SIMMAN 2008 workshop as well as tests performed for the planned second SIMMAN workshop. Tests marked in grey performed at other conditions than the nominal conditions for the simulations at the workshop

	CAPTIVE						**FREE**	
	PMM app. deep	**PMM app. shallow**	**PMM bare deep**	**PMM bare shallow**	**CMT app. deep**	**CMT bare deep**	**Free app. deep**	**Free app shallow**
KVLCC1	MOERI (1999) INSEAN (2006)	INSEAN (2006)	-	-	NMRI (2006)	-	HSVA (2006) MARIN (2007) CTO (2007)	-
KVLCC2	MOERI (1999) INSEAN (2006) BSHC (2011)	INSEAN (2006) FHR (2010)	INSEAN (2006)	INSEAN (2006) FHR (2010)	NMRI (2006)	-	HSVA (2006) MARIN (2007) CTO (2007)	FHR (2010)
KCS	CEHIPAR (2006) FORCE (2009)	FHR (2010)	FORCE (2009)	-	NMRI (2005) -	-	SVAP (2006) BSHC (2007) IHI (2008) MARIN (2009)	BSHC (2008) FHR (2010)
5415[1]	FORCE (2000) MARIN (2007)	-	FORCE (2004) IIHR (2005) INSEAN (2005)	-	MARIN (2007)	BEC (2006)	MARIN (2000)	-

For KCS the PMM tests performed at CEHIPAR were done using a constant torque strategy and with unresolved issues for the dynamic tests. After the workshop a new set of appended hull PMM tests in 4 DOF has been performed at FORCE. The CMT tests at NMRI were done in 3 DOF, i.e. the model was restrained in roll.

For 5415 the PMM tests performed at FORCE were done for two approach speeds (18 knots and 30 knots, the latter being the primary test case) at the ship self-propulsion point, these being the only captive data available for 5415 prior to the workshop. A second set of captive data at the nominal conditions has later been made available by MARIN.

Free model test data. The nominal conditions for the free model tests comprised constant RPM at the model self-propulsion point (this being the traditional and simplest way of performing such tests) as well as a certain speed, rudder rate and GMT for each ship.

For both the KVLCC tankers free model tests were performed with the same models at the nominal conditions at three facilities: HSVA, MARIN and CTO. These tests revealed that the difference in manoeuvring characteristics between the two versions of the KVLCC was smaller than anticipated, when these hulls were selected for the workshop. For instance, the tests done at MARIN indicated that the difference in the 1st overshoot angle in the 10/10 zigzag test was less between KVLCC1 and KVLCC2 (0.4 deg) than between two subsequent tests performed with initial turn to opposite sides (1.5 deg). These results were to a large extent confirmed by the tests done at HSVA. For the KCS two sets of free model tests were available at the workshop carried out at BSHC and at SVA, however, both series were done with deviations from the nominal test conditions. The tank at BSHC imposed a limited distance for the acceleration phase, causing the initial release conditions to be biased including the approach speed being less than the nominal 24 knots. Nevertheless, the tests showed good repeatability. At SVA the tests were performed at a rudder rate of 4.1 deg/s instead of the nominal 2.32 deg/s in order to accomplish the zigzag tests within the width of the tank. The tests done by Hokkaido at IHI Model Basin were done after the workshop, differing in the approach speed (18.6 kn) and in the GMT-value which was 5.1 m instead of the nominal 0.6 m, thereby suppressing the roll motion. Therefore the latter were most suitable for comparison with the methods using 3 DOF. A new set of free model tests at the nominal conditions has later been carried out by MARIN.

For the 5415 naval surface combatant the free model tests at MARIN were carried out for the two approach speeds (18 knots and 30 knots). These initial test results used at the workshop showed a surprising asymmetry between the port and starboard turning circle manoeuvres, but has subsequently been checked and corrected.

4.3 Status of other benchmark data for manoeuvring

Ship-ship interaction. The project "KMB Investigating hydrodynamic aspects and control systems for ship-to-ship operations", co-ordinated by MARINTEK involved model tests at Towing Tank for Manoeuvres in Shallow Water at Flanders Hydraulics Research, Belgium. The results from a limited number of these tests have been made available to the public by Lataire et al. (2009a). The used service ship (SS) was an Aframax tanker with Lpp = 231m, while the ship to be lightered (STBL) was the KVLCC2 tanker with Lpp = 320 m. The open tests comprise five steady state tests with varying conditions including water depth, draughts, lateral distance and heading, as well as one dynamic test where the rudder angle of the service ship was varied harmonically. In all cases measured forces (X,Y) and moments (K,N) are given for both ships. See also section 4.6.

Manoeuvring in restricted water. An extensive model test campaign on the effect of banks was carried out at the Towing Tank for Manoeuvres in Shallow Water at Flanders Hydraulics Research, Belgium. Tests were done using models of a 8000 TEU container ship and an LNG carrier with 7 different designs of banks. The results from a limited number of these tests have been made available to the public in Lataire et al (2009b). These open tests consist of two subsets, where the first subset contains measured sinkage of the container carrier sailing along one of the bank designs at four different speeds and with four different distances between ship and bank. The second subset contains ten tests and includes all measured forces, moments and motions. The results are obtained by tests carried out with the model of the container carrier at different initially even keel conditions. This second subset consists of tests with a wide range of speeds, bank geometries, drift angles, propeller rates etc. See also section 4.6.

4.4 Evaluation of simulation tools for manoeuvring prediction

The following is a summary of the outcome of the SIMMAN 2008 workshop, as documented in Stern and Agdrup (2009). This provides evidence of the performance of various simulation tools, even if this evaluation cannot give a full picture of the state of the art, naturally restricted to those methods that were submitted by the participants at the workshop.

As mentioned in the 25th ITTC Report, the number of received submissions for free manoeuvres was large, especially for KVLCC1 and KVLCC2. There was a wide variation of methods being used, ranging from PMM- and CMT-based methods, over system identification and neural network tools to CFD-based methods and various empirical methods.

The simulation results showed a substantial scatter, as demonstrated in Figure 14.

Grouping and definitions. At the workshop it was clear that it was necessary to divide the large amount of submissions into groups in order to be able to make clear observations from the analysis. Therefore, the methods were divided into five groups as follows:

1. methods based on PMM tests ('PMM')
2. methods based on CMT tests ('CMT')
3. empirical and semi-empirical methods ('EMP')
4. methods based on RANS or DES ('CFD')
5. results from free model tests ('FREE')

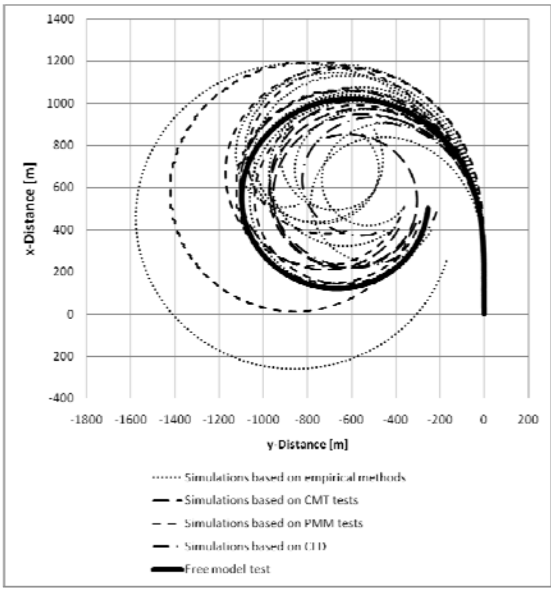

Figure 14: KVLCC1 simulations of 35 deg turning circle to port side, all submissions separated in different types (Stern et al., 2011)

Each of the four first groups were analysed separately, using the free model test results as reference for the comparisons, as documented in the final proceedings, see Stern and Agdrup (2009). The "post-workshop" grouping of the methods revealed some trends that were not clear before. However, there were still a number of "incomparable" submissions that disturbed the picture, either because they were based on model test data done at conditions deviating from the nominal ones, or because they used a method that was not applicable for the particular ship type. Therefore a second step in the post-process has been to remove such submissions from the analysis.

The objective of this analysis was to make quantitative evaluations of the performance of each type of prediction method. To this end the "RMS error", σ_e, is introduced here to express the scatter of a selection of prediction values relative to a benchmark. The RMS error, σ_e, is defined as:

$$\sigma_e = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_b)^2}{n-1}} \qquad (1)$$

where:

n is the number of predictions in the selection

x_i is the predicted value of for example tactical diameter

x_B is the benchmark value, taken as an average of the applicable free model test results

This quantitative evaluation has only been possible to carry out for the KVLCC tankers; for the other hulls there were simply not enough submissions left in each of the groups after removing the non-comparable ones. The calculated RMS error values for KVLCC2 are reported below. In the evaluation of the forced motion simulations by CFD the comparison error E is used, which is defined as:

$$E(\%D) = \frac{D - S}{D} \times 100 \qquad (2)$$

where D is the experimental data from PMM and S the computational result. For dynamic PMM tests this expression is summed up for all data points in one planar motion period to give the average comparison error.

Methods based on captive model tests (PMM and CMT). The simulation results for methods based on captive tests were very similar for the two KVLCC tankers. The simulation results for the tactical diameter of the 35 deg turning circle are shown for all KVLCC1 submissions in Figure 15. Five of these submissions were based on PMM tests, one of them on the INSEAN tests and the rest on the MOERI tests. One institute made simulations from both sets of PMM data, using the same 3 DOF mathematical model. The results showed a larger tactical diameter and smaller overshoot angles for the simulations based on the INSEAN data than for the MOERI data. This difference can partly be explained by the fact that the INSEAN tests were performed at model self-propulsion point (SPP) and at constant torque, while the MOERI tests were done at ship SPP and constant RPM.

Especially the influence of the propeller RPM strategy and the chosen self-propulsion point, has been a subject of discussion long before the topic became an issue at SIMMAN 2008.

Looking at the four submissions based on the MOERI tests, two of these used a modular MMG-type mathematical model and the other two used a whole-ship Abkowitz-type mathematical model. The mean value of the tactical diameter predicted by these four submissions correlated well with the benchmark, i.e. the mean of the free model test results, the error being 5.3% for the starboard turning circle. However, the scatter was substantial with an RMS-value of 9.7%, possibly connected with the different mathematical models. Here, as well as in other cases, the RMS error is significantly larger than the mean error, which implies that conclusions should not be drawn based on the mean error only.

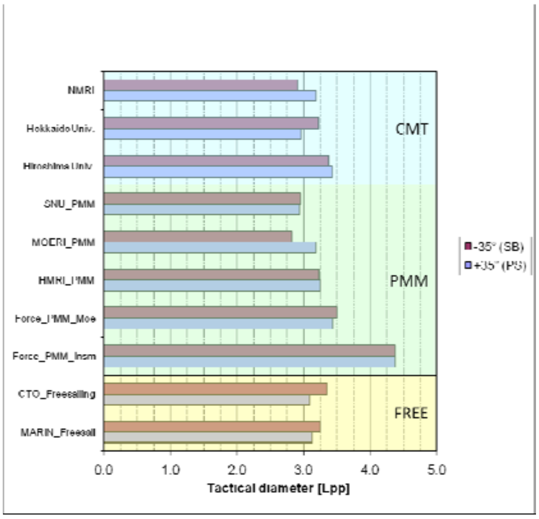

Figure 15: KVLCC1, tactical diameter derived from ±35 deg turning circle simulations, methods based on captive tests compared with free model tests

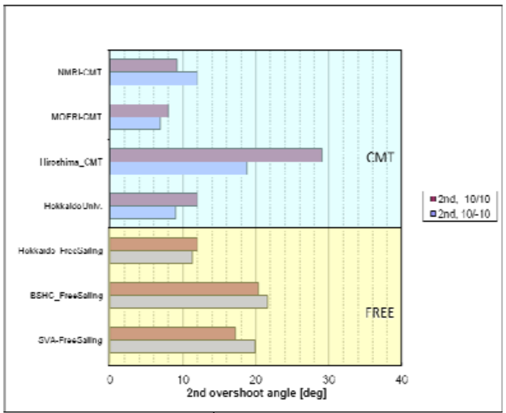

Figure 16: KCS, 2^{nd} overshoot angle in 10-10 zigzag simulations, methods based on captive tests compared with free model tests

Comparing the three CMT based submissions to the benchmark free model data, the correlation was somewhat better than for the PMM based submissions: the mean value was 2.7% from the benchmark result while the RMS-value was 7.4% for the portside turning circle. Nevertheless, this scatter is still relatively large, considering the fact that all three submissions were based on the same set of model test data (NMRI) and all used an MMG type model. It should also be noted that scale effects may have played a role in the differences between predictions based on MOERI PMM tests with a 5.6 m model and those based on NMRI CMT tests with a 3.0 m model.

