Manoeuvrability Committee

Final Report and Recommendations to the 21st ITTC

1. GENERAL

1.1 Membership and Meetings

At the last conference the following seven members: Dr C Coppola; Dr I W Dand; Dr S Grochowalski; Prof. L Kobylinski; Dr U Nienhuis; Dr E Nikolaev; and Dr S Sand retired. Members of the present committee wish to express their appreciation for the work done by these retiring members and for their effort on behalf of past Committees.

The Committee appointed by the 20th ITTC consisted of the following members:

Prof. K Kijima (Chairman)
Kyushu University.
Dr M Renilson (Secretary)
Australian Maritime Engineering CRC
Dr C Aage
Technical University of Denmark
Dr R Barr
Hydronautics Research Inc
Dr G Capurro
CETENA
Dr S Cordier
Bassin D'Essais Des Carenes
Dr M Hirano
Akishima Laboratories Inc
Prof. M Vantorre
University of Ghent
Prof. Wu Xiuheng
Wuhan Transportation University

Committee meetings were held as follows:

11-12 January, 1994, Bassin D'Essais Des Carenes, Paris, France.
5-6 September, 1994, Flanders Hydraulics, Antwerp, Belgium.
22-24 May 1995, Akishima Laboratories, Tokyo, Japan.
1-3 October, 1995, Hydronautics Research, Maryland, USA.
30 January - 2 February, 1996, Australian Maritime College, Tasmania, Australia.

1.2 Recommendations of the 20th ITTC

The recommendations of the 20th ITTC for future work were as follows:

1. Promote and evaluate methods for predicting manoeuvring performance to meet international standards. More work is needed especially with regard to theoretical prediction methods at both concept and detailed design stages and standardisation of models.
2. Promote further work in the manoeuvrability of high speed vessels and propose safety criteria relating to safe manoeuvring.
3. Continue to review the work of regulatory bodies and IMO so that the ITTC can provide unbiased multi-national support to the IMO on ship manoeuvrability.
4. Review new validation work and promote and evaluate relevant uncertainty analysis and benchmark data; the problem of scale effects should continue to receive careful consideration. Standard procedures and codes of practice developed by the Committee should conform to ISO9000.
5. Evaluate likely developments in navigational safety criteria and assess whether such criteria adequately reflect ship manoeuvrability and the extent to which they impinge on ship design.

2. SPECIAL GROUPS

2.1 MARIN Cooperative Research, Ships

During phase I of the project (1993-1994), a manoeuvring prediction program was updated, especially in the description of the non-linear hull forces. Tests on a segmented model were carried out and regression formula were developed to enable a cross-flow drag distribution to be incorporated (Hooft, 1994).

The prediction program is simple to use and provides results rapidly, making it suitable for preliminary design. The program is valid for single screw displacement ships and enables the simulation of all the manoeuvres considered in the IMO Resolution A.751(18).

Validation of the program was carried out with a total of about 30 ships of different type and dimensions. Results showed that the main manoeuvring characteristics are reasonably well predicted for ships with good manoeuvring qualities. Unfortunately, the prediction of the 10/10 zig-zag was still poor and discrepancies were observed for ships which do not meet the interim standards.

With the aim of improving this situation, a phase II project (1995-1996) was started. New segmented model tests on a hull with more modern lines and poor manoeuvring qualities were carried out during 1995. In a second stage, comparative tests with different types of rudders will also be performed.

2.2 SR221

The first task of this panel, established by the Japan Shipbuilding Research Association in 1993, is to develop a precise prediction method for the hydrodynamic forces. A solution method for the Navier-Stokes equation based on the finite-volume approach, is being carried out and these results will be published soon.

The second task will be to develop a prediction method for the interaction between hull, propeller and rudder.

2.3 MOSES

In 1992 the Marine Technology Directorate in the UK commenced phase I of a managed program on Manoeuvrability of Ships and Estimation Schemes (MOSES). This is concerned with improving the predictive capability of various hydrodynamic aspects related to a manoeuvring ship (Hearn and Clark 1993).

MOSES Phase II, which will develop software to assist with manoeuvring at the design stage, and will investigate the effect of local hull form on the manoeuvring characteristics, commenced in June 1994 and will run for two years.

2.4 SNAME Panel H-10

Panel H-10, Ship Controllability, has been collecting trials data over the last three years. It has been integrating these data into its existing PC-based ship trials data base. This effort received significant new impetus when hundreds of high quality trials data sets were received from Denmark. An effort has also been completed to transfer this data base to standard spreadsheet programs.

The Panel held a workshop on ship squat in October 1995. Proceedings of this will be published by SNAME in 1996.

A Panel supported effort to develop a better framework for modular manoeuvring models is nearing completion, and a final report on this work will be published in 1996.

Two cooperative programs with the American Pilot's Association were initiated in 1995. In the first, a number of auto-charting systems will be purchased and installed on US flag ships to evaluate their operation and performance. The second program is to use the expertise of a large number of pilots to evaluate methods currently used to present shipboard manoeuvring data and to develop a better format for pilot cards and wheelhouse posters.

The Panel's other activities include providing support to the US Coast Guard in review of the Explanatory Notes for the IMO Interim Manoeuvring Performance Standards, and to a US Marine Board Committee on *Ship-Bridge Simulation Training.*

3 PREDICTION OF FORCES

3.1 Introduction

A great deal of effort has been devoted to developing theoretical predictions of hull forces by applying advanced techniques. This will allow more precise prediction than the semi-empirical estimate formulae, taking detailed hull form data such as stern configuration into account. These methods will also be able to be applied to shallow water, propeller/hull/rudder interaction etc.

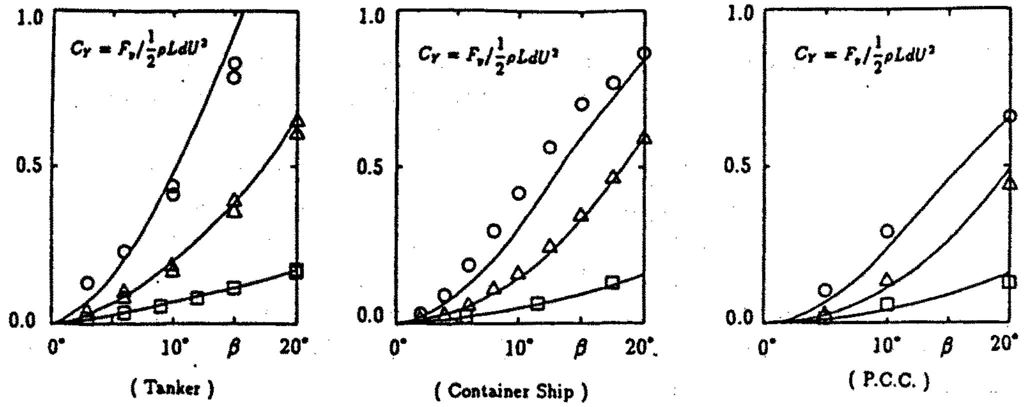
Various approaches of predicting the manoeuvring hydrodynamic forces are reviewed and discussed in this section, focusing mainly on recently-performed studies for theoretical and semi-empirical predictions using both mathematical and physical models.

3.2 Hull Forces in Deep Water

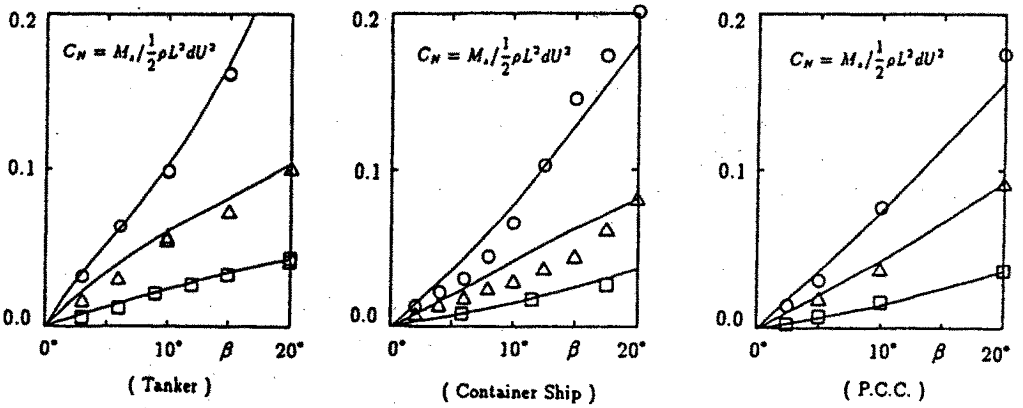
Theoretical Methods. There has currently been a remarkable progress in the area of theoretical predictions of hull forces. In addition to the improvement of prediction methods based on slender body theory, lifting surface theory etc., some new attempts to develop more reasonable prediction methods of hull forces have been begun by applying advanced techniques such as CFD.

Extending slender body theory to include the effects of stern vortices, Hearn & Clark (1993), calculated the linear derivatives and discussed the vortex effects on the lateral force and yaw moment. Landrini (1993) proposed a nonlinear hydrodynamic model for hull forces and discussed basic aspects of ship manoeuvring hydrodynamics through the analysis of the vorticity field.

Nonaka (1993) developed a theoretical prediction of hull forces which was deduced from the basic formulae for the lifting potential flow problem with the slender body assumption. The prediction can also be made for hull forces in shallow water. Computations were performed for the lateral force and yaw moment in oblique towing for both deep and shallow water conditions and compared with experimental results indicating a fairly good agreement as shown in Figure 3.1.



Sway Force (Cal. : ——— Exp. : ○ $H/d = 1.2$, △ $H/d = 1.5$, □ $H/d = \infty$)



Yaw Moment (Cal. : ——— Exp. : ○ $H/d = 1.2$, △ $H/d = 1.5$, □ $H/d = \infty$)

Figure 3.1 Comparison of Hydrodynamic Forces, Computed and Measured (Nonaka. 1993)

Hearn et al.(1994) proposed a calculation method to improve an existing slender body strip method by reflecting the influence of trailing vortices at the stern. This showed good agreement between computations and experiments for the longitudinal distribution of lateral force.

Vorobyov & Drobyshevskiy (1994) calculated hull forces at relatively large sway and yaw velocities for both deep and shallow water conditions, and discussed the validity of the prediction comparing computations with experiments.

Kijima et al. (1994) calculated hull forces with the use of the slender body theory, placing an emphasis on the effects of the generation point for the free vortex. They also examined how to treat the generation point in the computation. They then proposed a calculation method to improve this by employing a new model of the free vortex, and examined its validity, comparing computed results with experimental ones (Kijima et al. 1995).

Applying the panel method using Kelvin singularities, Ba et al. (1992) calculated hydrodynamic forces acting on yawed surface-piercing bodies with forward speed. They examined the effects of body thickness on the hydrodynamic forces. Zou & Söding (1994) calculated the lifting potential flow around 3-D surface-piercing bodies based on the panel method with the use of Rankine singularities, and numerical results were discussed for three kinds of ship hulls.

Applying the panel method, Matsui et al.(1994) presented predictions of hull forces, especially investigating the effects of the free vortex model on the hydrodynamic forces. The validity of the prediction was shown by comparing computations with experiments.

Applying cross flow theory, Kijima & Tanaka (1992) proposed a prediction method for cross flow drag acting on rectangular cross-sections, and the effects of radius of the round edge on hydrodynamic forces were examined. Based on this prediction method, Tanaka & Kijima (1993) calculated the cross flow drag acting on a ship moving transversely, focusing on the longitudinal distribution of the lateral force. Computations were compared with experimental results indicating a good agreement between them in general, as shown in Figure 3.2. The same authors (Tanaka & Kijima 1994) extended the prediction method of cross flow drag cited above to the more general case of the oblique towing condition and showed that computations agreed well with experiments.

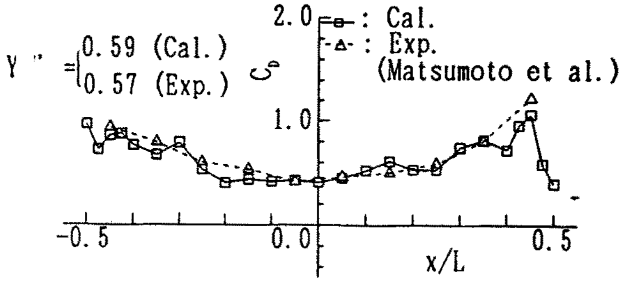


Figure 3.2 Distribution of Cross Flow Drag Coefficients over Ship's Length (Tanaka & Kijima 1993)

Ohmori & Miyata (1993) developed a method of solving the Navier-Stokes equations numerically by making use of the finite-volume method. Applying the solving method of the Navier-Stokes equation cited above, (Ohmori & Miyata (1993)), Ohmori et al. (1994) calculated the flow field around a ship hull in oblique tow. Computations were performed for two full hull forms with different stern shapes. A good agreement was shown between computations and experimental results for both the hull forces and the pressure distribution. The difference in the forces due to the stern shape was predicted well by these computations, as shown in Figure 3.3. Fujino et al. (1995a) extended the method developed by Ohmori et al. (1994) to calculate the flow field around a ship hull in a steady turn. Computations were performed for the same hull forms as used for the oblique tow cited above, and a good agreement between computations and experiments was shown. Fujino et al. (1995b) extended this work and showed the strong influence of hull form on the longitudinal distribution of the lateral force.

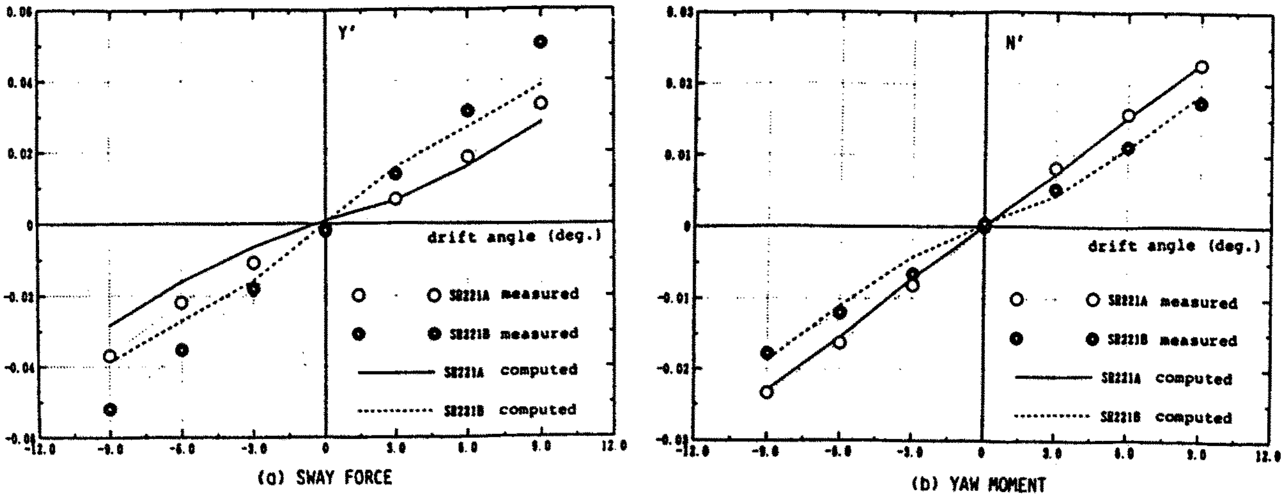
Campana et al. (1993) proposed a calculation method for the free surface flow past a ship hull with a drift angle on the basis of a viscous-inviscid approach. Viscous effects in the wake were considered by Reynolds Averaged Navier-Stokes equations.

Karasuno (1993) proposed a hydrodynamic force model for a ship hull performing a turning motion with a large drift angle. The hull force model consisted of six components of hydrodynamic forces and its validity was examined by comparing computations with experiments.

Yumuro (1993) calculated the hull forces acting on a super-slender twin hull ship based on the linear lifting surface theory and discussed interaction between the twin hulls, comparing computations with experimental results.

Semi-Empirical and Experimental Methods. Kijima et al.(1990) proposed practical estimate formulae for the lateral force and yaw moment in deep and shallow water based on model experiments and low aspect-ratio wing theory.

Kose et al. (1992) developed a database for the prediction of hydrodynamic forces and discussed the level of accuracy possible using the database approach. In order to improve this, they proposed that a database be constructed for each ship type with a similar hull form.



(a) SWAY FORCE

(b) YAW MOMENT

Figure 3.3 Comparison of Hydrodynamic Forces, Computed and Measured (Ohmori et al. 1994)

Measurements of the force on a model of a surface-piecing wing in both deep and shallow water were carried out for both oblique tow and turning motion (Beukelman, 1993, and Beukelman 1995). The experimental results were compared with computations based on potential theory.

Hooft (1994) performed measurements of the cross flow drag with segmented models and examined the longitudinal distribution of the non-linear components of the lateral force.

By comparing the experimental results obtained for three different stern shapes: conventional stern; moderate pram stern; and pram stern, Hooft & Nienhuis (1994) discussed the effects of hull form, and concluded that the linear derivatives are mainly determined by the overall dimensions of a ship hull (Figure 3.4.). It should be noted that this conclusion differs from that found by other authors and reported above.

Sohn & Lee (1994) investigated the hydrodynamic forces acting on a ship with a stern bulb based on the results of captive model tests, and discussed the effects of stern hull form on the hull forces and hull/rudder/propeller interaction.

Nonaka et al. (1995) conducted measurements of the flow field around the stern in oblique towing for three full hull forms with different afterbodies, and showed that the difference of aft hull form significantly affects the hull force characteristics.

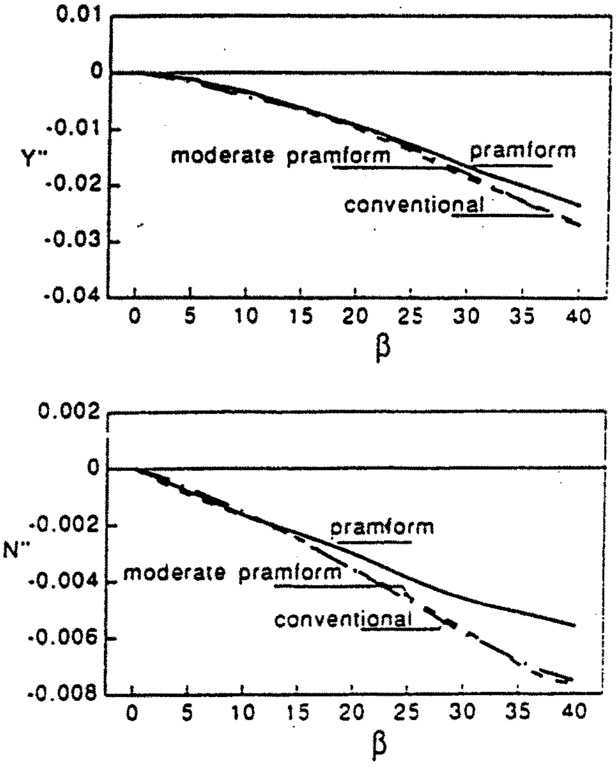


Figure 3.4 Influence of the Stern Form on the Hydrodynamic Forces on a Bare Hull of a Short Full Ship (Hooft & Nienhuis, 1994)

Eda et al.(1979) proposed a hydrodynamic force model with the inclusion of heel effects based on the results of captive model tests. Making use of this hull force model in which the heel effects were reflected only in linear terms of heel angle, they discussed the problem of yaw-roll coupling instability in the autopilot operation.

Hirano & Takashina (1980) proposed a different type of hull force model based on the results of captive model tests [illegible] hich non-linear coupling terms between [illegible], and heel and between yaw and heel play an important role. They investigated the turning ability of a ship with large heel angles using their hydrodynamic force model, and furthermore indicated a possibility of deterioration of the course keeping ability caused by heel coupling effects.

Son & Nomoto (1981) conducted measurement tests of hull forces with the inclusion of heel effects in oblique tow for a high-speed containership and proposed a polynomial hull force model with parameters of sway velocity, yaw angular velocity and heel angle.

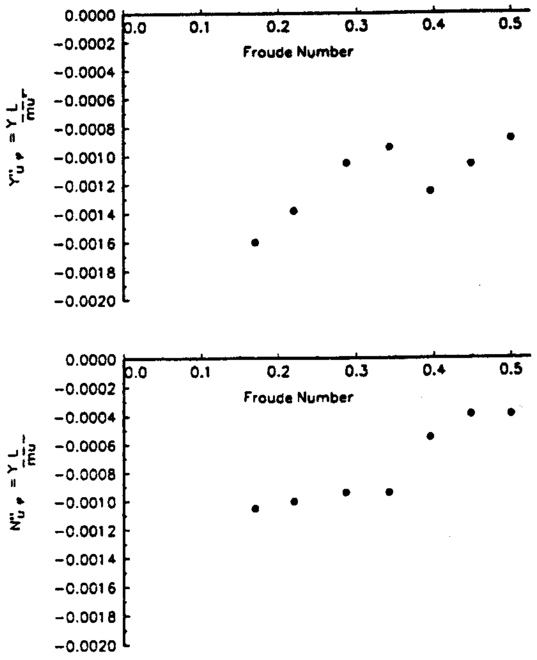


Figure 3.5 Speed Effects on Linear Derivatives for Heel Angle (Renilson & Tuite 1995)

Oltmann (1993) discussed effects of GM on the manoeuvrability of a high speed containership, in which hydrodynamic coefficients including heel coupling terms were determined by systems identification based on experimental results with a free running model.

Renilson & Tuite (1995) performed a broaching simulation with the inclusion of heel effects, in which the hydrodynamic coefficients were obtained by captive model tests. They also discussed speed effects on the linear derivatives of lateral force and yaw moment with respect to heel angle (Figure 3.5). Tuite & Renilson (1995) discussed effects of GM on the manoeuvrability of a high speed containership, for which the hydrodynamic coefficients were obtained by captive model tests.

3.3 Hull Forces in Shallow Water

Theoretical methods. Gong (1994) calculated the linear hydrodynamic coefficients in shallow water, based on slender body theory, and showed good agreement between computations and model experiments.

Applying the Rankine panel method, Zou (1995) calculated the three-dimensional free-surface flow about a yawed ship in shallow water and examined shallow water effects on the lateral force and yaw moment.

Yumuro (1995) proposed a prediction method for hull forces in shallow water based on low aspect-ratio wing theory, and examined prediction accuracy focusing on the effects of the shedding angle of the trailing vortex on the calculation. In addition, as described in section 3.2, Nonaka (1993), and Vorobyov & Drobyshevskiy (1994) calculated hull forces in shallow water based on slender body theory.

Semi-Empirical and Experimental Methods. Preliminary estimates of the hydrodynamic derivatives in shallow water can be obtained by the formulae proposed by Kijima et al.(1990).

Beukelman (1993, 1995) conducted hydrodynamic force measurements for a model of surface-piercing wing in shallow water, and discussed shallow water effects on hydrodynamic forces.

3.4 Hull/Rudder/Propeller Interaction

Theoretical Methods. Applying the non-linear lifting surface theory, Yasukawa (1993) calculated the hydrodynamic forces acting on a thin ship turning in shallow water taking the hull/rudder/propeller interaction into account. They showed good agreement between computational and experimental results.

Kirsten & Sharma (1993) calculated propeller/rudder interaction using a nonlinear vortex lattice method, and discussed the effects of propeller slipstream on the rudder load distribution.

Yasukawa (1994) calculated the rudder forces taking into account hull/rudder/propeller interaction. Lifting surface theory was applied for the hull and rudder forces, and the sink model was applied for the propeller forces.

Yang et al. (1994) developed a theoretical prediction of hull/propeller/rudder interaction in oblique towing using a panel method for hull force calculation. This was extended by Matsui et al. (1995) to the case of steady turning, in which a panel method was applied for the hull and rudder force calculation. They proposed a method to predict the hydrodynamic interaction coefficients.

Experimental Methods. Molland & Turnock (1994a) performed wind tunnel experiments for rudder/propeller interaction at low speeds in the four quadrants of propeller operation, and investigated the effects of propeller operation on rudder performance. The same authors (Molland & Turnock 1994b) discussed how to use the rudder/propeller interaction data for rudder design and ship manoeuvring simulation.

Yumuro (1994) conducted measurements of rudder forces behind a propeller in shallow water, and examined the shallow water effects on rudder forces, including the flow-straightening coefficients. He showed comparisons of experimental results with theoretical calculations.

Lee et al. (1994) investigated propeller/rudder interaction on the basis of captive model tests in a circulating water channel, and discussed a mathematical model for the effective wake fraction at the propeller and the effective rudder inflow angle.

Nakatake et al. (1995) performed measurements of flow velocities at the propeller plane in oblique towing, and discussed the effects of drift angle on the wake distribution and wake fraction.