For KCS the scatter of the submitted results for methods based on captive tests was also substantial, which was especially evident for the 2nd overshoot angle in the 10-10 zigzag test, as shown in Figure 16. As opposed to the KVLCC with a high GMT, the inclusion of the 4th degree of freedom (DOF) plays an important role for the KCS. This is clear from comparing the four CMT submissions that were all based on an MMG mathematical model using the same set of model test data from NMRI, but where one method included the effect of roll using an empirical tool. The first three fell closely together with an RMS-value of 2.1 deg and a mean value of 9.5 deg i.e. 2.2 deg (18%) below the benchmark 3 DOF tests performed at Hokkaido/IHI, while the latter method gave higher overshoot angles, closer to the SVA and BSHC tests in 4 DOF with a mean value 24.0 deg i.e. 4.2 deg (21%) above these results.

Of the two participating PMM-based methods for 5415M, one used a dedicated Abkowitz-type mathematical model, while the other used the PMM data to tune a LAMP-based code. Both methods were seen to correlate reasonably well with the free model test results, the mean error being 11.5%.

The results obtained through captive tests and simulations show a deviation which is unsatisfactory. Some differences can be explained, but others not. The not explained differences can be attributed to the degree of control over the consistency between model test data, fitting methods, and simulation model. It seems – somewhat disappointingly in view of *pooling* model data - that 'homegrown' methods are performing best.

Empirical methods. For KVLCC a very large scatter was observed for the submitted empirical methods: RMS of 23.1% with a mean error of 16.1% for the tactical diameter in the port turning circle. However, behind these overall figures were both a number of empirical methods that performed relatively well and a number of outliers that are not normally applied for this ship type. Also for KCS these methods showed a very large scatter in the predicted 10/10 zigzag overshoot angles, the 4 DOF methods giving an RMS-value of 8.4 deg with a mean value 5.7 deg (29%) below the benchmark. This indicates that several of these methods were used outside their field of applicability. For 5415 a total of 6 empirical methods were applied, showing a large scatter. Similarly to KVLCC and KCS, this was partly due to the use of methods that were not developed for a frigate type hull. If only the three dedicated methods are considered, the mean value of the tactical diameter was 0.6Lpp or 12.5% below the benchmark data, while the RMS-value was 20.3%.

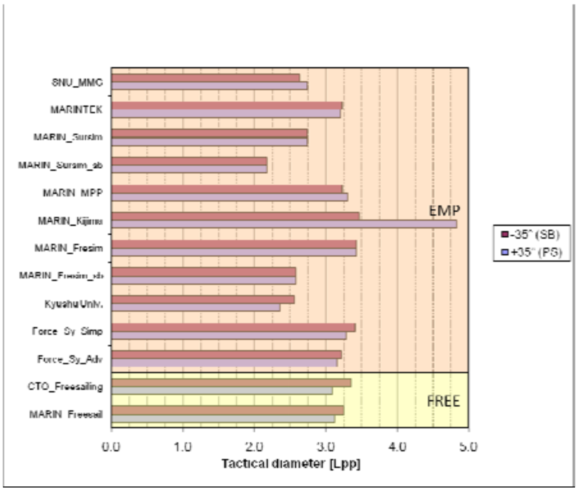

Figure 17: KVLCC1, tactical diameter derived from ±35 deg turning circle simulations, empirical methods compared with free model tests

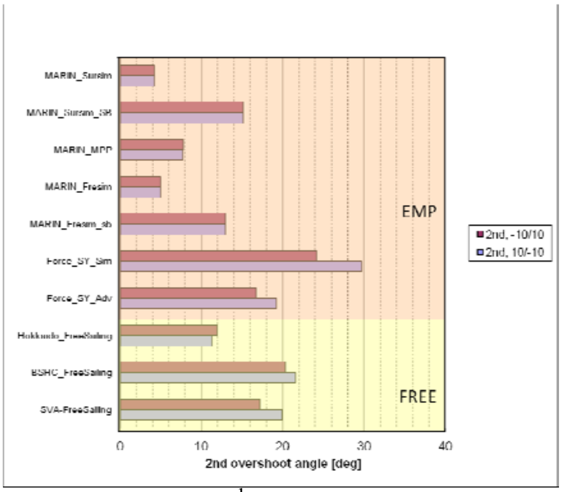

Figure 18: KCS, 2nd overshoot angle in 10-10 zigzag simulations, empirical methods compared with free model tests

<u>CFD based methods.</u> The evaluation of the CFD based methods at SIMMAN 2008 fell into two parts: those that were used to simulate singular forced PMM-type motions (the majority), and those that were used to simulate free manoeuvres (a few participants), either using a mathematical model based on a full set of forced motion calculations or performing a full time-domain simulation.

<u>Simulation of free manoeuvres using CFD.</u> Three institutes submitted CFD-based simulations for the turning circle of KVLCC1. One was a full "virtual PMM test" using RANS, a second consisted of a partial set of CMT tests combined with empirical rudder coefficients, while the third was a fully free sailing time-domain simulation of the first quarter of the 35 deg turning circle including the rotating propeller. The latter gave a reasonable prediction of the advance: 2.73Lpp compared to a mean value of 3.01Lpp in the free model tests. The first two "captive" methods gave predictions of the tactical diameter with a mean error of 14.8% for the port turn, but with the full RANS method with an error of only about 5%, i.e. achieving the same level of accuracy as for the model test based methods in this case. For the 5415 hull form there were two free manoeuvre simulations using CFD using the same RANS code, only with different propeller RPM strategy. These submissions showed good correlation with the benchmark data with an error of 4.4% for the starboard tactical diameter at constant RPM (as used in the free model tests).

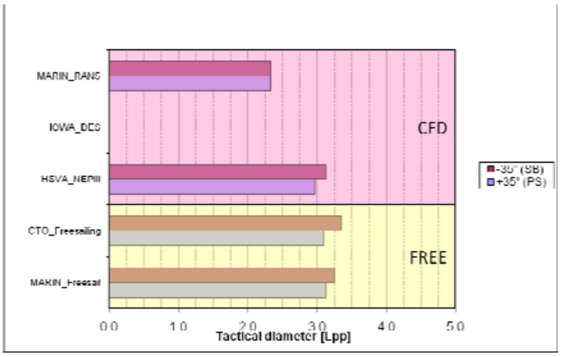

Figure 19: KVLCC1, tactical diameter derived from ±35 deg turning circle simulations, CFD based methods compared with free model tests

<u>Simulation of forced manoeuvres using CFD.</u> The submissions for the CFD part of the SIMMAN 2008 workshop included 13 ITTC institutions from 10 countries for appended KVLCC1&2 (9 submissions), appended KCS (2 submissions) and bare/appended 5415 (5 submissions). Nine different commercial/in-house URANS solvers were used. Some more details about these methods are given in Section 3.

Comparisons were made initially between the CFD result and the experimental result for the hydrodynamic forces and moments X', Y', and N' for both static and dynamic test cases. After the workshop the evaluation was extended to cover also linear hydrodynamic derivatives (i.e. slope of forces and moments versus dynamic variables and non-linear hydrodynamic derivatives (i.e. higher-order terms of the slope following a 3rd order Taylor series Abkowitz-type model). A summary of these results are given in Table 2 , showing the errors for hydrodynamic forces and manoeuvring derivatives averaged over all forced motion submissions for all test cases.

Table 2: Summary of simulations of forced motions by CFD: errors for hydrodynamic forces and manoeuvring derivatives averaged over all submissions for all test cases (Stern et al., 2011)

<table>
<tr><th rowspan="2">Cases</th><th rowspan="2">Geometry</th><th rowspan="2">E_X%D</th><th rowspan="2">E_Y%D</th><th rowspan="2">E_N%D</th><th colspan="2">Linear Manoeuvring Derivative</th><th rowspan="2">Non-linear Manoeuvring Derivative %D</th></tr>
<tr><th>Y'%D</th><th>N'%D</th></tr>
<tr><td rowspan="3">Static Rudder</td><td>KVLCC1, δ = 10°</td><td>3.5</td><td>59.7</td><td>-21.3</td><td>10-20</td><td>60</td><td rowspan="10"></td></tr>
<tr><td>KVLCC2, δ = 10°</td><td>50.8</td><td>50.1</td><td>-36.5</td><td>14</td><td>58</td></tr>
<tr><td>Average</td><td>27</td><td>55</td><td>-29</td><td>15</td><td>59</td></tr>
<tr><td rowspan="7">Static Drift</td><td>KVLCC1, β = 0°</td><td>14.6</td><td>-</td><td>-</td><td rowspan="2">10-20</td><td rowspan="2">60</td></tr>
<tr><td>KVLCC1, β = 12°</td><td>-14.4</td><td>-7.3</td><td>-11.9</td></tr>
<tr><td>KVLCC2, β = 0°</td><td>-19.3</td><td>-</td><td>-</td><td rowspan="2">14</td><td rowspan="2">58</td></tr>
<tr><td>KVLCC2, β = 12°</td><td>23.1</td><td>2.6</td><td>11.6</td></tr>
<tr><td>5415, β = 10°</td><td>-14.3</td><td>4.1</td><td>8.9</td><td></td><td></td></tr>
<tr><td>5415 appended, β = 10°</td><td>-23.1</td><td>-14.4</td><td>11.9</td><td></td><td></td></tr>
<tr><td>Average</td><td>18</td><td>7</td><td>10</td><td>15</td><td>59</td></tr>
<tr><td rowspan="6">Pure Sway</td><td>KVLCC1</td><td>22</td><td>10</td><td>10</td><td colspan="2">7.7</td><td>65</td></tr>
<tr><td>KVLCC2</td><td>18.6</td><td>11.3</td><td>11.3</td><td colspan="2">5.8</td><td>75</td></tr>
<tr><td>KCS</td><td></td><td></td><td></td><td>9.3</td><td>4.3</td><td></td></tr>
<tr><td>5415 bare</td><td>23.6</td><td>9.7</td><td>9.7</td><td colspan="2">6.9</td><td>30</td></tr>
<tr><td>5415 appended</td><td>21</td><td>30.5</td><td>30.5</td><td colspan="2">15</td><td>25</td></tr>
<tr><td>Average</td><td>21.3</td><td>15.4</td><td>15.4</td><td colspan="2">8</td><td>49</td></tr>
<tr><td rowspan="6">Pure Yaw</td><td>KVLCC1</td><td>38.3</td><td>20</td><td>20</td><td colspan="2">19</td><td>50</td></tr>
<tr><td>KVLCC2</td><td>35.3</td><td>22.3</td><td>22.3</td><td colspan="2">18</td><td>24</td></tr>
<tr><td>KCS</td><td></td><td></td><td></td><td>103.9</td><td>36.0</td><td></td></tr>
<tr><td>5415 bare</td><td>20.5</td><td>21</td><td>21</td><td colspan="2">16</td><td>-</td></tr>
<tr><td>5415 appended</td><td>37</td><td>40</td><td>40</td><td colspan="2">38</td><td>22</td></tr>
<tr><td>Average</td><td>33</td><td>26</td><td>26</td><td colspan="2">23</td><td>32</td></tr>
</table>

It was observed in the evaluation of the forced motion simulations that the correlation with the benchmark PMM data was generally better for linear hydrodynamic derivatives than for the higher order coefficients. Since non-linear effects are more critical for larger rudder and drift angles, it was expected that predictions results would show larger errors for such manoeuvres. The few results available for free manoeuvres seem to confirm this: the prediction of overshoot angles was significantly better for the 10/10 zigzag than for the 20/20 zigzag.

Other methods. There was only one submission using other methods than those covered above at the workshop, namely system identification by NSWCCD for 5415 at 18 knots, so no general conclusions can be drawn on this basis.

Overall comparison of methods. An attempt has been made to perform a quantitative evaluation of the simulation results for the KVLCC tankers, using the RMS error parameter as introduced before. All submissions that are not-directly-comparable have been left out in this analysis, i.e. simulations at ship self-propulsion point, with constant torque and methods meant for other ship types or based on model tests with conditions deviating from the nominal ones or with unresolved issues. It should be noted that the remaining number of submissions is relatively small, making statistical analysis somewhat unreliable. The results for KVLCC2 are given in Table 3, where the RMS error has been calculated for each group of methods relatively to the benchmark, i.e. the mean of the free model test results. The CFD results are removed from this table because there are not enough submissions for a statistical review.

Table 3: KVLCC2 simulations, deviation from benchmark for different method types for selected submissions

	benchmark (*1)		RMS error (all)		RMS error (captive)		RMS error (empirical)	
	port	stbd	port	stbd	port	stbd	port	stbd
Number of submissions(*2)	2/3	2/3	10/11	10/11	5	5	4	4
10/10 ZZ 1st OS (deg)	7.8	8.5	2.3	2.5	3.0	2.4	1.9	3.3
10/10 ZZ 2nd OS (deg)	15.7	17.6	5.3	6.5	4.6	8.5	7.6	5.5
20/20 ZZ 1st OS (deg)	12.8	13.0	2.6	2.9	3.2	2.7	2.2	3.9
20/20 ZZ 2nd OS (deg)	12.9	14.6	3.7	3.5	2.9	3.7	4.7	2.7
35 TC Adv (Lpp)	2.73	3.04	0.36	0.20	0.37	0.24	0.41	0.21
35 TC TactDiam (Lpp)	3.20	3.19	0.47	0.48	0.25	0.36	0.48	0.45

(*1) Benchmark value is average of applicable free model test results.

(*2) Number of submissions differs for zigzag and turning circle tests, in these cases both values are given.

Even after the described selection of submissions, it is clear from Table 3 that the overall scatter relative to the benchmark is substantial. The RMS errors are around 30% of the benchmark value for overshoot angles and around 15% for turning circle dimensions. The captive methods are representative for the overall picture with similar RMS errors, but performing somewhat better for the turning circle predictions. The empirical methods perform better than captive on some parameters, but worse on others including turning circle dimensions.

4.5 Concluding remarks

The procedure for Validation of Manoeuvring Simulation Methods (7.5-02-06-03) has been updated to incorporate these conclusions.

4.6 Recommendations for further work

Continue work in order to have a full set of well-documented benchmark model test data i.e. appended hull PMM and CMT tests as well as the corresponding free model tests for each of the four benchmark hulls (KVLCC1, KVLCC2, KCS and 5415).

Capitalize the momentum created by SIMMAN 2008 to continue the development of verification and validation of ship manoeuvring simulation methods. Thus, a second SIMMAN workshop with this aim would be useful.

One important objective of such a workshop should be to replace those of the existing data sets that cannot be clarified and corrected otherwise. Also an effort should be made to limit the scope and focus on fewer test cases. This will ensure that quantitative evaluation can be performed, which in turn should be the basis for clear observations and conclusions.

Hopefully, a second SIMMAN workshop will have more submissions which use CFD. Submissions should be encouraged on force level (for comparisons with captive model tests) and also for manoeuvring predictions (using virtual PMM or CMT) for comparisons to the free model tests. More reliable experimental data is needed to answer many questions which couldn't be cleared at the first SIMMAN.

5. MANOEUVRING AND COURSE KEEPING IN WAVES

Ship manoeuvring and course keeping in waves are studied by experimental methods with scale models. These methods are the most complete. Alternatively, computational methods are being used which superpose seakeeping theory with manoeuvring theory. Options for a time domain simulation program are "unified" theories (of which several have been developed during the last 3 decades), and "two-time scale models", which integrates the manoeuvring theory dealing with the low-frequency motion in the body-fixed axis system and the seakeeping theory dealing with the high-frequency motion in the inertial axis system.

Thanks to the technical progress achieved in the numerical and experimental aspects, new experimental researches on ship manoeuvring and course keeping in waves are carried out, and numerical studies by using CFD methods to directly simulate the manoeuvring motion in waves have been made possible. It is to expect that with the rapid development of computational techniques more academic studies on ship manoeuvrability in waves may be achieved and new insights may be obtained. The CFD simulations in this area are still very time consuming and practical application will be further ahead.

5.1 Experimental methods

Experimental methods are still the most reliable method to investigate ship manoeuvring and course keeping in waves. Adnan and Yasukawa (2008) presented experimental results for the ship motions and drift forces on a container ship, S175/SR108, moving obliquely in waves. An outline of the model test is presented. It is found that in general the ship motions and drift forces are influenced mostly by hull drift motion. In order to investigate the effects of wave drift forces on ship manoeuvring, Kinoshita et al. (2008) carried out PMM tests in waves to determine the hydrodynamic manoeuvring derivatives for a floating ship model. Lee et al. (2009) carried out an experimental study of ship manoeuvrability in regular waves. Model tests are conducted with one of the KVLCC models and the wave forces and moments are measured at various wave lengths and wave amplitudes. The wave effects on ship manoeuvrability are analysed. The wave forces and moments are considered up to the second order. Simulations using modular type mathematical model are performed that consider wave forces and moments measured by model tests on a ship model. As a result of the wave effects, the trajectory of the ship shows a quite different behaviour depending on the wave direction and wave amplitude. It is shown that the 2nd order wave forces have a dominant influence on the trajectories of the turning and zigzag tests.

5.2 Simulation methods based on two-time scale models

Yasukawa and Nakayama (2009c) presented a practical method for simulating ship manoeuvring and wave induced motions. The basic motion equations are separated into two groups where one is for the high frequency wave induced motion and the other is for the low frequency manoeuvring motion. The total 10-motion equations, which are composed of 6-DOF equations for the high frequency problem and 4-DOF (surge, sway, roll and yaw) equations for the low frequency problem, are derived. Wave induced motions in turning condition are predicted for a model of the container ship S-175. The predictions roughly agree with the free model test results.

Yasukawa et al. (2010) used a numerical method based on strip theory for the calculation of hydrodynamic forces and wave induced ship motions, with the lateral drift taken into account. Calculated motions for various drift angles are compared with experiments for a container ship. The results show that the proposed method captures the effect of drift on the wave induced ship motions, and that this effect is not negligible.

Seo and Kim (2011) calculated the manoeuvring performance in waves by using the time domain non-linear ship motion program which uses a Rankine panel method. The 2nd order wave drift force is calculated by a direct pressure integration method. The manoeuvring equations are solved using a modular model in separate manoeuvring equations. Validation was done by comparison with published experimental data for the S-175 containership in calm water and in waves (Yasukawa and Nakayama, 2009c).

5.3 Simulation methods based on unified theory

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

Skejic and Faltinsen (2008) studied the behaviour of a ship in regular waves during manoeuvring by using a two-time scale model. The manoeuvring analysis is based on non-linear slender body theory generalized to account for heel. Forces and moments due to rudder, propeller and viscous cross-flow are calculated by state-of-the-art procedures. The developed unified theory of seakeeping and manoeuvring is verified and validated for calm water by comparing experimental and calculated zigzag and turning circle tests. Linear wave-induced motions and loads are determined by generalizing the Salvesen-Tuck-Faltinsen Strip theory. The mean second-order wave loads in oblique regular waves are approximated by the classical potential flow theories. The considered theories cover the whole range of important wave lengths. Comparisons between the different mean second-order wave load theories and available experimental data are carried out for different hull forms with the ship advancing forward on a straight course. The methods have been incorporated into the manoeuvring model. Their applicability in manoeuvrability of the selected ship types is investigated in given wave environments. The wave conditions are valid for realistic manoeuvring cases in open coastal areas. It is demonstrated that the incident waves may have an important influence on the ship manoeuvring behaviour. The added resistance, mean second-order transverse force and yaw moment also play important roles.

Skejic and Berg (2010) carried out a numerical study on the hydrodynamic interaction effects between two ships going ahead in regular deep water waves during typical manoeuvres for ship-to-ship (STS) operations, such as lightering, replenishment, etc. A combined seakeeping and manoeuvring analysis of two ships involved in typical lightering operation is performed using a unified seakeeping and manoeuvring theory developed by Skejic and Faltinsen (2008). This approach allows the manoeuvring behaviour of the two ships involved in lightering operation in waves to be successfully described. The regular wave field effects upon the involved vessels are described by the mean second-order wave loads. The predicted mean second-order wave loads according to these theories are shown in the case of turning manoeuvre of a ‘MARINER’ ship in specific wave conditions. Automatic steering- and speed-control algorithms for both ships are employed to achieve high-precision and collision-free lightering manoeuvres in waves. This is illustrated by a numerical simulation involving an Aframax tanker and the KVLCC2.

Hermundstad and Hoff (2009) presented a unified seakeeping manoeuvring simulation model valid for surface ships and underwater vessels. Examples of the developed time domain simulation code are given for a submarine. These include simulations of the response and corresponding control plane forces of a submarine sailing on a straight line in regular waves at various headings. Turning circle simulations are conducted for the same submarine, and the results are compared to experimental results. Additionally, simulations of the response of a surface vessel (Wigley hull) with forward speed in regular waves at various headings are presented. The limitations in the developed method and further possible development of the method are also discussed.

Yen et al. (2010) described the development of LAMP (Large Amplitude Motion Program) for the direct simulation of a ship manoeuvring in calm water and in waves. A manoeuvring force model is used for forces and moments that are not included in the potential flow solution. For the results presented, the coefficients in the manoeuvring force model are derived from captive model test data. The technical approach, numerical implementation, and validation results are presented. A series of turning circles in regular waves are simulated and results are validated with experimental data.

5.4 Other simulation methods

Lin and Klamo (2010) describe a new method, describing ship wave interaction model and a solid body motion model. The numerical simulations are compared to experimental data for an undisclosed vessel.

5.5 Simulation methods using CFD

During the last years, there are only a few publications with regard to direct prediction of ship manoeuvrability in waves by using CFD. Ferrant et al. (2008) used the SWENSE (Spectral Wave Explicit Navier-Stokes Equations) approach to simulate the viscous flow around a manoeuvring ship in waves by combining the description of undisturbed incident waves by a non-linear spectral scheme based on potential flow theory and the computation of the non-linear viscous diffracted flow using the free surface RANS-solver ICARE. The simulation result is presented to demonstrate the capacity of the numerical model to simulate a self-propelled ship manoeuvring in waves.

5.6 Control system for course keeping in waves

Fossen and Perez (2009) described the main components of a ship motion control system and two particular motion control problems that require wave filtering, namely dynamic positioning and heading autopilot. They discussed the models commonly used for vessel response and showed how these models are used for Kalman filter design. They also briefly discussed parameter and noise covariance estimation, which are used for filter tuning. To illustrate the performance, a case study based on numerical simulations for a ship autopilot was considered. The material discussed conforms to modern commercially available ship motion control systems.

Fang and Luo (2008a) presented a non-linear hydrodynamic numerical model with multiple state proportional derivative (PD) controllers for simulating the ship’s track in irregular seas. By way of the rudder operation, the track keeping ability of the PD controller on the ship is examined using the line-of-sight (LOS) guidance technique. Furthermore, the roll reduction function using the rudder control is also included in the PD controller. From the simulation results, it is shown that the single-input multiple-output (SIMO) heading/roll PD controller developed works for roll reduction and for track keeping.

In order to investigate the dynamic stability and safety for a ship towing system operated in waves, Fang and Ju (2009b) developed a non-linear mathematical model including seakeeping and manoeuvring characteristics to simulate the dynamic behaviour of the towing system in irregular waves. In addition to waves, wind is also included in the calculations. The time history simulations of 6DOF motion for both the towing and the towed ships are solved by a fourth order Runge-Kutta method. The effects of the tow point's position, towline length and towing speed on the yaw stability and towline tension are analysed with respect to different wave and wind directions. Suitable operation conditions for the ship towing system are investigated and can be suggested as a reference for improving the stability and safety of towing operations at sea.