3.5 Forces by Means of Control

Rudder. Kang (1993) calculated the lift forces on a 2-D flap rudder and discussed the effects of a gap between the fore and aft parts of the rudder.

Willis et al. (1994) calculated the hydrodynamic forces acting on a rudder by applying the vortex lattice method. They examined the characteristics of the rudder side force, including the effects of a plate above the rudder and a deadwood ahead of the rudder.

Xu & Zhang (1994) performed tests on a rotating cylinder rudder and showed it had much higher lift force than the conventional rudder.

Zhu & Wang (1994) conducted model experiments for the hydrodynamic forces on a circulation controlled rudder, showing it had higher lift characteristics than a conventional rudder.

Thruster. With respect to the thruster forces acting on the lower hull of an offshore platform, Furukawa & Kijima (1993) proposed a theoretical prediction method based on non-linear lifting surface theory, together with a source distribution over the hull surface taking the interaction between the thruster jet and lower hull into consideration. They showed that their computations agreed with experimental results for forward speed effects. Kijima & Furukawa (1994) extended the prediction method to the case of a thruster within a ship hull (Figure 3.6).

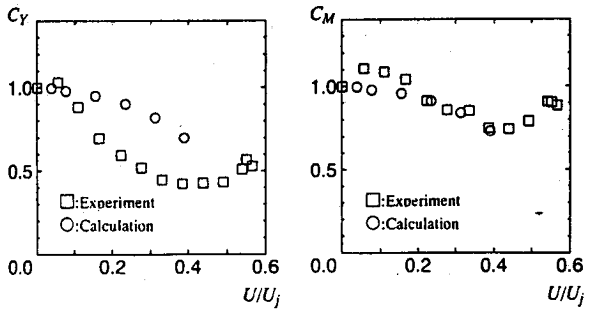


Figure 3.6 Lateral Force and Yaw Moment from a Thruster (Kijima & Furukawa, 1994)

Tug and Others. Brandner & Renilson (1993 and 1994) discussed the hydrodynamic aspects of shiphandling tugs for an omni-directional stern drive tug using performance envelopes in which tug hull forces were obtained by model experiments.

Dupuis & Goodkey (1993) developed a prediction method for the hydrodynamic forces generated by a minehunter's cycloidal vertical axis propeller, and discussed the propeller operating system's control algorithms.

Cordier et al. (1994) calculated the performance of a fin on a ship hull with the use of different numerical approaches, and discussed the validity of those approaches, comparing computations with experimental results.

Pan & Zhang (1994) conducted force measurements acting on a circulation controllable hull and noted that it produced a larger turning moment than a conventional hull with rudder.

Cordier et al. (1995) proposed a simplified method of numerical calculation of the forces on a fin in which the fin is replaced by its equivalent force field in the Reynolds Averaged Navier-Stokes simulation used for the viscous flow around a hull. They showed encouraging results by comparing with computations based on a fully meshed fin.

3.6 Interaction Effects

Forces between Two Ships. Applying slender body theory, Zheng (1994) proposed a calculation method for the hydrodynamic interactions between two ships in restricted water, and compared the computed results with those from experiments.

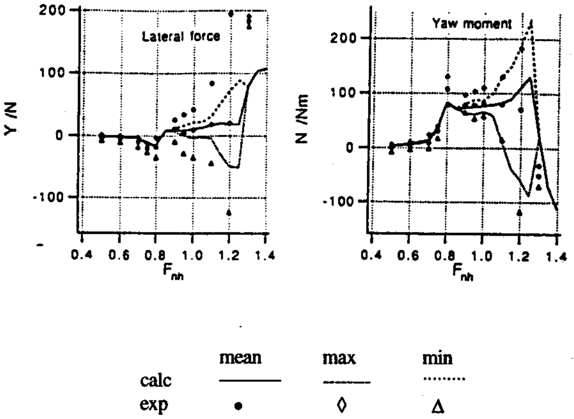


Figure 3.7 Comparison of Computed and Measured Hydrodynamic Forces (Jiang et al. 1994)

Bank Effects. Ch'ng et al. (1993) conducted a series of model experiments to measure the ship/bank interaction forces in restricted water by varying six parameters such as ship-to-bank distance, water depth etc. Based on the experimental data, empirical equations were developed to estimate the hydrodynamic forces in restricted water. Ch'ng & Renilson (1993) conducted measurements of the lateral force and yaw moment on a ship in astern operation in restricted water and discussed the effects of astern revolutions on the hull forces in restricted water.

Jiang et al. (1994) calculated the lateral force and yaw moment acting on a slender ship moving at high speed in a restricted water, based on the technique of matched asymptotic expansions. They discussed hull force characteristics which vary with the Froude number - especially in the critical speed range -

showing comparisons of computations with experiments (Figure 3.7).

Xiong & Wu (1994) calculated the hydrodynamic forces on a ship moving parallel to the banks by applying the panel method with the use of Rankine singularities in which the free surface was incorporated.

Vantorre (1995) proposed a mathematical model to estimate the hydrodynamic forces in a canal based on captive model tests, and discussed the effects of drift angle and rudder action.

3.7 External Forces

Wind. Blendermann (1994) made a parametric study of the wind forces on ships based on wind tunnel tests and proposed a semi-empirical loading function.

Wave. Hirayama & Kim (1994) proposed a method of predicting wave drift forces for short wavelengths on the basis of existing formulae for resistance increase in waves, and investigated the manoeuvrability of a full ship in short waves with a directional spectrum.

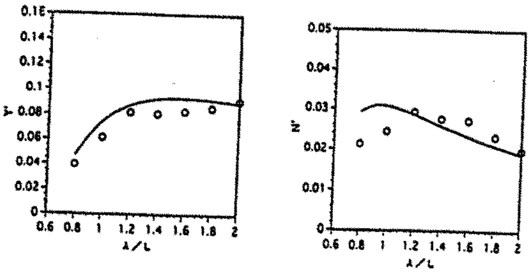


Figure 3.8 Comparison of Wave-induced Hydrodynamic Forces, Computed (o) and Measured (—) (Umeda et al. 1995)

Ann & Rhee (1994) calculated the second order wave drift forces by applying the 3-D panel method, and discussed ship manoeuvrability in waves.

Umeda et al. (1995) systematically carried out wave force measurements acting on a ship in quartering waves with zero and very small encounter frequencies. Measured results were compared with computations obtained using a prediction method proposed by the authors. This showed a fairy good agreement as can be seen in Figure 3.8.

4. SIMULATION OF DYNAMICS

4.1 Introduction

Current work on ship manoeuvring simulation models is primarily evolutionary, rather than revolutionary, in nature, but rapid developments are being made in important areas such as the modeling of human operators.

The development of simulation methods is currently being driven primarily by the need to support ship manoeuvring simulators and the need to determine, during its design, the ability of a ship to meet the new IMO Interim Manoeuvring Performance Standards as discussed in Section 7.

4.2 Modeling of Ship Dynamics

Significant activity continues in the field of simulation model development. This activity includes combining of manoeuvring/seakeeping simulation models, development of new bases for the equations of motion, refined treatment of force terms in existing models, expansion of the capability of existing models through addition of tugs, and propulsion/manoeuvring devices.

Simulation methods are being developed for an ever-widening range of non-conventional ship types. Section 5 provides a description of such models for SWATHs, hovercraft and sailing yachts.

Equations of Motion and Degrees-of-Freedom. Previously, simulations have been carried out for low and moderate speed ships using primarily coupled, three-degree-of-freedom (3DOF) surge-sway-yaw equations of motion in body axes. 4DOF equations, which include roll, have typically been used only for fast ships. Use of 4DOF equations including roll motion and coupling is now increasing, particularly in wind and waves. Renilson & Tuite (1995) have documented the effect of including roll on coursekeeping of a trawler in following waves.

Oltmann (1993) proposed a generalised set of 4DOF equations of motion. This simulation model gives results that are in excellent agreement with model data and fairly good agreement with ship trials turns. Using this simulation model, Oltmann demonstrated that for a 240 metre long containership operating at a speed of 16 knots, GM and roll, have a rather profound effect on manoeuvring, Figure 4.1.

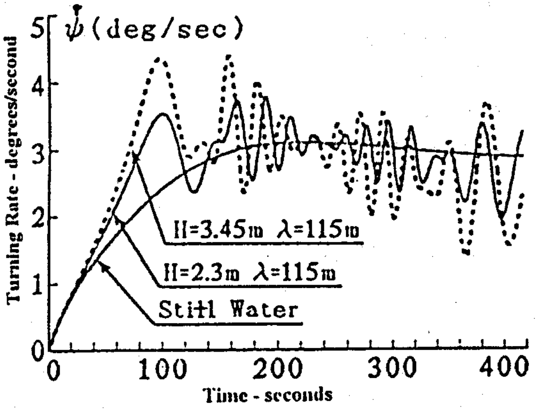


Figure 4.1 Variation of Turning Rate with GM (Oltmann 1993)

At one time a rather heated debate existed about the relative merits of cubic and square-ıbsolute non-linear damping terms. Today, ›ore and more simulation equations include ›oth types of damping terms, Barr (1993). Table 4.1 illustrates these types of sway damping models.

a. Square Absolute Damping

$$F(y) = Y_v' uv + Y_{vv}' v v + Y_r' ur + Y_{rr}' r r + + Y_{vr}' v r$$

b. Cubic Damping

$$F(y) = Y_v' v + Y_{vvv}' vvv + Y_r' r + Y_{rrr}' rrr + + Y_{vrr}' vrr + Y_{vvr}' vvr$$

c. Square Damping with Cubic Term(s)

$$F(y) = Y_v' uv + Y_{vv}' v v + Y_r' ur + Y_{rr}' r r + + Y_{vr}' v r + Y_{vrr}' vrr$$

Table 4.1 Comparison of Alternative Forms of Sway Damping (Barr 1993)

Jensen, et al (1993) provide an overview of Den-Mark 1, a comprehensive simulation method which uses look-up tables for prediction of forces. The method treats motions in six-degrees-of-freedom, and includes 22 effects which are characterised by more than 5000 variables.

Hooft & Nienhuis (1994) employ non-linear damping forces determined using stripwise-integration of crossflow drag. A comparison of turning performance parameters obtained using their simulation program and full scale trials data, Figure 4.2, indicates good agreement for ships with block coefficients between about 0.6 and 0.8, but rather poor agreement for the finest and fullest ships considered. Agreement is fair for the first overshoot angle and rather poor for the second overshoot angle for zig-zag manoeuvres of a very full ship, as seen in Table 4.2.

Whole Ship versus Modular Models Modular simulation models, which treat separately the forces acting on the hull, rudder and propeller (the modules), are assuming a dominant role compared with whole ship simulation models which are based on total forces acting on the hull, rudder and propeller. The goal of most recent modular model developers is to use available model test data and empirical or theoretical/empirical methods to predict forces acting on the rudder, propeller, and the hull, and all interaction forces between these modules. Sedat & Fuller (1994) discuss various modular models.

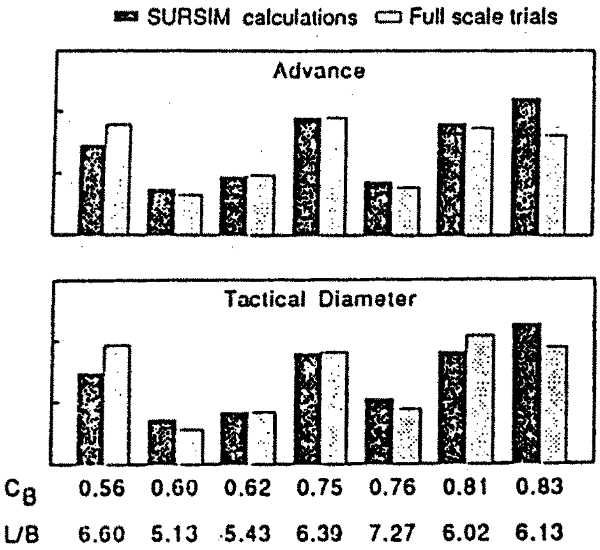


Figure 4.2 Comparison of Simulated and Trials Results for Turning Manoeuvres for 8 Ships (Hooft & Nienhuis, 1994)

Description of manoeuvre	First overshoot angle		Second overshoot angle	
	Model tests	Simulations	Model tests	Simulations
SPP of [illegible] constant [illegible]				
20/20 P	42	40	20	47
20/20 SB	31	40	30	47
10/10 P	40	35	28	63
10/10 SB	21	35	>55	63

Table 4.2 Comparison of Simulation and Model Results for Zig-Zag Manoeuvre for a Full Ship (Hooft & Nienhuis, 1994)

Kaplan & Ankudinov (1995) present a modular model intended to be more firmly based on theory than previous models. However, initial, limited results indicate somewhat disappointing agreement between simulated and trials trajectories for deep water turning of the Esso Osaka. Kijima (1993) presents a modular model which can be applied to all loading conditions. Results of simulated 10-10 zig-zags for a ULCC, Figure 4-3, indicate generally good agreement for most loading conditions considered, including results for a case with three percent trim. Agreement for the first overshoot angle is excellent for all six loading conditions considered.

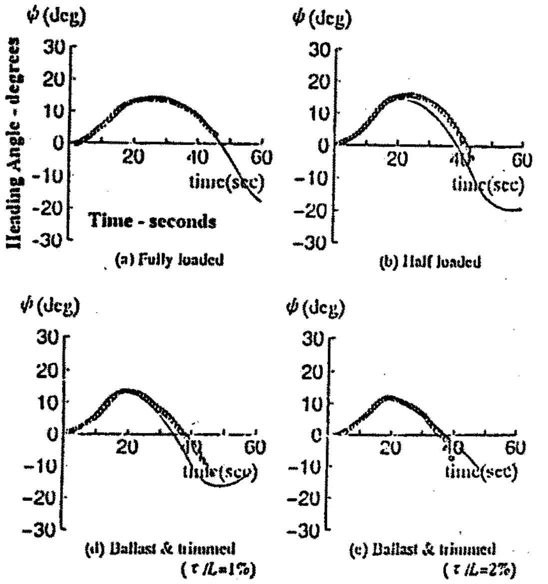


Figure 4.3 Comparison of Simulation and Model Test Results for 10/10 Zig-zags for Various Loadings (Kijima, et al 1993)

A crucial requirement for modular models is the ability to accurately predict hull-rudder-propeller-controller inter-action. Some recent developments in the prediction of these interactions are described by Molland & Turnock (1994), Yasukawa (1994) and Yang, et al (1994). Vantorre (1995a) describes use of multi-modal captive model tests and Vantorre, et al (1995) discuss use of systematic model tests for evaluation of rudder/hull propeller simulation models. Hirano, et al (1995) discuss the behaviour of open-stern tankers and conclude that the effect of stern shape is large, and that simulations for such hull forms must be based on suitable force data and coefficients. Sohn & Lee (1994) discuss manoeuvring simulations for a ship with a stern bulb.

Enhancement Features. The capability of most simulation models increases with time as new features are added. These may include treatment of unusual propulsors and manoeuvring devices, propulsion and manoeuvring machinery dynamics, moorings, anchors and towing lines, tugs and mooring structures.

It is now recognised that memory effects can be important for high speed manoeuvring where significant wavemaking occurs, when the effect of wave frequency motions is considered or when energy dissipation mechanisms are present. Vantorre (1992) has discussed the implementation of non-stationary forces or memory effects in manoeuvring simulation models and Laforce & Vantorre (1994) have discussed the treatment of such forces in the simulation of ship contact with quay wall fendering.

Ottosson (1994) has outlined a PC based simulation model which is used to simulate ship behaviour during harbour transit and docking. This includes the effects on ship dynamics of all types of environmental influences, various types of steering devices, fenders and quays, and complex arrays of tugs. No calculated results or validation are provided. Brandner & Renilson (1993) discuss simulation of tug assisted manoeuvres and Varyani (1994) discusses towing simulations. Simulation of external forces due to mooring and warping lines are discussed by Dand (1993).

Difficulties met during the simulation of backward manoeuvres, with emphasis on hull/propeller/rudder interaction were investigated by Baumgarten (1994).

Greater attention is now being directed to accurate simulation of machinery dynamics. Turner (1993) describes a machinery simulation model suitable for use in modular manoeuvring simulations, and Zhang & Weng (1994) describe simulation methods using parallel computers for ship and machinery. Yoshimura, et al (1993) present results of simulations for the coasting behaviour of a single-screw ship in which the CPP wheel is set to zero pitch angle to slow the ship. Figure 4.4 indicates that the resulting simulation model predicts general behaviour of the ship but does not accurately predict the track as the ship slows.

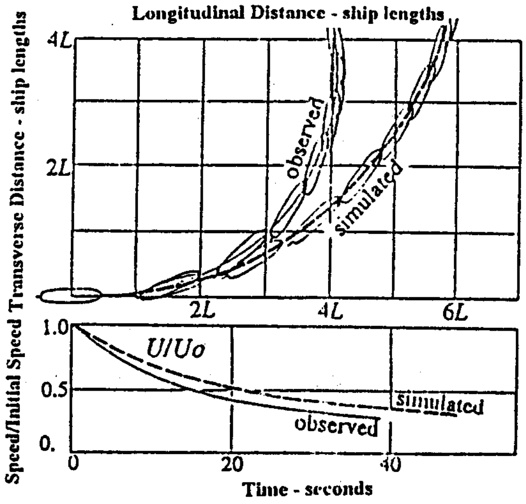


Figure 4.4 Comparison of Results for Coasting Turn (Yoshimura, et al 1993)

A number of investigators including Kijima, et al (1995), Kose & Yang (1995), Grabowski and Sanborn (1994), Papenhuijzen (1994), Zhang & Xu (1994), Papoulias (1994), Shouji & Ohtsu (1993), Hasegawa and Kitera (1993) & Kasai (1993) have discussed development of piloting models, autopilots or controllers for piloting, collision avoidance, berthing and dynamic positioning. These models are based on a wide variety of methods including optimal control theory, expert systems, neural networks. More details on some of this work is given in Section 7. Webster (1992) discussed the problems in developing a general, adaptive model of a human pilot - despite this level of intense activity, a valid piloting model does not yet appear to exist.

4.3 Modeling of External Influences

The physical environment in which a ship operates has a significant effect on ship behaviour and safety. This environment includes both local topography, local wind, waves and currents, and other ship traffic. Simulation of ship behaviour for realistic operating conditions will require inclusion of these factors.

Restricted Water Influences Little reliable model test data exist for underkeel clearances less than 15 to 20 percent of draft, and even less data exist for non-rigid, deformable, bottoms (see Section 7).

Gronarz (1993) investigated the use of interpolation/extrapolation methods and polynomial fits for estimating coefficients at arbitrary draft-depth ratios, Figure 4.5. From these results it can be observed that interpolation is preferred within the range of the test data but that carefully derived polynomial fits will probably give the best results outside the range of data.

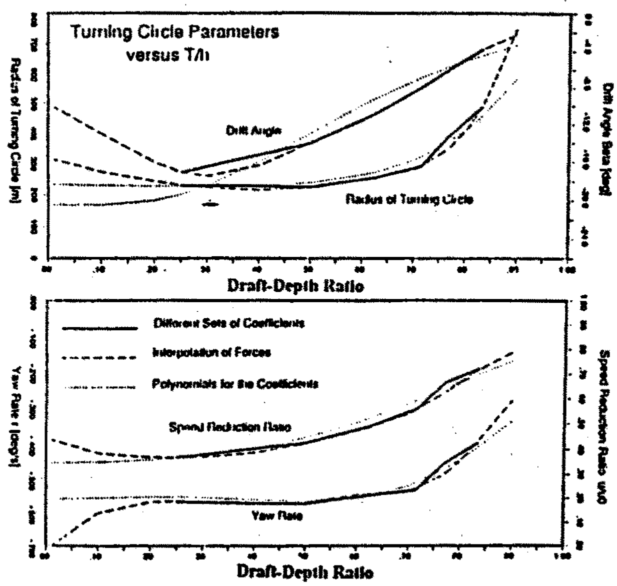


Figure 4.5 Effect of Alternative Methods for Modeling Variation of Forces with Depth on Turning (Gronarz 1993)

Vantorre (1995b) and Ch'ng, et al (1993) discuss force modelling for operation near banks. Vorobyov & Drobyshevskiy (1994) describe a method for simulating restricted water manoeuvring and indicate good agreement of simulated and ship trials results for a twin-screw ship.

Environmental Influences. Critical ship manoeuvring typically takes place in the presence of waves, wind and/or current. Most simulation models now include some means for modelling the effect of at least current and wind. Inclusion of the effect of waves has received much recent attention.

Prediction of first-order wave-induced forces in the time-domain requires the use of convolution integrals which are computationally demanding and not always compatible with real-time simulations. These integrals can be replaced with algebraic series, or approximated by the Froude-Krylov forces which can be directly evaluated in the time-domain. Ann & Rhee (1994) discuss the use of 3-D panel Methods for analysis of manoeuvring in waves.

In order to facilitate prediction of ship manoeuvring in waves, Hamamoto & Kim (1993) have proposed the use of Horizontal Body Axes which are identical to normal body axes except that the origin remains at the CG, rather than the undisturbed free surface as the ship heaves. Their results (figure 4.6) indicate the expected moderate distortions of turning and zig-zag manoeuvres and rather large wave frequency modulations of heading and yaw rate.

Kobayashi (1993) also describes a simulation method for evaluating manoeuvring in waves. His results indicate general agreement between simulated and measured lateral drift due to bow waves, but rather poor agreement of simulated and measured first-order wave-induced roll motions. Other developments in simulation of manoeuvring in waves are described by Renilson & Tuite (1995), Ambrossovski & Rumyantzev (1994) and Hamamoto, et al (1994), which present results for course-keeping in waves, and by Kopp (1993).

Laforce (1992) describes factors to be considered in the simulation of wind effects in the complex physical environment of a harbour. Ochi (1993) discusses measured over-ocean wind spectra and concludes that the peak energy of the unsteady wind occurs at a much lower frequency than predicted by commonly used spectra such as those of Davenport (1961) and Harris (1968).

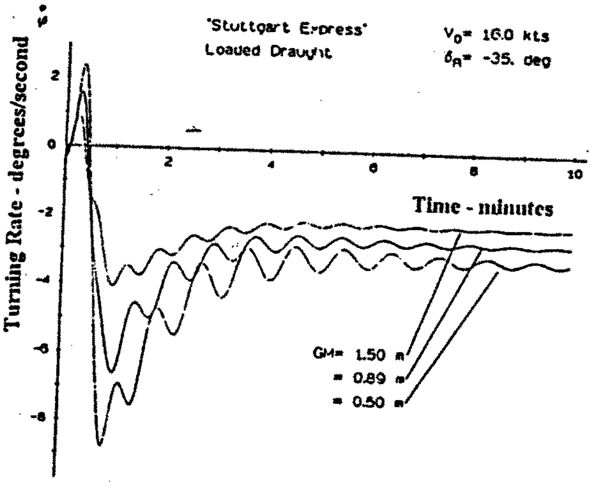


Figure 4.6 Variation of Simulated Yaw Rate with Wave Height during Turning Manoeuvre (Hamamoto & Kim 1993)

4.4 Validation of simulators and simulation models

Since the limitation of most simulation models is not in their ability to predict definitive manoeuvres in open water, but to adequately reproduce real manoeuvres in restricted waters involving rapid and irregular changes in helm and throttle commands, it is still necessary to rely heavily on mariners as the final judge of validity or fidelity. Webster & Young (1993) state that:

> *validation is performed subjectively, often by pilots themselves, but preferably by a selected team of experts.....who observe and evaluate the simulation; and validation is usually an iterative process in which aspects of the mathematical model and physical components of the display are refined until consensus is reached.*

This is discussed further in section 6.

5. NON-CONVENTIONAL CRAFT

5.1 Introduction

Given the variety of non-conventional craft and of their maneuvering problems, it is not surprising that knowledge in this area is much more sparse and less detailed than in the case of conventional (monohull, displacement) ships.

A large part of this section covers developments in high speed craft caused by renewed interest for high-speed transportation.

Submersibles, and in particular, AUVs have also been the subject of numerous recent studies.

Finally, the intense efforts carried out to conquer the America's Cup and to improve sailing craft performance has brought several published contributions in the field of maneuvering: forces of a yawed and heeled sailing craft.

5.2 High Speed Craft

Test Techniques The recent interest in high-speed craft has brought new urgency in understanding and resolving problems associated with the maneuverability of these craft.

Although the use of PMM facilities for fast craft can be limited because of model size, speed, or frequency of motions, this type of equipment can be used to obtain the hydrodynamic coefficients of high-speed craft (Ishiguro, 1993).