Dolinskaya et al. (2009) presented an investigation on the optimal short range routing of a vessel in a stationary random seaway. The calculations are performed in head and oblique seas. The evaluation of the added drag is performed by computing the time average wave force acting on the vessel in the longitudinal direction. Subsequently, the added drag is superimposed on the calm water drag. In this manner, the fastest path between the origin point A and the destination point B can be evaluated, taking into account operational constraints. To obtain the fastest path between two points, the underlying structure and properties of the maximum mean attainable speed are analysed.

Under the control constraint of rudder angle, Ho et al. (2010) developed an online optimal course handling control with a quadratic performance index for the non-linear continuous time ship manoeuvring systems with wave disturbances. The ship manoeuvring systems are represented by a linear sequential model which is derived by using the orthogonal functions. This approach permits the linear feedback control law to be applied to the non-linear continuous-time ship manoeuvring systems. The proposed optimal controller can accommodate the effects caused by wave disturbances. The online optimal course keeping handling control, course tracking handling control and course changing handling control for a ship manoeuvring system with wave disturbance are presented to illustrate the considerable promise that the proposed method exhibits.

6. MANOEUVRING IN CONFINED WATERS

In this review, as a continuous work of the 25th ITTC report by the Manoeuvrability Committee (2008), the following aspects will be focused on:

- Manoeuvrability in confined water
- Force predictions in shallow water
- Bank effects
- Ship-ship interaction
- Squat

6.1 Manoeuvrability in Confined water

Manoeuvring Simulations. Gronarz (2009a) carried out model tests in shallow water to investigate the forces acting on a vessel in inhomogeneous current, which was reproduced by the current facility and a fictitious harbour entrance. The forces and moments acting on different vessels placed at varying positions and courses in the inhomogeneous current were measured. Based on the experimental results, he discussed the manoeuvring simulation in inhomogeneous current. Kim et al. (2009) carried out turning simulations in shallow water using a mathematical model with a low speed model. The simulation results were compared with existing experiments (Yoshimura, 1988). Son and Furukawa (2009) have used free model tests in deep water, performed system identification using the MMG model, and corrected the coefficients to obtain shallow water coefficients using the Kijima and Nikiri (2004) shallow water corrections. Using that mathematical model, a shallow water collision avoidance model was tested numerically.

Free Model Tests. Milanov and Chotukova (2009) carried out free model tests in different water depths (*h/T* = 1.5, 2.0, 2.5 and 11.46) using a container ship model. Shallow water effects on the turning, 20/20 zigzag manoeuvre and spiral curve were presented. Also roll motions during manoeuvres were shown and discussed. De Jong et al. (2010) present the results of simulations based on a mathematical model for a submarine sailing at the surface which is based on captive model tests, free model tests and CFD calculations. Regular hydrodynamic coefficients came from PMM tests, while bank suction forces were obtained by panel methods. These results were combined into a mathematical model describing a submarine manoeuvring in very shallow water.

6.2 Force Predictions in Shallow Water

Wang et al. (2009a) simulated the viscous flow around an Esso Osaka tanker model undergoing steady turning motion in shallow water using RANS and an improved two-equation turbulence model is applied. Numerical simulations were conducted at different water depths, and the shallow water effect on the hydrodynamic forces was investigated by comparing the results of shallow and deep water. The validity of the numerical method is demonstrated by comparing with experimental results (Berth et al., 1998). Wang et al. (2009b) also calculated the viscous flow and hydrodynamic forces of a laterally moving ship in shallow water by applying the unsteady RANS code with two different turbulent models. The numerical results for a Wigley hull were presented and compared with the numerical and experimental results by Lee et al. (2003).

6.3 Bank Effects

Daggett (2009) gives an historical overview of the researches that were carried out on full scale in the Houston Ship Channel and in the Panama Canal. He emphasises that it will be important to make the translation from measured academic geometries towards transient situations in real life. Lataire et al. (2007) report extensive measurements that demonstrate how the bank suction forces and moments depend on the bank slope and the geometry of the hull. The results of the measurements are compared to the bank model of Norrbin (1974) and new formulations are proposed, see Figure 20.

Eloot et al. (2007) present a new methodology based on a comparison of the control forces (rudder forces) to the disturbing forces (bank forces). Although there are more parameters that play a role, the proposed methodology gives a quick scan on the feasibility of manoeuvres. This may be a useful test before going to fast time and real time simulator runs. Lataire et al. (2009b) present a subset of an enormous amount of measurements that have been carried out on bank effects. A limited amount of this data is free to use. Based on the results, a mathematical model for bank suction, which includes effects of changing bathymetries, is proposed. Fenical and Carter (2009) describe the validation of a numerical model based on a finite volume method for solving in time domain the non-linear shallow water equations and Boussinesq equations. Validation was carried out based on the measurements of Lataire et al. (2009b).

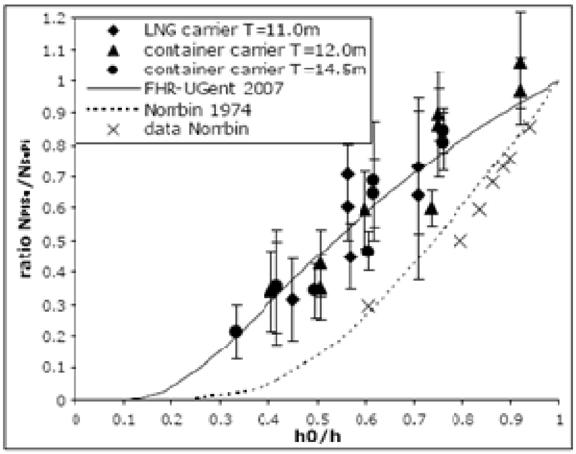

Figure 20: Comparing the measurements of Lataire et al. (2007) to Norrbin's model (1974)

Naaijen (2009) calculates the waves due to ships. The calculation method is validated based on experiments with a barge. Firstly, the barge sails in a rectangular canal, secondly, the barge sails in a canal with an obstruction. Results show that it is possible to predict wash waves reasonably well. Gronarz (2009b) has investigated whether there is an interaction between sailing straight along a bank or under a drift angle, and whether superposition is allowable. The experimental results based on an inland vessel and a vertical wall, indicate that there is indeed a cross-coupling between the two, as shown in Figure 21 showing the side force due to suction with the pure drift and the pure bank effect subtracted. Duffy et al. (2009) have developed a method to predict sway forces and yaw moments due to flooded and surface piercing banks, and have implemented this in the bridge simulator. To this end, captive model tests were carried out (ship parallel to the bank) on a containership (the S175) and two bulk carriers (of the Marad Series).

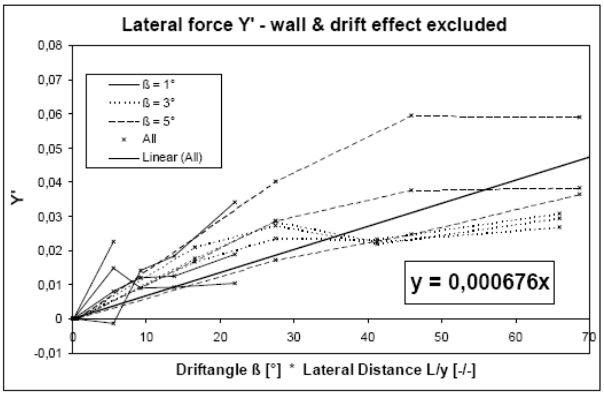

Figure 21: Bank effects - Empirical fit through data by Gronarz (2009b)

Uliczka and Kondziella (2009) reported bank effects and their effect on squat not only in model scale, but correlated this with full scale measurements on a container vessel in the Elbe. Figure 22 shows a comparison between the measured squat in model scale and in full scale. Maimun et al. (2009) performed PMM tests on a LNG carrier in shallow water and in the proximity of a bank. A mathematical model was fitted through the measurements, and simulations were carried out to demonstrate the effect of increased rudder area on the manoeuvring behaviour.

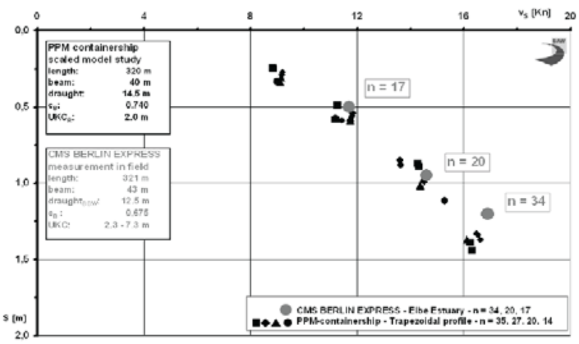

Figure 22: Comparison of squat by Uliczka and Kondziella (2009)

6.4 Ship-Ship Interaction

In addition to the papers referenced in the following, it should be mentioned that a dedicated Ship To Ship (STS) Interaction conference is being organised in May 2011. However, this conference is just too late for the proceedings to be included in this ITTC report.

Drouin and Bussieres (2009) discussed a failed overtaking manoeuvre in confined waterway: the overtaking manoeuvres is understood to be one which presents greater risks due to the prolonged time period the hydrodynamic forces are present as well as their increased strength when overtaking is performed in a confined waterway. The trend towards larger vessels and smaller under keel clearance aggravates this situation. The development of localized quantitative overtaking guidelines for pilots and mariners can be a cost-effective risk reduction measure in the operation of a confined waterway.

To develop a guidance system for the ship navigation officers that can assist in navigating in close proximity for Ship-to-ship (STS) lightering operation, Yoo et al. (2009) carried out a field observation and full-scale measurements on board the Shioji-Maru conducting an approach towards, and operation alongside, a virtual ship. Data of own ship's position, speed, course, engine and rudder actions were logged from the Voyage Data Recorder. Velocity Information GPS (VI-GPS) system, which consists of GPS receivers and PDA (Personal Digital Assistant), providing precise velocity of a moveable body, was applied to measure relative distances and speeds. They analyse the correlation coefficients with approaching surge and sway speeds to the virtual ship and own ship's data of main shaft rpm, rudder angle, wind speed and direction to figure out which are the significant factors on STS operations to enhance the operational safety and efficiency.

Skejic and Berg (2009a) investigated the applicability of the unified seakeeping and manoeuvring model developed by Skejic and Faltinsen (2007, 2008) by combining the Newman and Tuck (1974) theory for predicting ship-ship interaction forces. Particular attention was paid to approach/abeam/separation phases during the lightering operation for 'Aframax' and 'KVLCC2' tanker ships. Numerical results related to the main manoeuvring parameters were discussed from the navigational safety point of view. Sutulo and Soares (2009) simulated the manoeuvring motions of two ships moving in close proximity using a procedure on the basis of the classic Hess–Smith method in the potential theory. Simulated trajectories and time histories were presented for two interacting ships in uncontrolled and controlled motion.

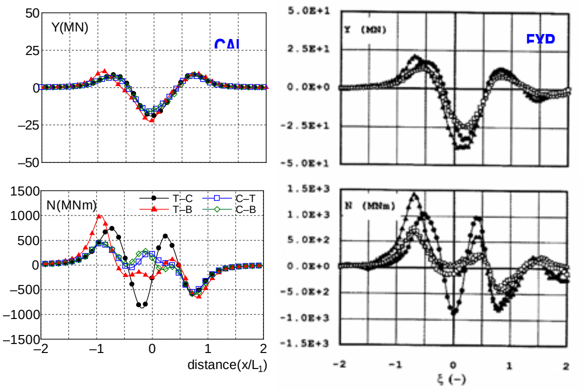

Figure 23: Comparison of lateral force and yaw moment acting on encountering ship model (left: calculation by Yasukawa, 2009d, right: experiment by Vantorre, 2002)

Yasukawa et al. (2009d) evaluated ship-ship interaction forces by a 3D panel method with assumption of a rigid free-surface. Through the comparison with a model test conducted by Vantorre et al. (2002), the robustness of the 3D panel method was investigated. The 3D panel method was able to capture the qualitative tendency of the interaction forces. However, the quantitative accuracy was insufficient as seen in Figure 23. Lataire et al. (2009a) and Berg and Petterson (2009) introduced the research project entitled "Investigating Hydrodynamic Aspects and Control Strategies for Ship-to-Ship Operations" and gave an overview of the entire model test program. Lataire (2009a) shows results of experiments.