Rotating arm facilities are particularly well adapted to high speed vessel testing because of the possibility to run at high speed in steady conditions for a relatively long time, Lewandowski (1994).

In order to assess the dynamic transverse stability of fast monohulls, laboratories have developed special dynamometers which usually restrain the model in sway and yaw. Roll motion (Werenskiold, 1993) or rolling moments (Washio, 1993) are measured at different heel angles while being towed. Because of the necessity to run at high-speed, and to model the effect of the propulsor, free, self-propelled models are being used more intensively. Since the self-propelled models are also used for powering studies, large models are preferable to reduce scale effects (Abrahamson, 1992). Given the size and speed of these models, laboratory test facilities are too small and the experiments are performed on lakes or sheltered waters with radio-controlled models. An example of the type of model used is shown on Figure 5.1 in the case of a hydrofoil ship.

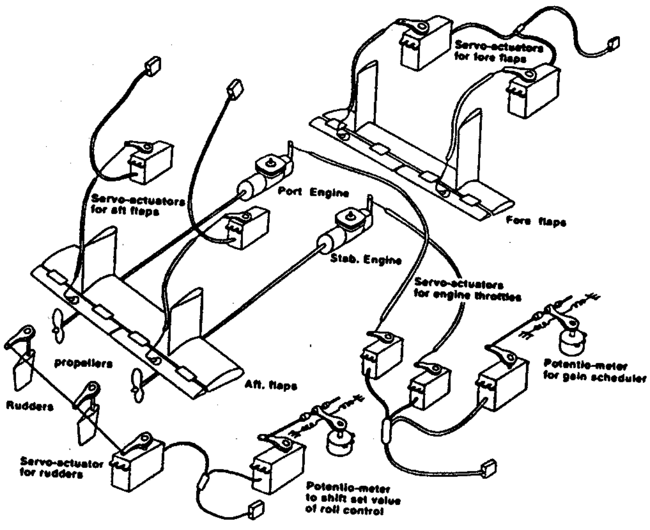


Figure 5.1 Radio Controlled Hydrofoil Model with Actuators (Toki, 1993)

In addition to radio-controlled models, for large projects such as the Techno Super Liner concepts (SES, Ozawa 1993, and the HYSWAS, Kaji, 1992) or other concepts such as high-speed catamarans (Ishiguro, 1993, Yamamoto, 1993), or hydrofoil ships (Kihara, 1993), manned prototype "models" are also built. These prototypes are used to evaluate propulsion, seakeeping, and manoeuvring performance and to test the capacities of ride control systems in manoeuvres, particularly when hydrofoils are concerned.

The use of tests outside laboratories has been facilitated by developments in trajectography technology such as Differential Global Positioning System (DGPS) or "Raydist" (Capurro, 1993) which can achieve high levels of accuracy. DGPS is claimed to be accurate to better than 1 m according to Kobayashi (1995).

Planing Craft Interest in planing craft maneuverability has risen recently with the increase in size of civilian vessels (Moret, 1993). Also, the drive to minimise craft resistance, has created a need for precise methods for dimensioning skegs and rudders.

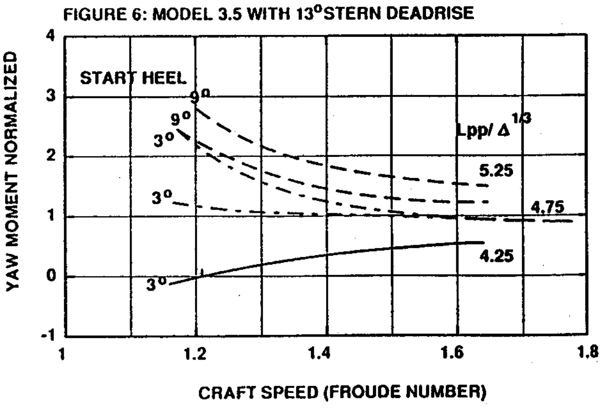


Figure 5.2: Yaw moment versus craft speed - influence of initial heel angle and of displacement (Werenskiold, 1993).

The manoeuvring of planing craft is characterised by large roll motions and associated variations in underwater hull form which are speed dependent and markedly increase the difficulty of generating accurate manoeuvrability models. The transverse stability is primarily dependent on hull shape, rudder and propulsor forces, and centre of gravity location. A discussion of the influence of hull shape can be found in the 18th ITTC. New data shows how initial heel and displacement significantly influence yawing moments (Figure 5.2). This work also shows how the rudder forces needed to counter hull yawing moments significantly reduce dynamic stability. Further evidence of this coupling and of the effect of KG is shown on Figure 5.3. Washio (1993), shows how the presence of "flap shines" and spray strips improve the dynamic transverse stability of a planing craft.

The coupling with transverse stability is of primary importance since it involves safety. IMO has issued a statement regarding this aspect of the problem[1] although it does not specify which trials would be needed. Based on his studies, Werenskiold (1993) suggests possible full-scale trial procedures to assess planing craft dynamic stability. In particular, he proposes running tests starting from a static heel angle of 3° and checking that heel does not exceed 10° at 100% RPM (8° at 90% RPM). He also recommends using rudder forces to keep on a straight course so that the rudder rolling moment is included.

Several models of the behaviour of a planing craft in turns have been proposed recently. Denny (1991), developed a simple relationship between speed loss in turns and turning radius based on full scale data on 12 craft where he introduces the semi-empirical constant K_C which is, in effect, a measure of rudder effectiveness:

$$\left(\frac{U_C}{U_A}\right)^2 = 1/\left[1+K_C\left(\frac{L}{R_C}\right)^2\right] \text{ with } K_C = \frac{30.F_{n\nabla}^2}{\alpha}$$

U_C : steady speed in turn U_A : approach speed

L : craft length R_C : turning radius

α : rudder angle in deg. $F_{n\nabla}$: displ. Froude number

Capurro (1993), compared this model with independent full-scale tactical diameter trial data using measured speed reductions and found poor correlation. More detailed modelling of rudder effectiveness, propulsor type, hull shape, and roll coupling may be needed in order to increase the generality of this type of method.

Lewandosky (1994), proposes a more detailed 4DOF model of a planing craft which is written in the craft's co-ordinate system. The necessary hydrodynamic coefficients are obtained through extensive rotating arm tests.

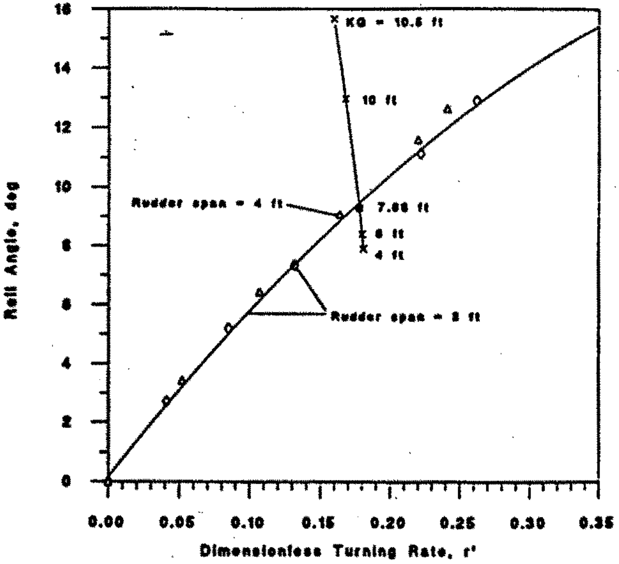


Figure 5.3: Roll angle versus yaw rate - influence of KG (Lewandowski, 1994)

In a more general but simplified approach, Nakato (1993), has generated a 6DOF model of a racing craft introducing both wind and wave forces in order to predict the envelope of safe operation. In this original approach, hull forces are simplified based on the instantaneous wetted surface of the craft. Because of the very shallow hull draft, the hull transverse force and moment are essentially provided by the appendages.

While the generalised use of waterjets and the suppression of rudders may simplify the

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[1] IMO - HSC code: "The roll and pitch stability on the first or other craft of a series should be qualitatively assessed in safety trials. The results of such trials may indicate the need to impose operationnal limitations"

problem of propulsor and rudder forces on recent constructions, the knowledge of the complete hull hydrodynamic force tensor will require further study in order to achieve accurate predictive tools for planing craft manoeuvrability.

Hydrofoil The work recently published on the manoeuvrability of hydrofoil craft is mainly concerned with industrial projects with very few basic research oriented papers. This trend shows the maturity of the hydrofoil ride control technology which typically yields excellent manoeuvring ability.

Hamamoto (1993), presents a 5DOF model of hydrofoil craft with a large surface piercing foil in front and a smaller T foil astern. A detailed analysis of the foil forces is carried out in order to derive a model which is linearized and reduces to 2 independent systems of equations, one of them containing the roll, sway, yaw degrees of freedom. The roots of this system of equations are found and directional stability is established using the root locus method. The rudder effectiveness $(\frac{\partial\psi}{\partial\delta})$ calculated by the model is compared to experimental data obtained on a radio controlled model. The assumption of constant speed seems to be a heavy limitation in a model where the speed dependence is large. Further comparison with experimental data would be desirable.

The large submerged hydrofoil craft project Super-Shuttle 400 gave rise to an original control system development starting with tests with a 1.2m, propeller driven, radio controlled model. Further developments using a 3m model in a towing tank allowed for simulations of take-off and ride control stability. The tuning ability of the craft was verified during full-scale trials (Kihara, 1993).

The HYSWAS type craft is similar to a submerged hydrofoil craft because the strut(s) typically will not offer any stiffness and the ship is essentially flying. The main difference will come from the submerged float which will generate hydrodynamic forces during manoeuvres. The development of the control system was tested on a 1/20th scale self-propelled radio-controlled model (Figure 5.4) on which take-off, turns, zig-zag, and splash-down manoeuvres were performed.

Air Cushion Vehicles Few recent references are available on the subject of ACV manoeuvrability which is governed by skirt friction, which is particularly difficult to predict, and aerodynamic superstructure, propulsion, and rudder forces. Murao (1993) derives a model of a loop segmented skirt shape based on the equilibrium of internal forces in the cushion. This model is used to calculate the skirt contact area with a surface which is assumed rigid. Using a more experimental approach Yoshino (1993) showed how a constitutive model of the dynamics of an ACV can be derived from model tests: cushion forces in a towing tank, superstructure, propeller and rudder forces in a wind tunnel. The simulations are compared to sea trial performance where the importance of initial ship speed on advance and tactica diameter is clearly shown.

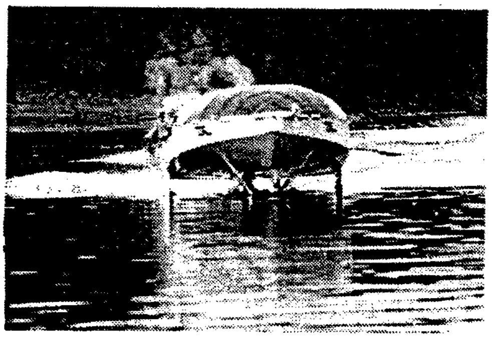

Figure 5.4: HYSWAS model in a turn (Kaji, 1993)

Surface Effect Ship As for other types of ships, the more recent work concerns large projects which required extensive studies on models and prototypes. This is the case for the TSL-A project where a 6DOF mathematical model was derived based on model tests (Sakamoto, 1992) and verification of the craft performance were later performed on a 12.7m, 9t, 23kts, manned model (Ozawa, 1993). The model results show a large dependence of yaw moment on trim angle for the model in oblique tow. The results of tactical diameter manoeuvres on the manned model are shown on Figure 5.5 where surprisingly little speed dependence is noticeable.

Mølgaard & Chislett (1994) investigated the steering and manoeuvring performance of a large Surface Effect Ship by means of captive model tests and numerical simulation of standard manoeuvres. The results of the simulations indicated that the vessel's steering and manoeuvring performance is typical of a fast vessel with trim by the stern, ie it has good dynamic course stability, making it easy to keep on a straight path, and a correspondingly rather large turning circle diameter when compared with conventional ships. Heel angle when turning was negligible.

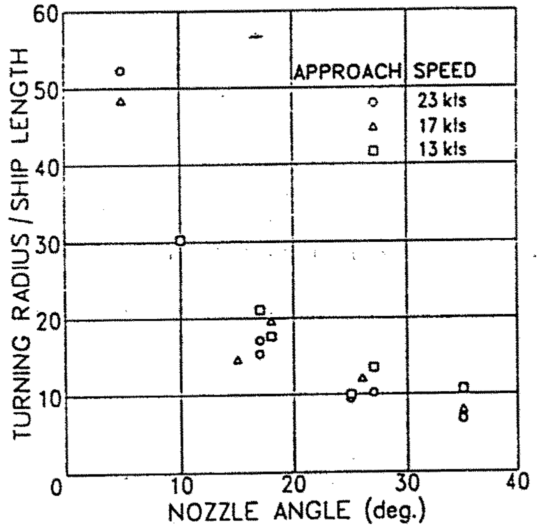

Figure 5.5: Tactical diameter of TLS-A 12.7 m model versus waterjet nozzle angle (Ozawa, 1993)

Catamarans High-speed, very slender hull catamarans have been the subject of numerous recent studies, most of them associated with the development of a commercial projects. Ishiguro (1993) presents extensive PMM and rotating arm test data on the hydrodynamic derivatives of a "super slender" catamaran with two different after bodies designed for either waterjet or propeller propulsion. Large dependence of the linear derivatives on Fn was found (Figure 5.6) and it was shown that there is negligible interaction between hull and waterjet forces. Results of tests performed on a 10.8m, 3.5t, 23.8kts manned prototype of a high-speed catamaran are presented by Yamamoto (1993). Yamashita (1993) presents in some detail the results of sea trials of 4 very similar catamaran ships about 30m in length with propeller and waterjet propulsion.

Yumuro (1993) models the hydrodynamic derivatives using a potential flow approach and linear lifting surface theory with a simplified wave making potential. The effect of hull spacing and Fn (Fn<0.5) on the linear derivatives are estimated and compared with experimental results.

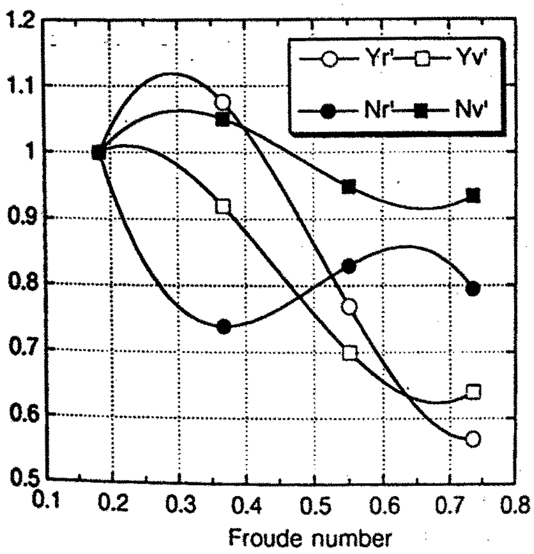

Figure 5.6: Effect of Fn on the linear derivatives of a catamaran - derived from PMM tests. (Ishiguro, 1993)

5.3 Small Waterplane Area Twin Hull

Although the SWATH concept has gained recognition, the number of new builds is not very large and a limited number of contributions were published.

Hirano (1992) has proposed a 3DOF model of SWATH manoeuvring motions where the linear hydrodynamic derivatives of lateral force and yaw moment are defined as the product of 3 functions:

$X = f_{\tau=0;F_n=0}(\kappa, \varepsilon, b') . g(F_n) . h(\tau)$ where:

$f_{\tau=0;F_n=0}$: derivative at low F_n and no trim (τ)

κ : Strut aspect ratio

ε : Float diameter / Length

b' : Distance between floats / Length

The function *f* is calculated based on low aspect ratio biplane wing theory and the results agree with experimental data. The functions which correct this result (*g* & *h*) are obtained experimentally. Rudder and propeller forces are calculated using standard models (section 3). This model is compared with full scale data on a steady turn manoeuvre in terms of trajectory and yaw rate. The results show good correlation for a 31m, 340t SWATH.

In the course of the design of a 600t, 22kts research vessel the station keeping ability of this craft in current and waves was studied (Papanikolaou, 1993). Axial and transverse forces of the ship in yawed conditions were measured at low Fn. The combined actions of bow thrusters, propellers and rudders were taken into account and predictions of craft holding capacity was assessed in terms of wind speed and wave height.

In one of the few large SWATH projects recently completed, the US Navy T-Agos 19 series, results of sea trials were published by Sandison (1994). Extensive sea trials were conducted to assess seakeeping and manoeuvring performance on this ship. The effectiveness of the rudders depend heavily on ship speed, and can be further increased through the use of the canards as shown on the tactical turn manoeuvres in Figure 5.7.

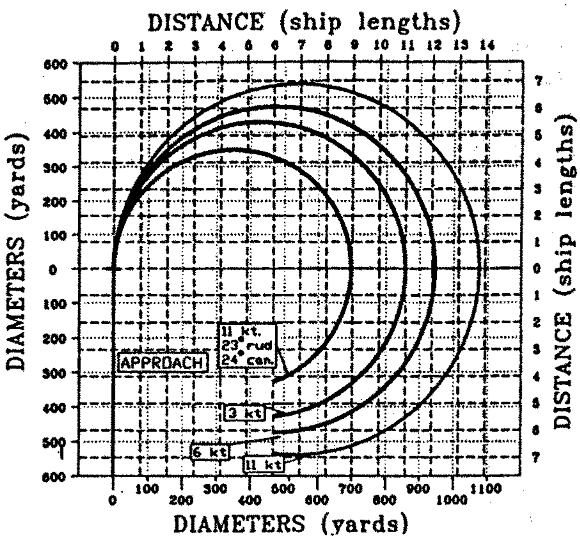

Figure 5.7: Tactical diameter of SWATH vessel (Sandison, 1994).

5.4 Submersibles

Submarines Estimating the hydrodynamic forces on an appended submarine at a given angle of attack is still a challenging problem. Several fundamental fluid dynamics studies have been carried out to understand the dynamics of vortex formation and flow separation on yawed slender bodies.

In an effort to generate a physical manoeuvring model, Ward (1992) and Ward & Wilson (1992), present an experimental program dedicated to building the model SUBSIM. A data base was compiled and although the mathematical model which uses this is not described, the difficulty in modelling the interaction between hull and sail vortices is advanced by the author as an explanation for the presence of "out plane forces" which need to be included in a manoeuvring model (Figure 5.8). Further experimental data on forces and separation lines in yaw is provided by Wetzel (1993a) for the US Navy 688 class submarine. The sting mounted model is tested with different combinations of appendages at a

Re=6.8 million with turbulence stimulation. Reynolds effects on separated flow force measurements are discussed. Further work by the same author on the same body (Wetzel, 1993b), has concentrated on the control of separation. Results show how vortex fins along the length of the model are effective in changing the behaviour of the separated flow and dramatically alter the forces (Figure 5.9).

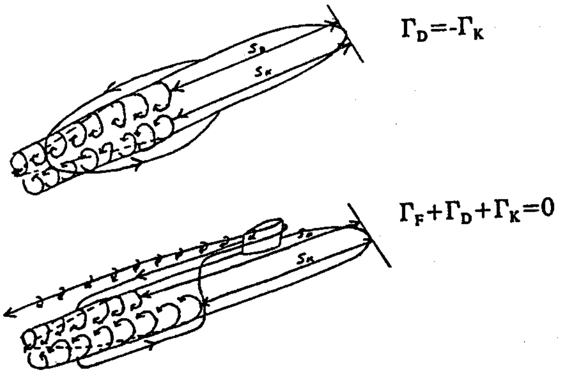

Figure 5.8 : Vortex interaction on a yawed submarine (Ward & Wilson, 1993).

The use of Navier-Stokes code is becoming increasingly popular to calculate flow fields, pressure distributions, and fluid forces in hydrodynamics. An example of this approach is illustrated by the work of Yang (1994), based on the AKRON, airship database. The results compare favourably with local pressure, and section force measurements. Since Navier-Stokes codes have the capacity of solving unsteady flows, it is to be expected that their use will become increasingly widespread.

Aside from the knowledge of steady forces, research is also carried out on the manoeuvrability of submarines by simulations including complete control systems. Papoulias et al. (1994a), studied the problem of multiple steady-state solutions in the dive plane of submarines under depth control at low speed when submarine lift forces become smaller then hydroplane forces.

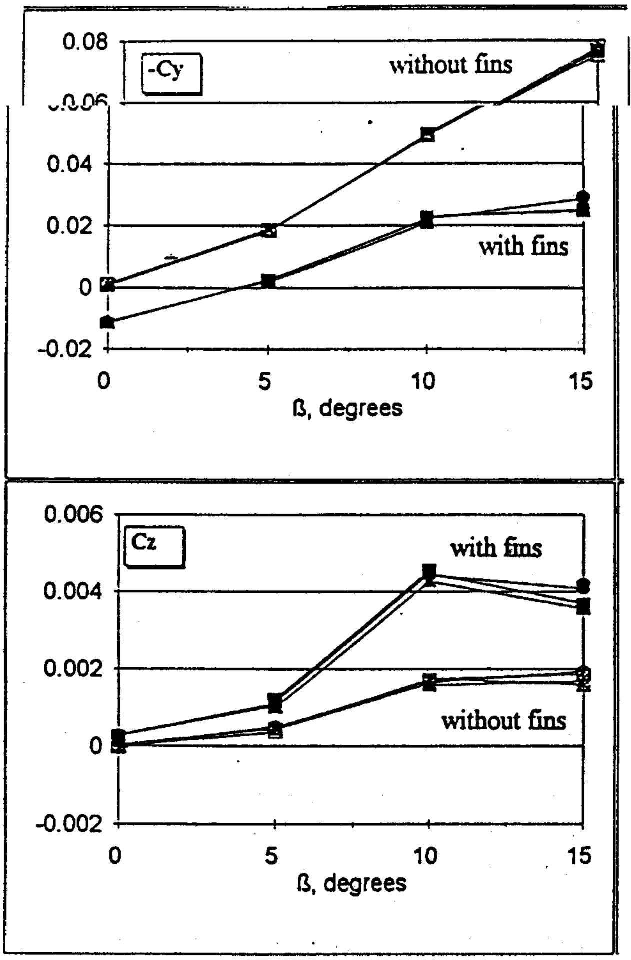

Figure 5.9: Effect of vortex fins on yaw moment (Wetzel, 1993b).

Similar work was performed by Pavaut, (1993). Depending on the amplitude of the rudder angles the response of the craft is very different.

Autonomous Underwater Vehicles AUVs often require specific a development program in order to verify their manoeuvring performance which is often essential to their missions.

Extensive towing tank and rotating arm tests are needed to evaluate the influence of fins and propulsors (Aage, 1994, Kimber, 1994, Packwood, 1993, Ueno, 1993)

5.5 Barge Transportation.

The results of a study into the manoeuvrability of barge-push train sailing in inland waters were presented by Wu et al. (1995). Full-scale and model scale tests information were collected and organised in a proper data base and program, which were described by Liu et al. (1995).

5.6 Sailing Craft

The advances in sailing craft developments are now centred around the tuning of Velocity Predictor Programs (VPP) which incorporate a hydrodynamic model of the hull and appendages and a manoeuvring model. Because of the overwhelming importance of upwind performance, these models must incorporate very accurate predictions of sway forces and yaw moments of the hull, keel and rudder combination to determine an optimum equilibrium state when sail forces are present. A complete VPP is presented in detail by Van Oossannen (1993) while Milgram (1993), presents a methodology for constituting such a model based on experimental data. Flay (1993) compares side force data for two type of hulls with varying appendages in a towing tank and in a wind tunnel.

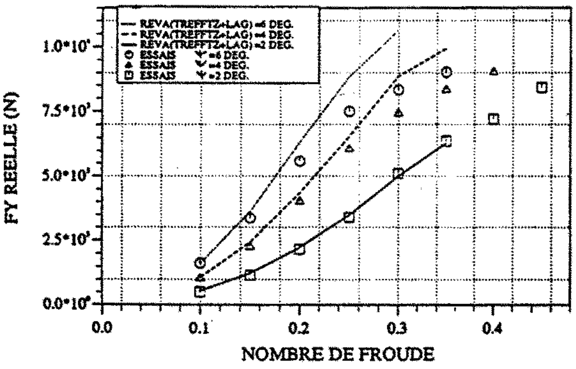

Figure 5.10: Calculated and measured lift on a sailing craft (Talotte, 1993)

Talotte (1993), presents a comparison of numerical methods based on a CFD code which include lifting surfaces. The comparison of forces calculated on a hull, keel, and rudder combination agrees well with experimental data as shown in Figure 5.10.