Pinkster (2009) is using potential flow theory to calculate the forces that the passing ship generates on a moored vessel. The results are compared to experimental measurements. Bunnik and Toxopeus (2011) have extended Pinkster's theory to include viscosity and discuss the viscous effects. The addition of viscosity gives an improved correlation of Pinkster's theory with the experimental results for drift angles. Chitrapu et al. (2007) reported on the 6 DOF behaviour of a pair of interacting vessels subject to oblique wind, waves and currents, manoeuvring effectors, mooring lines and fenders. The method comprises coupled equations of motion of a pair of interacting vessels in the time domain at zero and non-zero speeds. Hydrodynamic and mechanical dynamic contributions are modelled separately and combined in the time domain simulation environment at the force level rather than the motion response level. Three types of hydrodynamic contributions are computed: calm water manoeuvring forces, calm water manoeuvring interaction forces, and coupled vessel seakeeping forces.

6.5 Squat

Barrass (2009) discussed squat together with worked examples for container ships, RO-RO vessels, passenger liners and super tankers. Briggs (2009) examined the sensitivity of several ship and channel parameters on predicted ship squat for a containership based on empirical formulas. Allenström et al. (2009) carried out model tests covering different speeds at different water depths to measure the squat. Based on the test results, a new formula for the squat for single screw ships was proposed where the attitude of the ship (bow or aft trim) is provided. It is based on main ship dimensions, such as *L/B*, displacement, etc. Debaillon et al. (2009) calculate ship squat near a bank by calculating iteratively the hydrodynamic pressures on the submerged body using a panel method and integrating the pressures to obtain sinkage, trim and roll. These calculated data were compared to the experimental results for a container vessel sailing at two different lateral positions in a channel by Lataire et al. (2009b). Sano and Yasukawa (2009) proposed a new method to solve a ship steady wave making problem in two layers with a mud layer. Considering only dense-stratification (neglecting viscosity), the potential flow was assumed for its formulation. The Esso Osaka tanker was used for the calculations. The simulations show that the ship is influenced considerably by the interface in the wave making resistance, sinkage and trim when navigating with small under keel clearance above the lower layer with large depth.

7. UNCERTAINTY ANALYSIS

7.1 Introduction

A workshop was held at NRC, St. John's in June 2010 on uncertainty analysis (UA) for ITTC members. Amongst other topics, UA in the area of manoeuvring was partly treated as a subject. The outcome was less satisfactory than expected because many aspects of the uncertainty are still focussed at establishing the uncertainty of measuring devices such as force transducers, ballast weights and model length. The uncertainty of the main manoeuvring result such as an overshoot angle or a tactical diameter was not treated at the workshop.

The required transfer of the existing procedure on UA for captive tests towards ISO approach will require a considerable amount of work. This became apparent at the workshop in 2010. The methodology of the existing procedure 7.5-02-06-04 for captive manoeuvring tests could be translated, but the elaborated example cannot be translated so easily, and additional measurements and calculations would be required. Especially a worked-out example is a pre-requisite for a procedure such as this one to be useful. Therefore, the UA procedure for captive model tests was not updated. It is suggested to harmonise the procedures for uncertainty for captive model tests as set-up by Vantorre et al. (2002) and Stern (2005) and bring them in line with the requested ISO procedure.

It is observed that in the past, and also in the present ITTC period, UA has been applied for captive model tests at various facilities. The outcome has been the uncertainty of the measured hydrodynamic forces and moments during one particular test or several tests. The committee acknowledges that this is a very important step in the right direction. However, this step does not provide the required information such as the uncertainty of the end result such as the overshoot angle or the tactical diameter. Although this achievement is not likely met on a short term, knowledge on the uncertainty of the outcome of the mathematical model as a whole should be the “leading star” for the next manoeuvring committee.

7.2 UA on captive tests

Etebari et al. (2008) describe the UA procedure applied on rotating arm tests on the SUBOFF submarine model. During the experiments, measurements were carried out on the flow field (using Stereo PIV), the static pressure field at two cross sections and the forces and moments on the model in the 6 DOF. The paper elaborates the UA calculation formulae for all three measurements. A selection of the resulting total uncertainties is presented.

Ueno et al. (2009) present an uncertainty analysis of circular motion tests (CMT) and oblique towing tests. Tests were carried out for 3 different models: the KCS, KVLCC1 and KVLCC2. The results of the uncertainty analysis (which followed the ASME standards) are believed to help further the discussion about validation of experimental and computational prediction methods for hydrodynamics of ships in manoeuvring motion.

7.3 UA on free model tests

A guideline for the uncertainty analysis for free model tests has been initiated by the manoeuvring committee. This guideline is based on a pragmatic approach in which many sources of uncertainty are listed and the model basins are responsible for obtaining and quantifying the sources of uncertainty within their own organisation. A fully elaborated example should be added in the future.

7.4 UA on simulation models

A procedure on UA for simulation models has not been set-up yet. An elaborated example of UA for a simulation model would be desired. It is acknowledged that this is a lot of work. It follows the procedural sequence of captive tests, (harmonic) analysis of results, fitting and modelling, simulation and analysis of the simulation. It is recommended to do this after finalizing the UA procedure on captive tests.

8. SCALE EFFECTS

8.1 Introduction

For manoeuvring, there is no established standard test and correction method to overcome scale effects yet. Before establishing a correct test and correction method for scale effects, it is essential to understand hydrodynamic phenomena during model tests and full-scale tests. Furthermore, reliable model test data and full-scale trial data are also required. Recent advances in CFD are opening the possibility for research on scale effects. In this section, the state of the art of scale effects is reviewed. Since this topic has not been treated explicitly in the last two manoeuvring committees, older papers are also included in the review. Based on the review, recommendations for future studies on scale effects are proposed.

8.2 Scale effects by component

To increase the understanding of possible scale effects, scale effects on the components 'rudder', 'hull', 'propeller rudder interaction', and 'self propulsion model' are discussed.

Scale effects on the rudder forces. For streamline bodies such as rudders, the lift coefficient is assumed to depend only on the angle of attack, and hence independent of the Reynolds number (Newman, 1977). Figure 24 supports this assumption with experimental data for lift characteristics of two-dimensional foil (Abbott and Doenhoff, 1959). The Reynolds number has no effect on the lift characteristics at small angle of attack but only at larger angles, where separation starts to play a role. Figure 24 illustrates that flow separation starts playing a role after about 10 degrees, for this theoretical, 2 dimensional case.

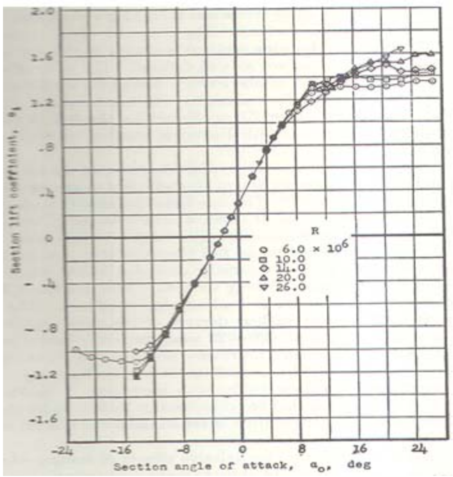

Figure 24 Effects of Reynolds number on the lift characteristics of two-dimensional foil (Abbott and Doenhoff, 1959)

However, other researches demonstrate that there is a small dependency also of the lift slope on the Reynolds number. This is shown in Figure 25.

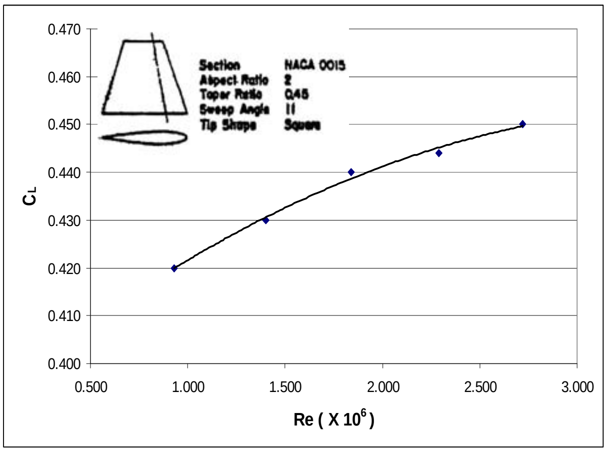

Figure 25: Effect of Reynolds number on lift coefficient at 10° angle of attack for a NACA 0015 airfoil with aspect ratio 2. (Whicker and Fehlner, 1958)

However, for a rudder behind a rotating propeller, the turbulent flow in the propeller slip stream reduces the effect of the Reynolds number. The lift and drag of a rudder in a blade frequency depending oscillating behaviour of the propeller slipstream is different from the lift in a uniform flow, certainly at higher rudder angles.

Shen et al. (2010a) observed that the turning circles at full scale were larger than at model scale. Five potential modelling effects were discussed:

- Reynolds scale effects on the boundary layer thickness on the rudder surface
- Differences in propeller loading between full-scale and model propellers
- Cavitation on full-scale rudders
- Dynamic stall on rudders
- Dissimilarity due to the power controller in full-scale versus constant RPM on model scale

An analysis was made by studies in a large cavitation tunnel and by RANS computations. The calculations show lower rudder efficiency at model scale than at full-scale. In addition, the cavitation occurs at high speed, causing a breakdown of lift force for high speed, which is not seen on model scale. Together with the reduction of RPM during the tests, the authors explain that the full scale turning circles should be larger than the model scale turning circles. This is opposed to other references such as Yang et al. (2009), Sung et al. (2009) and Son et al. (2010). The observation that different trends are reported indicates that additional research is necessary.

Scale effects on hull forces. The 22nd ITTC (2002) investigated geosim model test results on Esso Osaka and concluded that no significant scale effects have been found. However, this conclusion cannot be generally accepted due to limited dataset and inconsistent reduction of hydrodynamic coefficient. Nevertheless, scale effects may be expected on side forces and turning moments as function of Reynolds number.

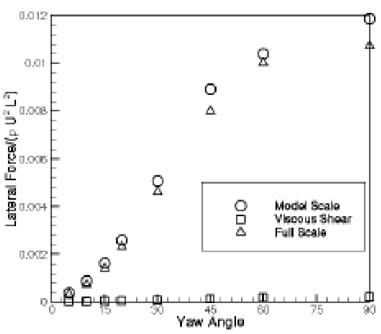

Figure 26: Comparison of full-scale and model-scale hull forces on 5415 by RANS computations (Kim et al., 2003)

Kim et al. (2003) performed model scale (Rn=12·10^6) and full scale (Rn=9·10^8) RANS computations on a bare hull 5415 at various drift angles. Figure 26 shows the comparison of lateral forces. The effects of Reynolds number on lateral forces at small drift angles are small because the dominant component of lateral force is the pressure difference on the hull which are less affected by Reynolds number than the viscous shear stress force. However, at large drift angles, the different boundary layer thickness between model scale and full scale creates a difference of vortical flow structure and the surface pressure on the hull, which results in a difference in lateral forces between model scale and full scale Reynolds number. This indicates that non-linear hydrodynamic coefficients will be more affected by Reynolds effects.

Nikolaev and Lebedeva (1980) performed model tests with geosim models of 2, 4, 6, 8 and 30 meter in length. A significant difference in results was only observed for the 2 meter model. The 2m model was more directionally stable than the larger model. The hypothesis that this scale effect is due to the flow breakdown on the hull was investigated by repeat tests with a sand-roughened hull. This sand roughness caused that the results obtained with the small model came very close to the results with the larger model. Figure 27 shows the results of this series and another model where the same was investigated.