A manoeuvrability model of a sailing craft can be used to investigate the benefits of different trajectories (Masuyama, 1993).

6. VALIDATION, SCALE EFFECTS AND FULL SCALE TRIALS

6.1 Introduction

The validation of manoeuvrability predictions, as based on model tests, theoretical investigations, or combinations thereof, is closely linked to the problem of scale effects, and is dependent upon the availability of systematic and reliable full scale trials.

A logical classification of the different types of manoeuvrability experiments has been presented by van Berlekom (1992) as follows:

(a) The full scale test with the real ship.
(b) The straightforward model test, i.e. the same test as in full scale is performed with a scale model.
(c) The sophisticated model test, i.e. the model test is used to provide input to a mathematical model, which is used for prediction of the full scale behaviour.
(d) The numerical experiment (simulation) based on empirical-theoretical mathematical models.
(e) The numerical experiment (simulation) based on a pure theoretical mathematical model.

A comparison between any two of these five types of experiments can in principle be used to validate the prediction methods to some extent. However, two kinds of problems appear when different prediction methods are to be validated by comparison of a small number of experiments.

The first problem is of a fundamental nature: an experiment cannot in principle be used to prove a theory, but only to disprove one. An excellent agreement between two of the above types of experiments could be due to errors in both. Of course, if a large number of tests with many different types of ships and different types of experiments show good agreement, then there is a good probability that the prediction methods are valid.

The second kind of problems is more specifically reladed to ship manoeuvring data:

- In contrast to the wealth of published model test results, very few full-scale manoeuvring trials are carried out at a scientific level that make them suitable for validation purposes. Unfortunately, of the many full-scale trials carried out few seem to be reported and fewer show comparison with prediction methods and model tests.
- The level of accuracy obtainable in model tests and full-scale trials differ typically by an order of magnitude, which means that a good simulation or model test method may be rejected because of errors in the full-scale results.
- The most critical use of simulation is evaluation of manoeuvres that occur during pilotage and operation in restricted waters, while most validation efforts use results for definitive manoeuvres typically carried out in deep, unrestricted waters.
- Trials data are frequently available only for ballast or light load conditions, while critical manoeuvring performance often occurs at full load condition.

6.2 Validation

Full-scale Tests (a) versus Purely Theoretical Simulations (e). Kaplan (1995) has investigated the manoeuvrability of SES craft at speeds up to 49.5 knots by a purely theoretical model and has made a comparison between the predictions and full-scale trials with a 100-ton test craft. The agreement is very good, perhaps with a slight tendency for the theoretical model to predict smaller motions than measured in full scale.

Masuyama et al. (1993) have investigated the optimum tacking procedure of a 10.6m cruising yacht and compared simulations with full-scale measurements. Especially interesting in this context are the turning circle and zigzag tests where excellent agreement has been obtained.

Jiang & Sharma (1993) have studied the motions of a single-point-moored tanker by a purely theoretical simulation program and state that scale effects can be of significance for the motions, hawser tension, and stability of moored tankers in the horizontal plane.

Full-scale Tests (a) versus Experimentally Based Simulations (d). Barr (1993) considered the agreement between, and potential accuracy of sway and yaw damping components of the many published simulation models for the Esso Osaka, as well as simulation and free-running model tests for typical Osaka manoeuvres. The comparisons raised questions about the potential accuracy of simulation models and the possible existance of significant scale effects (see 6.3).

Hirano et al. (1992) have studied the manoeuvrability of SWATH ships by a theoretical method with hydrodynamic derivatives supported by model tests, and compared the numerical predictions with full-scale trial results of several vessels. The agreement between full-scale trials and predictions is excellent for the low speed, whereas the high-speed full-scale turning diameter is slightly larger than predicted.

Kijima et al. (1992) have studied the manoeuvring characteristics of different ship types as function of the loading conditions and water depth. Of particular interest in this context are the comparisons between experimentally based simulations and full-scale trials on a bulk carrier. Turning circle and zig-zag trajectories show good agreement. The simulations show slightly smaller turning circle diameters and smaller zig-zag overshoot than the full-scale trials. These findings are similar to those of Hirano et al. (1992), Oltmann (1993) and Labes (1994).

Yoshino et al. (1993) have compared full-scale trials on a 105-passenger hovercraft with simulations based on windtunnel tests. The agreement on tactical diameters is good on the average, but with a large scatter in the full-scale results.

Ishiguro et al. (1993) have investigated the manoeuvrability of a Super Slender Twin Hull (SSTH) vessel, a prototype for a 40 knot car ferry. Models of lengths 2.0 m and 2.5 m have been used for PMM captive model tests, powered by propellers and water jets, respectively. A 30m long experimental vessel has been tested in turning circles, zig-zag and crash stop tests. Very good agreement was obtained between large-scale trials and simulations, when proper corrections were made for disturbances from wind and current.

Oltmann (1993) has studied the influence of roll on the manoeuvrability of a containership. The zig-zag trajectory of a free-running model is analyzed by system identification to give the necessary input to the simulation program. The original model zig-zag manoeuvres as well as simulations have been compared to full-scale zig-zag and turning circle trials with very good results. The full-scale overshoots are slightly larger than in the model tests and simulated model tests.

Full-scale Tests (a) versus Free-sailing Model Tests (b). Labes (1994) has carried out manoeuvrability and stop tests on a 164 m containership and repeated the tests on a free-sailing radio-controlled scale 1:32 model in a towing tank. For the 10°/10° zig-zag test at 20.1 knots the ship had a somewhat larger overshoot angle than the model (6.9° versus 4.5°), larger angular velocities (around 10%), and a longer stopping distance (11.95 ship lengths versus 10.95). The turning circle diameters were quite similar. All observed differences can be explained by the lower Reynolds number on the model giving a relatively higher drag and damping. The model was not equipped with any drag compensation devices.

Free-sailing Model Tests (b) versus Purely Theoretical Simulations (e). Hirayama (1994) has investigated the manoeuvrability of a ship in directional waves. Free-running zig-zag model tests have been carried out in a model basin with directional waves. Very good agreement was found between model tests and simulations in still water as well as in waves.

Sophisticated Model Test (c) versus Experimentally Based Simulations (d). A comparison with full-scale data is usually considered the ultimate test of any prediction method. However, Vantorre (1995) underlines that full-scale trials can only give information of the kinematics of the ship, which means that force predictions can be validated only indirectly. Therefore, additional captive model tests covering a large range of operational conditions can be more useful regarding the details of simulation methods.

6.3 Accuracy of Simulated Manoeuvres

Assessment of accuracy Misiag & Kose (1994) have addressed the potential accuracy of simulations by studying the effect on simulated performance in turns and zig-zag manoeuvres of errors in various terms in the simulation. They found that the second overshoot angle was most sensitive to such changes, the first overshoot angle was less sensitive and turning parameters least sensitive. Figure 6.1 shows their predicted changes in second overshoot angle with changes in various terms in the simulation equations.

Factors Adversely Affecting Accuracy of Simulated Manoeuvring. The computational accuracy and validity of simulation models are adversely affected by a number of factors including: a still less than adequate knowledge of: scale effects in model tests; modification of ship hydrodynamic forces produced by other ships and structures and by operation in severely restricted waterways; and the complex interactions between propeller/rudder/hull.

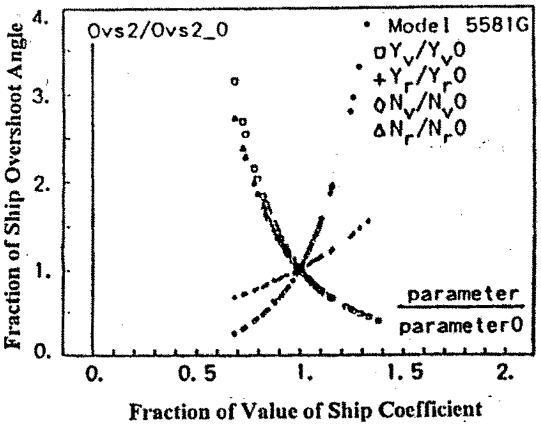

Figure 6.1 Variation of 10-10 Zig-Zag Overshoot Angle with Values of the Linear Hydrodynamic Coefficients. (Misiag & Kose 1994)

Based on available data it is difficult to assess the significance of scale effects in model tests or the minimum acceptable size of appended and bare hull models. Barr (1993) concluded that scale effects could be important for model lengths less than about 3 metres. Norrbin (1993), indicated probable existence of significant scale effects for a 1.5 metre long model of the Esso Osaka. Initial data from recent tests of a systematic series of fifteen 1.77 metre long models, Sedat & Fuller (1994), indicate potentially large scale effects at large drift angles. Scale effects are likely to be primarily a function of Reynolds number (and hence both length and operating speed or Froude number) and of hull form.

7. SHIP OPERATION & SAFETY, IMO STANDARDS

7.1 Introduction

Designers use marine simulators for assessing the merits of the various designs of ships, harbours or waterways and determine the level of risk related to handling a ship in a particular situation.

IMO is contributing significantly to ship safety with the adoption of interim manoeuvring standards. Now designers and operators are slowly becoming aware that ship's manoeuvring performance has to be considered as one aspect in a ship design.

7.2 Shiphandling, Human Factors and Control

Applications of shiphandling simulators. Shiphandling simulators have been used to solve a range of specific problems.

Manoeuvring safety of ships in harbours and narrow waterways was considered by Nakamura et al. (1993), who proposed procedures for systematic assessment, by Kuo (1993), who reviewed the state of the art in Taiwan, and by Hollocou & Lam (1993).

Evaluation of the navigation environment and the related difficulties of ship control in restricted water was discussed by Arai et al. (1993) and by Heikkilä et al. (1993) who showed that using a new display (Figure 7.1), an improvement in shiphandling performance, even by inexperienced pilots, was obtained. Simulation techniques used as aids to piloting were discussed by Inoue et al. (1993a).

A manoeuvring simulator installed on board and used by the crew was described by Lehtosalo (1993).

Many applications as a tool in design of fairways (Webb et al., 1994; Heikkilä et al., 1994) or berths (Laforce & Vantorre, 1994) were described.

Implementation of ECDIS into marine simulators. The development of ECDIS (Electronic Chart Display and Information System) and ECS (Electronic Chart System) was discussed by Riches (1995).

The potential of ECDIS to improve the accuracy of navigation, increase awareness of dangerous conditions and reduce the mariner's workload, was confirmed using the capabilities of a full-mission ship's bridge simulator (Smith et al., 1993).

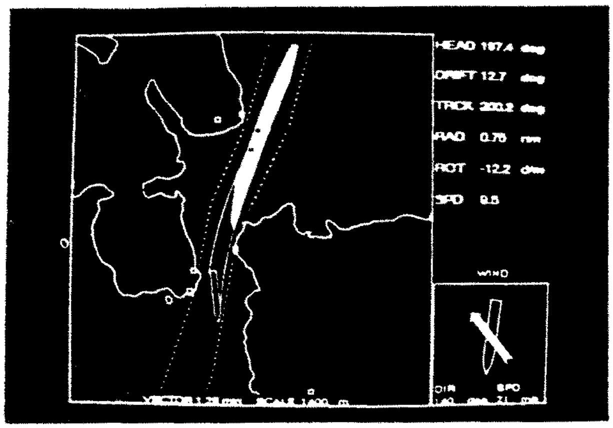

Figure 7.1 The New Display Format with Prediction of Motion (Heikkilä & Norros 1993)

A similar research project involving ECDIS was carried out in Canada. The results of the study, described by Mercer (1994), indicated that navigational performance is improved and workload is reduced when ECDIS is used to present information to the mariner. The same conclusions on the potential of ECDIS were obtained by Gonin et al. (1995) during a sea-test.

The integration of a ship manoeuvring mathematical model with electronic chart technique in a newly developed simulator was described by Jia et al. (1994).

Manoeuvring information/Human factors. Mariner/ship interaction as a fundamental aspect of ship controllability was discussed by Lowry (1994). The results of an international survey of naval architects and shiphandlers were presented.

The strengths and weaknesses of information exhibited on the bridge was given by Knierim (1994). The main conclusion was the need for naval architects and pilots to learn to speak a common language so that pilots can make use of the information that ship designers can provide to them.

Schraagen (1993) described the results of a task analysis of pilot information usage on the Rotterdam waterways. The relation between human handling characteristics and the type of information was discussed by Kobayashi (1993).