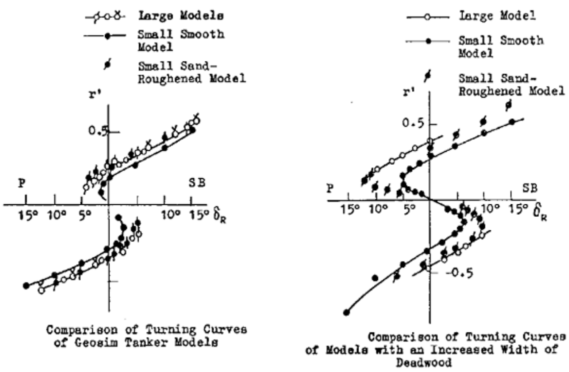

Figure 27: Influence of sand roughness and model size on reverse spiral test curve (Nikolaev and Lebedeva, 1980)

Nikolaev (1986) hypotheses that the vortices shed from the bilge radius were causing a different bottom cross flow. This hypothesis was investigated by attaching sandpaper only one side. The results (shown in Figure 28) indicate that sandpaper is effective only when the sandpaper is attached to the side where the flow is coming.

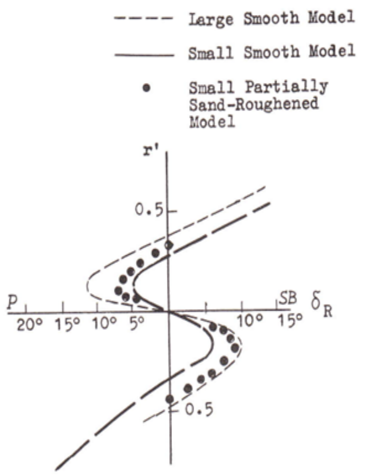

Figure 28: Effects of partially sand-roughened model on turning characteristics (Nikolaev and Lebedeva, 1980)

Scale effects on the propeller and rudder wake field, and flow straightening. Scale effects on the flow around the rudder, affecting the rudder forces directly, are connected with the scale effects on the wake and propeller slipstream during manoeuvring motion. Yumuro and Yamamoto (1992) investigated experimentally scale effects on the direction of the flow behind a hull in oblique flows. They proposed a method to estimate the flow straightening effect due to the hull and propeller slipstream based on the assumption to decompose the free stream velocity into lengthwise and crosswise components. Their method showed reasonable comparisons with experimental data. The flow directions on three different tanker sizes (2m, 4m, 7m) are measured and found that flow straightening decreases with increasing model size. However, theoretical considerations suggest that the flow straightening should increase with model increasing model size.

Lee et al. (2008) have investigated hull-propeller-rudder interactions for Series 60 (C_B=0.8) by RANS computations. The rudder forces are calculated for four different inflow conditions: a rudder in a free stream, a rudder behind a hull, a rudder behind a propeller, a rudder behind a hull and a propeller, see Table 4. Computations estimate the effect of hull and propeller on the rudder reasonably and show similar tendency with the experimental data for similar cases from Molland and Turnock (2002), in the rightmost column. The effects of Reynolds number on lift coefficient are small, except for the rudder behind a hull (Hull+Rudder) without propeller. It is however strange that the lift coefficient is decreased with increasing Rn: normally, we would expect an increase of lift coefficient due to the decreased wake fraction.

Case	Lift Coefficients C_L		
	Rn=1.46 x 10^6	Rn=4.68 x 10^7	Molland
Rudder	0.855	0.854	0.92
Hull+Rudder	0.600	0.502	-
Prop.+Rudder	1.896	1.781	1.7
Hull+Prop.+Rudder	1.310	1.350	1.4

Table 4: Comparison of Rudder Lift Coefficients

8.3 Effects of propulsion point

The question whether manoeuvring tests should be carried out at model self propulsion point (MSPP) or at ship self propulsion point (SSPP) is still controversial. This is related with a problem how to make an inflow to a rudder dynamically similar between model and full-scale ship. With SSPP, a propeller slipstream can be dynamically similar between model and full-scale ship whereas decreased inflow to the propeller due to thicker boundary layer in the model cannot be considered. Traditionally free model test has been carried out at MSPP. Supporters of MSPP believe that higher propeller loading by MSPP can be cancelled out or balanced with higher model wake. This of course may only apply to single screw ships.

Oltmann et al. (1980) investigated the effects of propeller slipstream on manoeuvrability systematically using a CPMC which could applied for a controlled external towing force in the longitudinal direction required to balance the propeller overload. From this experimental study, they could reduce the discrepancy between model test and full scale measurements noticeably by choosing a propulsion point which best generates the corresponding estimated rudder inflow velocity of the full-scale. This optimum propulsion point needs of course neither coincide with MSPP nor SSPP. The drawback of this pioneering study was that the towing assistance force was not adapted to the instantaneous model speed.

Sung et al. (2009) carried out PMM test on an undisclosed vessel with a model length of 7 meter. Tests are performed at MSPP and SSPP. and the hydrodynamic coefficients are derived and compared. The effects of propeller loading was estimated by using the measured rudder forces. Figure 29 shows the ratio of inflow to rudder (u_R) to inflow to propeller (u_P) with variation of propeller loading. It is seen that the 26% higher RPM of MSPP results in 60% increase of propeller loading and 14% increase of rudder inflow speed and 30% increase of rudder efficiency.

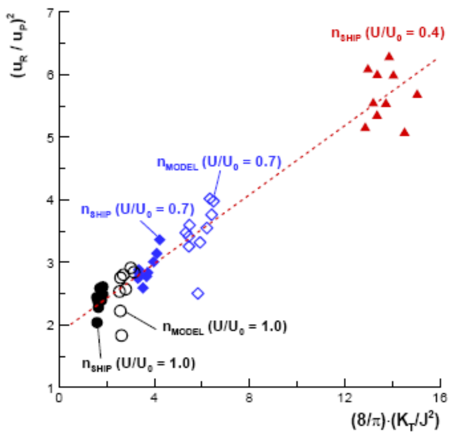

Figure 29: Rudder inflow acceleration ratio with propeller loading (Sung et al., 2009)

Son et al. (2010) have investigated the effects of the propulsion point on zigzag and turning circle tests for the KCS container ship, by using additional towing device designed for providing frictional force correction (see Figure 30). A winch is used to assure a constant additional towing force to the model. At ship-self propulsion point, both turning diameter and overshoot angle increase respectively by 10% and 20% compared to the model self propulsion condition. Similar as Oltmann et al. (1980), the towing force was not adapted to the instantaneous model speed. This experience is opposite to the experience of Shen et al. (2010a), but it must be said that Shen et al. were investigating a twin screw vessel, where Son et al. were investigating the KCS.

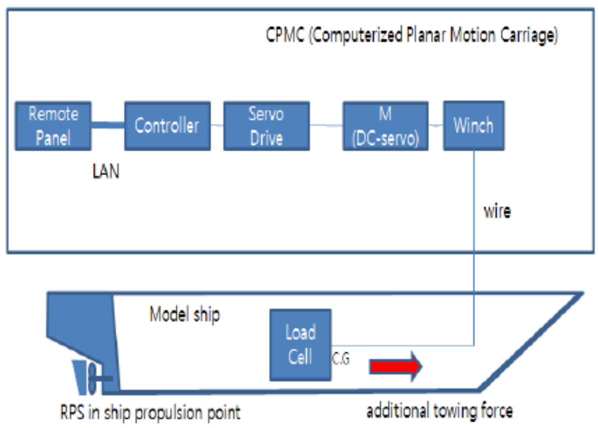

Figure 30: Schematic view of additional towing device (Son et al., 2010)

8.4 Review of existing correlation methods

Several correlation methods have been proposed in the past to deal with scale effects in predicting manoeuvring performance.

Free model tests. Model-ship correlation method for free model test can be categorised into three methods: pre-test methods, post-test methods and during-test methods (Thime, 1966, Rakamaric, 1972).

Pre-test methods take place before the tests, and handle test conditions and model state, before the test, to minimize scale effects. The change of rudder dimensions and rudder sections and attaching turbulent stimulators (see Nikolaev, 1986) are pre-test methods. Shen and Hess (2010b) are proposing a method to modify the rudder size of free model to allow for Reynolds scale effects on rudder lift forces.

Post-test methods correct the test results based on available knowledge on scale effects and a formula or mathematical model to predict the characteristic of manoeuvring performance. System identification method may be used for post-test methods. There are no examples of this.

During-test methods are methods applied during the tests. To make a flow around a model dynamically similar during test, Rakamaric (1972) proposed a boundary layer control method by suction, injection or heating on the surface of the model. Oltmann et al. (1980) applied towing force during test to carry out the test at optimum propulsion point. Shen and Hess (2010b) proposed a rudder angle correction method to consider scale effects on rudder forces for submarines. For submarines, the rudder is in the boundary layer, not impacted by a propeller in front of the rudder. Because the boundary layer is relatively thicker on model scale than on full scale, the rudder forces will be relatively lower on model scale. Figure 31 shows a possible rudder deflection for a turning test. The magnitude of correction for command rudder angles is varying with a phase to consider effective inflow angle to the rudder. It is obvious that such a method would require knowledge about lift, wake and flow straightening on model scale and full scale.

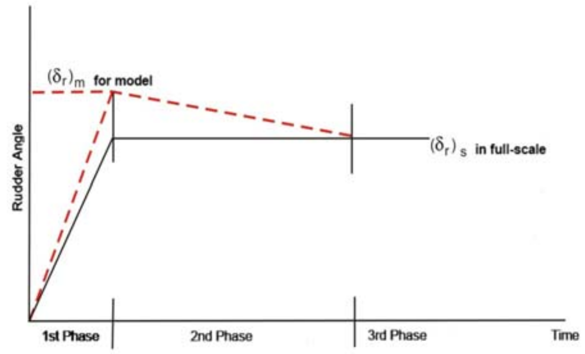

Figure 31: Proposed rudder angle deflection in free model tests for submarines for Reynolds scale correction (Shen and Hess, 2010b)

All of above correlation method require sufficient knowledge of flow mechanism and hydrodynamics during the test. This knowledge can be obtained from either empirical data or theoretical computation.

Captive model tests and simulations. In case that manoeuvring performance is made based on the captive model test and subsequent simulations, scale effects can be accounted for in the simulation model by correcting frictional resistance and wake of model with those of full-scale ship, see 20th ITTC manoeuvring committee's report. The corrections of the inflow to the rudder and the wake depend on the mathematical model. In case of modular model, the correction can be done easily just by replacing the model wake with full-scale wake whereas in case of whole-ship model hydrodynamic coefficients also needs to be corrected.

8.5 Suggestions for future research on scale effects

- Collect and investigate model-ship correlation data in manoeuvring.
- Stimulate the research on effect of the propulsion point depending on ship type and scale.
- Develop a method to identify in advance whether model test results will suffer from scale effects or not.
- Identify hydrodynamic coefficients which

have large scale effects and develop their full-scale correction method.

- Investigate a ship-model correlation of hydrodynamic coefficients by CFD.
- Promote research to measure full scale flow into the propeller and rudder during manoeuvres.

8.6 Concluding remarks

There have been occasional researches on scale effects during the past decades. However, recent some studies indicate that the current manoeuvring prediction based on free model test or captive model test could fail to predict a full-scale performance accurately in certain situations. Such risk can be greater especially for unconventional ships with little experience and lack of database.

The proper propulsion point during manoeuvring test is still controversial. Some guideline for choosing optimum propulsion point depending on ship type and scale factor to predict full scale manoeuvring performance is required.

Recent fast development of CFD technology shows a promise in computing full-scale manoeuvring motion in near future. CFD can be a useful tool to clarify scale effects.

It is necessary to establish a standard model-ship correlation method for predicting full-scale manoeuvring performance from model tests. For this, systematic EFD and CFD researches on scale effects are necessary. It is also recommended to promote collection of reliable model-ship correlation data.

9. SLOW SPEED MANOEUVRING MODELS

9.1 Introduction

Nowadays, there are several ship operations in open seas and in harbour that require low speed and high yaw angle manoeuvring conditions. In the offshore operation, it is common to observe this kind of manoeuvring operation with shuttle tankers, ocean tugs, crane barges, etc. However, the mathematical models used for those specific manoeuvring conditions are different from classic manoeuvring models. When a ship navigates with design speed and makes some traditional manoeuvring operation, the drift angle is moderate (e.g. 30 degrees) and hydrodynamic forces can be obtained from conventional manoeuvring model tests. However, when the ship tries to manoeuvre slowly and drifts with large angles using a DP system or with help of tugs, the hydrodynamic forces acting on the hull are completely different from traditional manoeuvring models.

Figure 32 shows a typical variation of lateral force coefficient C_Y with drift angle. Usually, the traditional manoeuvring models focus on moderate drift angles and the lift force domain is more intense although the drag components affect this force. For larger drift angle however, the dominant force is cross drag forces caused by flow separation, as shown in Figure 32.

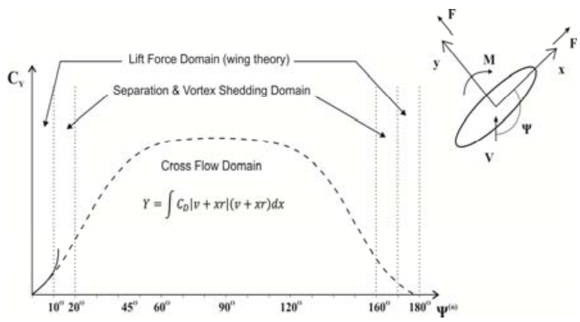

Figure 32: Lateral force variation with drift angle

There are several approaches to obtain mathematical models for slow speed flow and large drift angle: Obokata (1983,1987), Oltmann and Sharma (1984), Jiang et al. (1987), Kobayashi and Assai (1987), Kijima et al. (1987), Wichers (1988), Takashina and

Hirano (1990), Sohn (1992), Hooft (1994), Simos et al. (2001), Tannuri et al. (2001) introduced some different approaches to describe the phenomena. Several combinations of conventional manoeuvring derivatives or methods based on cross flow drag models were used.

Overviews of mathematical models which have been proposed over the years are given by Wichers (1988), Hasegawa (1993), Pawlowski (1996) and Eloot (2006). Different names are given to label the different models. In the overview, it is attempted to give a consistent label to group the mathematical models. Recently, Yoshimura et al. (2009) presented an integrated mathematic model considering both a low speed and a high speed mathematical model that incorporated all domains of hydrodynamic forces so that it can be used for high speed and for low speed manoeuvring with large drift angles.

Those models are very important in the simulation of the manoeuvring of ships in the Harbour Berthing, Anchor Handling Operation, Pipe Laying, Offloading, Subsea Equipment Installation, etc. and on Moored Ship under steady flow. Also in Dynamic Positioning operations, the precise hydrodynamic forces estimation in low speed and high yaw angle has been required. It is clear that every (fast time or full mission) simulator model where ships will perform arbitrary manoeuvres, needs a mathematical model able to handle the large variation of drift angles and yaw rates that will be encountered.

9.2 Mathematical models of low speed and large drift angles

Traditionally, manoeuvring in low speed and large drift angle has been investigated by simulation methods using 3-DOF mathematical models. The hydrodynamic force coefficients are determined by two different formulations. The first one is based on cross flow models and the second one is based on traditional force derivatives, but for low speed manoeuvring models.

Cross Flow Models. The cross flow drag model has been studied by several authors like Oltmann and Sharma (1984), Wichers (1988) and Obokata (1983). Although there are some differences, the concept of the models is the same. The horizontal forces and moment acting on the hull are given by Obokata (1983), for example (for the non-linear part):

$$
\begin{aligned}
&\frac{\partial\varphi}{\partial t}+\frac{1}{2}\left|\nabla\varphi\right|^2+\frac{P}{\rho}+gy=C(t)\\
&X_h'=-\frac{1}{2}\rho T\int_{-L/2-x_G}^{L/2-x_G} Cd_x(\psi_{crx})V_{crx}{}^2dx\\
&Y_h'=-\frac{1}{2}\rho T\int_{-L/2-x_G}^{L/2-x_G} Cd_y(\psi_{crx})V_{crx}{}^2dx\\
&N_h'=-\frac{1}{2}\rho T\int_{-L/2-x_G}^{L/2-x_G}\begin{bmatrix}Cd_y(\psi_{crx})V_{crx}{}^2+\\ -Cd_y(\psi_{cr})V_{cr}{}^2\end{bmatrix}xdx\\
&-\frac{1}{2}\rho DL^2Cd_z(\psi_{cr})V_{cr}{}^2
\end{aligned}
\tag{3}
$$

in which:

$$
\begin{aligned}
&V_{cr}{}^2=u_r{}^2+v_r{}^2\\
&V_{crx}=\sqrt{(u_r)^2+(v+x\,r-V_c\sin\psi_{cr})^2}\\
&\psi_{crx}=\tan^{-1}\left(\frac{v+x\,r-V_c\sin\psi_{cr}}{u_r}\right)
\end{aligned}
\tag{4}
$$

Where: ρ is the water density; L is the ship length; Cd_x (ψ_{crx}) and Cd_y (ψ_{crx}) are the drag hydrodynamic force coefficients on the centre of ship on coordinate system x and y directions, respectively; Cd_z (ψ_{crx}) is the yaw moment coefficient as function of the flow incidence angle ψ_{cr} in the transverse section of coordinate x obtained from towing tank tests, as shown in Figure 33. The differences between the models may be how the pure turning will be defined, because r’ will become infinite. Oltmann and Sharma (1984) applied their method on the ship manoeuvring area, whereas Wichers

(1988) was mainly focussed on offshore applications such as a tanker on a single point mooring. Oltmann and Sharma (1984) and also Karasuno and Igarashi (1993) proposed a much more detailed combination of more meaningful forces components. Also recently, Kim et al. (2009) proposed a cross flow model including shallow water.

A fundamental aspect of the cross flow models, which is overseen by many academic studies such as Kim et al. (2009), is that either the cross flow drag coefficient is not constant as function of drift angle (see Hooft, 1994 and Hooft and Quadvlieg, 1996) or the velocity which is used for the cross flow drag formula is not constant (see Yoshimura et al., 2009).

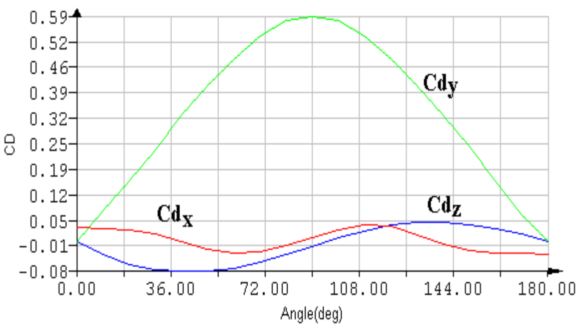

Figure 33: Drag coefficients curves by Nishimoto et al. (2002)

<u>Polynomial Models</u>. Another class of models that represent hydrodynamic forces due to flow and ship relative motion is the manoeuvring models originated by Abkowitz (1964) and Norrbin (1971) using hydrodynamic force derivatives. A low speed manoeuvring model uses hydrodynamic derivatives obtained from different towing tank tests combined with traditional PMM tests. Takashina and Hirano (1990) developed a test methodology called *yaw rotating tests* to obtain the hydrodynamic forces in low speed and high drift angles. The main difference of this model is that it represents hydrodynamic forces derivatives in higher drift angles while traditional models represent hydrodynamic force derivatives only for small or moderate drift angles. Although the model has been developed originally to represent low speed manoeuvring condition, the hydrodynamic similarities make it ideal to be applied also in the analysis of moored ships in current flows. This model, originally developed for the deep water condition, was later modified to take into account the effects of shallow water.

The equations obtained by Takashina and Hirano (1990) for the 3DOF hull hydrodynamic forces and moment are:

$$X_H = \tfrac{1}{2}\rho L T U^2 \left(X'_u u' + X'_{vr} v' r' \right)$$
$$Y_H = \tfrac{1}{2}\rho L T U^2 \begin{pmatrix} Y'_v v' + Y'_{vvv} v'^3 + Y'_{vvvvv} v'^5 \\ + Y'_{ur} u' r' + Y'_{ur|r|} u' r' |r'| + Y'_{v|r|} v' |r'| \end{pmatrix}$$
$$N_H = \tfrac{1}{2}\rho L^2 T U^2 \begin{pmatrix} N'_v v' + N'_{uv} u' v' + N'_{vvv} v'^3 \\ + N'_{uvvv} u' v'^3 + N'_r r' + N'_{r|r|} r' |r'| \\ + N'_{ur|r|} u' r' |r'| + N'_{vvr} v'^2 r' \end{pmatrix} \qquad (5)$$

where u',v' and r' are the non-dimensional surge, sway and yaw velocities, respectively, defined as:

$$u' = \frac{u}{U}, v' = \frac{v}{U}$$
$$r' = \frac{rL}{U} \qquad (6)$$
$$U = \sqrt{u^2 + v^2}$$

The coefficients in equation (5) are known as the non-dimensional hydrodynamic force derivatives similar to those obtained from traditional manoeuvring models or MMG. However, the model as well as the coefficients were obtained from yaw rotating tests instead of pure yaw tests. The forces and moments are taken into account in the model by substituting the absolute surge, sway and yaw velocities, u ,v and r, respectively, in equation (5) by the corresponding relative ones. It is observed that these formulations may approach infinity for the condition of U=0 and r≠0. However, in the longitudinal flow formulation Cdx is the ship advance resistance coefficient that should take into account the Reynolds effects to calculate the hydrodynamic longitudinal force, because this force will affect strongly the dynamics of the ship manoeuvring at low speed.

Fourier Expansion Models. These models consider the hull forces as a combination of sinus and cosinus expansions. Amongst others, Khattab (1987) and more recently Toxopeus (2007, 2011) are using those models. They are in principle a mix of the robustness of cross flow models and the accuracy of polynomial models at smaller drift angles.

Tabular Manoeuvring Models. Tabular mathematical models are models that are based on interpolation in experimental results. Chislett (1996), Eloot and Vantorre (2003) and Eloot (2006) report those models. The forces of those models are stored in logical data structures, non-dimensional (Chislett, 1996 and Eloot, 2006). During the simulation, the simulation software interpolates between these data points using physically motivated parameters.

Models based on RANS CFD. Apart from model test based models, full numeric CFD methodology like URANS or DES can be used to determine the coefficients or forces for low speed manoeuvring models. Several of these techniques are already discussed in section 3.

Pinto-Heredero et al. (2010) showed numerical results of hydrodynamic forces in oblique motion of a ship using a RANS method, but no comparison was made with experimental data. Wang et al. (2009c, 2009d) calculated hydrodynamic forces using RANS in the oblique motion and compared them with experimental results.

9.3 Applications for low speed and large drift angles

In the recent years there were several published papers showing the simulation of ship manoeuvring conditions that are associated with low speed and large yaw angles. However, those papers just report the simulation results and do not clarify the manoeuvring model used to obtain the simulation result.

Bovens et al. (2009) presented a development of the simulator that help training the pilots to make anchor installation using AHV in low speed and high drift angle, but the mathematical models are not explained. Fang and Lee (2009a) showed a numerical approach of the DP system vessel simulator for ROV operations that needs low speed and high drift angle manoeuvring model, but the model presented in the paper is generic without further explanation. Armaoğlu et al. (2009) obtained a mathematical hydrodynamic manoeuvring model for Ship Docking Module (an escort tug). The tug is designed with two azimuthing thrusters and operates at low speed and high drift angle. The captive test to obtain derivatives is described including higher order derivatives. In the area of dynamic positioning there have been multiple papers. Reference is given to the Report of the Ocean Engineering committee for these papers.

It is observed that it would be advantageous to class the mathematical models which are used by these applications. This may in the future lead to a better understanding of the different methods used. Therefore, more investigation about the procedure or, at least, some standardization in obtaining mathematical models for low speed and large drift angle will be desirable.

9.4 Validation data

Since there is no common understanding of the models, the mathematical models used for the low speed and high drift angle manoeuvring simulations are diverse. Mathematical models can be derived from model tests, CFD simulations or even empirical methods. It is observed that most of the validations are carried out on "force level", which means that the forces from the mathematical model forces will typically be compared to forces measured on the physical model. It is very rare that results from actual manoeuvres, i.e. motions, are compared. We refer to the SIMMAN 2008 workshop, where the results of manoeuvring simulations were compared both on force level and on motion level, however, only at speed. Such a validation exercise would require that a series of typical low speed manoeuvres would be selected and standardised to be used to validate the mathematical manoeuvring models.

10. PROCEDURES

10.1 Status of MC QM procedures

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

- 7.5-02-06-02 Captive Model Tests: the procedure was updated recently, no necessary changes found.
- 7.5-02-05-05 Manoeuvrability of HSMV: no necessary changes found.
- 7.5-02-06-01 Free Model Tests: based on the experience from the SIMMAN2008 workshop some changes have been found necessary; a preliminary work has been conducted and could be completed by the next ITTC MC.
- 7.5-02-06-03 Validation of Manoeuvring Simulation Methods: based on the results of the SIMMAN 2008 workshop, the procedure has been updated. The recommended benchmark cases are indicated, whereas benchmark cases that are now obsolete are marked, i.e. it is recommended to perform validation using modern ships with new measurements instead of using the data for the Esso Osaka and Mariner models. Furthermore, the structure of the stepwise validation is clarified and extended.
- 7.5-02-02-01 Full Scale Manoeuvring Trials: no necessary changes found.
- 7.5-02-06-04 Force and Moment Uncertainty Analysis on Captive Model Tests: as mentioned in section 7, the required transfer of existing work towards ISO approach requires a considerable amount of work, which was not available in this ITTC period. Therefore this procedure was not rewritten.

Additionally the MC was given the task to prepare new procedures and guidelines as follows:

- Procedure on Uncertainty Analysis for Free Model Tests: some progress has been made. The theoretical part is completed; pending is the inclusion of an example to complete the procedure.
- Guideline on the Use of RANS Tools for Manoeuvring Prediction: a guideline has been prepared. The methodology of the proposed guideline is described in Section 10.2.
- Guideline on Validation and Verification of RANS tools in the Prediction of Manoeuvring Capabilities: a review of the state of the art has been done; a first draft of the procedure has been written; sources of errors have been identified, different approaches for the evaluation of the uncertainty have been discussed; methodology for the validation of unsteady RANS predictions has also been discussed. This should be used as a starting point by the next MC.
- Draft outlines of procedures for Experimental and Numerical Methods that will serve as a basis for Recommended Procedures for manoeuvring in restricted waters: An overview was produced on the numerical techniques in shallow and restricted waters, however, this has not lead to an outline for a procedure. Experimental techniques have not been treated.

10.2 Guideline on use of RANS tools for manoeuvring prediction

The guideline presents the description of different techniques based in the solution of the unsteady RANS equation to obtain feasible manoeuvring prediction results, either in a direct way in the time domain or used to determine manoeuvring derivatives. The guideline furnishes recommended practices and is dedicated to surface ships in unrestricted waters, where usually only four degrees of freedom (surge, sway, yaw, roll) are relevant for manoeuvring.

Some general considerations which are valid both for the direct simulation of the manoeuvre and for the simulation of forced motion for the estimation on the hydrodynamic derivatives are given first. This overview regards scale effects, the governing equations and in particular their closure by means of a suitable turbulence model, the coordinate frame (computations can be performed either in ship fixed or in earth fixed frame of reference), the boundary conditions and the free surface treatment.

Particular attention has been paid in the considerations made for the propeller model and computational grid used. Indeed, one of the main issues is how to treat the propeller(s). Taking the real geometry of the propeller into account and considering the rotating propeller during the RANS simulation is possible but extremely time consuming. Thus, body forces, which are added to the right hand side of the RANS equations, are frequently used to approximate the effect of the propeller on the flow. Also the choice of the propulsion point can be crucial, selecting the one corresponding to full scale or to model scale, should be decided following similar criteria as for model tests (see procedure 7.5-02-06-02).

Considering the computational grid, it has to be noted that when the turning propeller or a deflecting rudder within direct manoeuvring simulations is to be modelled, a RANS code with sliding grid or overlapping grid capability is needed. Anyhow, it has to be remembered that, whenever possible the grid has to kept unchanged during the computation in order not to deteriorate its quality, which directly influences the convergence behaviour and the quality of the results. However, when this is not possible (for example when considering squat in shallow water or approaching a quay) a suitable grid deformation technique can be an alternative to overlapping grids. Moreover, during the grid generation phase, attention should be paid in the near-wall region, where the grid should be planned, so that the requirements of the used turbulence model are fulfilled.

Considerations have been made for both the direct manoeuvring simulations and for the simulation of forced motion. In the first case, typically rudder manoeuvres like zigzag tests and turning circle tests are simulated by solving the motion equations of the ship together with the RANS equations for the fluid. This kind of manoeuvring simulation is extremely time-consuming but, since there is no mathematical model for the hydrodynamic forces involved, in principle it is easier than by means of manoeuvring derivatives. It may represent the best approach once comprehensively validated. In this context two important aspects deserve attention: the mathematical model describing the ship motion and the coupling between the ship motion and the flow. These aspects are treated thoroughly in the guideline.

The simulation of forced motions can be considered has a valid alternative to the direct simulation of the manoeuvre, mainly due to the enormous computational effort required for the direct simulation. It consists in simulating the usual PMM or CPMC tests numerically by solving the RANS equations around the ship or ship model when performing prescribed motions. The strategy fully resembles the classical, well accepted PMM tests followed by the determination of derivatives and seems already practicable for commercial applications.

Nevertheless a mathematical model (e.g. a set of coefficients of Abkowitz type or coefficients of formulae for the forces of a modular simulation method) is involved, introducing a further source of uncertainty into the prediction. In the guideline an example of this approach is presented.

11. CONCLUSIONS

11.1 Progress in experimental techniques (section 2)

For free model tests on ships with pods, the inclusion of an RPM-control (constant RPM or constant torque) is of prime importance to obtain realistic results. When captive tests are used for the prediction of manoeuvres, it is essential that enough degrees of freedom are considered. Four degrees of freedom (including the roll motion) is already often used. The effect of the roll motion can be very important. For higher speeds, the trim and sinkage can also be very important. The publications show a trend towards increased use of free model tests, even for areas where captive tests have been used up to now, such as high-speed vessels and submarines.

11.2 Progress in simulation techniques (section 3)

Manoeuvring prediction based on virtual PMM, CPMC or CMT tests have become more popular and have proven to be able to yield good results. However they are still only sporadically applied by towing tanks.

Direct simulation of manoeuvres in time domain has become more feasible in terms of computational effort and quality of results. However they are still restricted to research projects.

A systematic validation of RANS based methods for manoeuvring is still needed; few examples can be found for forced motion tests, even less for the direct simulation of manoeuvres. The workshop SIMMAN 2008 represents a step in this direction. The CFD methods seem to perform well, but there were not enough submissions to draw definitive conclusions.

Body force models have been improved and are commonly used instead of rotating propellers as a compromise between computational effort and accuracy. However usual body force models based on flow calculation (e.g. panel codes, vortex lattice methods) seem to underestimate the thrust variations and propeller side forces due to oblique propeller inflow.

11.3 Benchmark data and capabilities of prediction tools (section 4)

The SIMMAN 2008 workshop has given a large amount of valuable benchmark data for the KVLCC1, KVLCC2, KCS and 5415 hull forms. However, some of these data sets still require clarification and correction or replacement with data that meets the nominal conditions that were set up for the workshop.

The overall results from the comparisons with free model tests indicated that there is a large number and variety of methods being used for predicting standard IMO manoeuvres for conventional ship types. However, a larger-than-expected scatter in the results was observed even if ignoring the non-comparable submissions.

The large part of the submissions was based on captive model test data. The results indicated that it is essential that there is consistency between the model test program and the applied mathematical model. No general conclusions could be made regarding the comparative performance between modular methods and whole-ship methods. It could be concluded that it is important to include the 4th degree of freedom, i.e. roll, for ships with low

GM_T.

The workshop confirmed that empirical methods are still in wide use, but it was concluded that they should be applied with caution. Some of these methods can give reasonable predictions, however, only when restricted to the application (i.e. ship type) for which they were developed.

The results indicated that RANS CFD has the potential to provide data fully equivalent to PMM/CMT data to serve as basis for simulations. Also direct simulation of manoeuvres in the time domain showed promising results. However, there were very few submissions based on CFD that were used to predict free manoeuvres, so it is difficult to draw definitive conclusions at this point.

11.4 Manoeuvring and course keeping in waves (section 5)

The requirement for a safe and energy-efficient navigation of ships in real sea conditions has called for a great deal of efforts in investigation on ship manoeuvrability in waves. The rapid development of computational techniques has provided a powerful tool for simulation-based study on ship manoeuvring in waves and accurate prediction of ship manoeuvrability in waves may be achieved in the near future. However, the mechanism of ship manoeuvring motion in waves is not fully understood yet. More experimental research is needed to provide objective benchmark data for comparison and validation purposes.

11.5 Manoeuvring in confined waters (section 6)

Manoeuvring in shallow and confined waters and ship-ship interaction received much attention in the past three years. Even dedicated conferences are organised in this area. The methodologies for model testing and simulation are not the same in various researches. The applicability of RANS tools opens new possibilities, but needs also proper validation.

11.6 Uncertainty Analysis (section 7)

The use of UA for manoeuvring at facilities around the world is slower than expected, judging from the published material.

11.7 Scale effects (section 8)

Some recent research indicates that the present manoeuvring prediction techniques based on free model tests or captive model tests could fail to predict the full-scale performance accurately. This may be due to scale effects. Careful review of the present model test technique is required in view of scale effects.

The proper propulsion point during manoeuvring tests is still controversial. Some guideline for choosing optimum propulsion point to predict full scale manoeuvring performance is required.

Recent fast development of CFD technology shows a promise in computing full-scale manoeuvring motion in the future.

It is necessary to establish a standard model-ship correlation method for predicting full-scale manoeuvring performance from model tests. For this, systematic EFD and CFD researches on scale effects are required.

11.8 Slow speed manoeuvring models (section 9)

Although there are many publications which treat current forces and low speed manoeuvres, the mathematical models used for most of these researches are not explained up to a scientific detail. There are different approaches in mathematical models applied.

Knowing that it is unrealistic that a unification of these models is achieved, a proposal for a label to these groups is made, and it has to be promoted to use these labels for identification of models used in studies. It is recommended to extend this labelling to the Ocean Engineering committee. Adequate experimental validation material for this group of applications would be welcomed, not only on force level, but also on trajectory level. RANS calculations represent an opportunity.

11.9 Procedures (section 10)

A new guideline for "Use of RANS tools for Manoeuvring Prediction" has been written. This should prove useful for ITTC members and others.

A new procedure for "Uncertainty Analysis for Free Model Tests" has been initiated, but not completed.

A new guideline (V&V for RANS tools for Manoeuvring) and a draft outline of a procedure (Numerical Methods in Restricted Waters) have been started. This work will hopefully be a useful basis for the next manoeuvring committee's work.

The procedure 7.5-02-06-03 "Validation of Manoeuvring Simulation Methods" has been updated taking into account the experience gained in SIMMAN 2008.

12. RECOMMENDATIONS

Continue work in order to have a full set of well-documented benchmark model test data i.e. appended hull PMM and CMT tests as well as the corresponding free model tests for each of the four benchmark hulls (KVLCC1, KVLCC2, KCS and 5415).

Capitalize the momentum created by SIMMAN 2008 to continue the development of verification and validation of ship manoeuvring simulation methods, in deep water, but also in shallow and restricted water.

It is recommended to the ITTC that the coming Manoeuvring Committee should propose standard manoeuvres for the validation of low speed manoeuvres.

Adopt the new guideline, "Use of RANS Tools for Manoeuvring Prediction" and the revised guidelines on the validation and verification of mathematical models.

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