Control. In general, intelligent control consists of three methodologies: expert, fuzzy and neural. A comparison of the relative merits of each approach was given by Witt et al. (1993); neural network is considered the most appropriate method for further developments of the ship control problem. Zhang et al. (1993) described the feasibility of identifying future movements of a manoeuvring ship using a back-propagation based neural network. The application of the back-propagation on-line training based neural controller to ship course keeping control was described by Hearn et al. (1994). A more complex application of the neural networks was discussed by Hasegawa et al. (1993, 1994). The mathematical model of harbour manoeuvring of a ship and the artificial neural network (ANN) suitable for automatic berthing control including tug operation were described. A comparison between traditional and neural identification of dynamics was presented by Morawski et al. (1995).

An application of fuzzy logic to a classical tracking problem was described by Smith (1995). Wang (1993) presented a design method for a ship autopilot using a self-organising fuzzy control strategy. An application of fuzzy control theory to a dynamic positioning system was presented by Inoue et al. (1993b).

Yamato et al. (1993), and Kobayashi et al. (1995) discussed automatic berthing and proposed a control system that make use of joy-stick controller. Kasabeh et al. (1993) described a research project aimed to provide a complete simulation of a vessel automatically berthing in a generic port, and Ohtsu et al. (1994a), (1994b) discussed the application of optimal control theory to berthing, focusing on the minimum time berthing problem.

Application of optimal control theory to ship manoeuvring motion was discussed by Shouji (1992, 1993a, 1993b). Yumuro et al. (1995) presented and discussed the solution of an optimal control problem with magnitude-constrained input for the manoeuvring motion of a tanker type ship equipped with a rudder and a bow-thruster.

The application of a novel variable structure control scheme (VSC) to ship steering was discussed by Zhang et al. (1994). Burns (1995) considered the possibility of a fully automatic intelligent integrated ship guidance system. An Integrated Navigation System (INS) to provide supporting information for operators' decision-making was described by Kose et al. (1995).

Function and operation of an advanced joystick control system, together with results of full-scale experiments on board, were presented by Igarashi et al. (1994) and Oda et al. (1994).

The application of the inverse linear quadratic optimal servo theory to the control system of dynamic positioning system for ships and comparison with linear quadratic optimal regulator theory was discussed by Kijima et al. (1995).

Ship Behaviour in Muddy Areas. A review of the present knowledge on interaction between a ship and a fluid mud layer on the bottom is given by Vantorre (1994).

Systematic model tests above mud-simulating layers were carried out at MARIN (Sellmeijer & van Oortmerssen, 1983), Flanders Hydraulics (Vantorre & Coen, 1988; Wens et al., 1990; Vantorre, 1991; Van Craenenbroeck et al., 1991) and SOGREAH (Brossard et al., 1990a, 1990b) under very different conditions.

Full-scale tests were carried out in Rotterdam (van Bochove & Nederlof, 1979; Sellmeijer & van Oortmerssen, 1983), Nantes - Saint-Nazaire (Brossard et al., 1990a), and Zeebrugge (Kerckaert et al., 1988; Van Craenenbroeck et al., 1991).

Theories were developed by Ferdinande & Vantorre (1991), Zilman et al. (1994); numerical calculations were presented by Tulin et al. (1993), Wu (1993), Avital & Miloh (1994), Miloh (1995).

Most mud-ship interaction effects are related to interface undulations, Figure 7.2, and are most important in a low speed range, where an internal jump occurs under the ship's keel. According to Vantorre (1991), the upper limit of this range is given by:

$$V_{crit}=\sqrt{\frac{8}{27}gh_1\left(1-\frac{\rho_1}{\rho_2}\right)}$$

although other authors consider the maximum propagation velocity of internal waves as a critical speed (Sellmeijer & van Oortmerssen 1983, Zilman et al 1994):

$$C_{max}\approx\sqrt{gh_2\left(1-\frac{\rho_1}{\rho_2}\right)}$$

(h_1: water depth, h_2: mud layer thickness, ρ_1: water density, ρ_2: mud density)

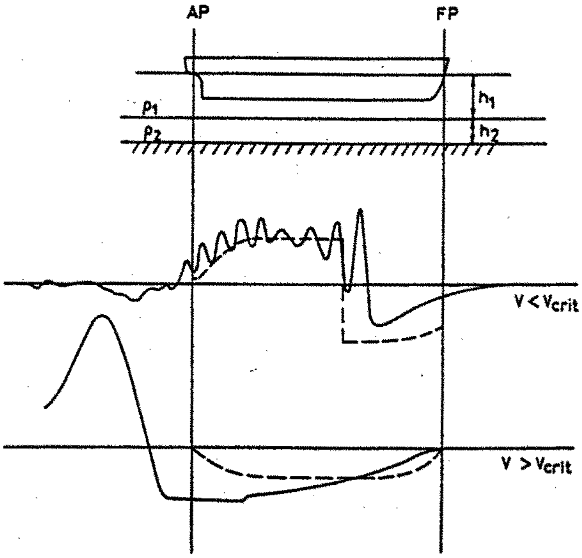

Figure 7.2 Undulations of Ship-Mud Interface: Influence of Ship's Speed (Vantorre, 1991)

Effects of fluid mud on ship dynamics are discussed by Sellmeijer & van Oortmerssen (1983). Mud generally tends to slacken steady motions (lower forward speed, drift, rate of turn), and to accelerate dynamic motions (smaller overshoot in zig-zag tests). Most effects, however, including rudder instabilities described by Vantorre (1991), are very sensitive to speed and under keel clearance.

Some characteristics are far from being understood. For instance, controllability may be heavily affected if a ship's keel is in contact with a plastic consolidated mud layer.

7.3 Safety Aspects in Manoeuvring, Criteria and Indices

Numano et al. (1993) proposed a method of safety assessment for a newly developed system with safety margin as an index. An experimental investigation of the safety navigation of a high speed craft in a congested sea area was shown.

New manoeuvring criteria for the river Rhine were proposed by Dijkhuis et al. (1993). In crowded and restricted waters the capability to change lanes, has to be considered a fundamental characteristics of ship manoeuvring. To assess this manoeuvring behaviour the authors proposed a modified zig-zag test that, instead of the course angle, uses the rate of turn as a trigger (Figure 7.3). Advantages of this manoeuvre were discussed and five dimensionless manoeuvring parameter proposed to assess the results of the trial.

Biancardi (1993) reviewed critically some of the existing approaches for dealing with ship manoeuvrability and ship safety, and proposed some fresh understandings of the terms "Manoeuvrability" and "Safety".

A general methodology for the assessment of the inherent manoeuvring characteristics of ships was presented by Spyrou (1994) who applied this to ferries. As a result, areas of good or poor manoeuvring performance were identified. The methodology can be used in early ship design as well as in developing vessel type-specific manoeuvrability standards.

A review of existing manoeuvrability measures and criteria was presented by Sutulo (1995) and a procedure based on the use of a shiphandling simulator was outlined.

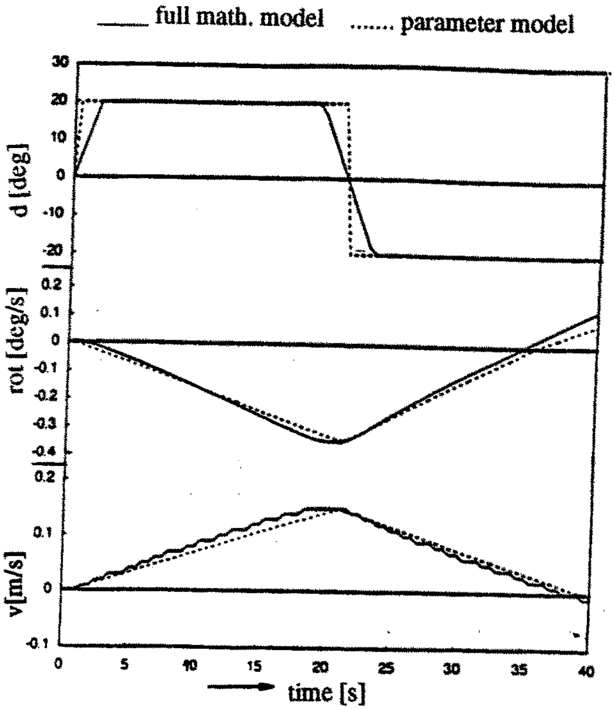

Figure 7.3 "Change of Rate of Turn" Manoeuvre (Dijkhuis et al, 1993)

The relation between propeller RPM variation and ship manoeuvring safety was discussed by Bavin et al. (1995). Diagrams of dangerous distances and time intervals to warn shiphandlers of potential risks were obtained from model and full-scale investigations.

Methods of defining a safe manoeuvring region were presented by Gucma (1995). Simulation techniques to define safe manoeuvring region in terms of safety criteria were also discussed.

A theoretical study of the assessment of the risk of collision between ships and offshore installations was described by Zhao et al. (1994b). The causes of collision and the methods of evaluating the risk of collision were reviewed. Safety criteria to evaluate the collision risk for ships navigating at high speed were proposed by Inoue et al. (1994a). They were applied to data obtained from an experimental study using a shiphandling simulator and it was confirmed that the criteria were able to evaluate the collision risk (1994b). The collision avoidance problem in congested sea areas was discussed by Hara et al. (1993). Imazu et al.(1993) investigated 122 cases of ship collision accidents for large ships and obtained the critical range for collision avoidance which increased with an increase in the ship's directional instability.

Inoue et al. (1993c) supported the thesis that in harbour entrance design, it is useful to consider mariners' preferences. An evaluation model was proposed to show the sense of safety mariners would feel during the passing manoeuvre at a harbour entrance, by a quantitative index. The crucial problem of the assessment of the risk associated with the maritime traffic when designing a harbour was also extensively discussed by Sand et al. (1994).

Guidelines for concept design purposes were formulated by PIANC-IAPH WG30 (1995).

7.4 IMO Standards

In 1993, IMO adopted Resolution A.751 (18) "Interim Standards for Ship Manoeuvrability" given in the report to the 20th ITTC.

Explanatory notes to the standards were also agreed and issued in the MSC/Circ.644: "Explanatory Notes to the Interim Standards for Ship Manoeuvrability", May 1994.

The standards are to be considered interim for a period of 5 years from the date of their adoption, and should be reviewed in the light of new information and the results of experience with the present standards and ongoing research and developments.

A comprehensive review of IMO's activities on ship manoeuvrability from 1968 to 1993 was presented by Srivastava (1993).

The role of IMO in the field of ship manoeuvrability and the importance of the establishment of international standards was also highlighted by Palomares (1994).

Norrbin (1993) analysed critically the new IMO Standards emphasising the lack of reference to the "spiral characteristics" of ships. He suggested a dynamic stability parameter, containing the factor 1/K' and the relative rudder area: $(A_r/T^2) / K'$

The parameter can be obtained from ship trials, conforming to the new IMO standards but including additional moderate-helm turning circles with pull-out manoeuvres or spiral-type tests where these are feasible.

Another analysis of the IMO Standards, focusing on ships' directional stability, was made by Yoshimura et al. (1993). To evaluate the relation between the human perceived difficulty in ship control and the level of directional instability, on-board investigations and manoeuvring simulations were performed under the support of Japan Pilots' Association.

Further discussions on the IMO Standards was provided by Yoshimura (1994) and by Yoshimura & Kose (1995), especially pointing out that the stopping criterion becomes too severe for large ships, such as VLCCs. This is confirmed by a number of full-scale trial results (Figure 7.4). Clarke & Hearn (1994) examined the stopping behaviour of a range of ships and also showed how very large ships could exceed the stopping criterion included in IMO Resolution 751(18).

Capurro (1995) showed the results of an extensive application of a manoeuvring prediction program that was specifically developed for naval architects to demonstrate compliance with the IMO Standards.

7.5 Squat

Recent research. A theoretical/numerical approach was published by Bessho & Sakuma (1992) and Yasukawa (1993). Eryuzlu et al (1994) undertook thorough model tests with general cargo ships and bulk carriers in laterally non-restricted water with restricted depth ($1.1 \leq h/T \leq 2.5$). The effect of channel width, W, was investigated in supplementary model tests ($W/B \geq 4$). An empirical formula, valid for both channels and canals, was obtained and evaluated by means of full scale measurements:

$$s_b = 0.298 \frac{h^2}{T} \left(\frac{V}{\sqrt{gT}}\right)^{2.289} \left(\frac{h}{T}\right)^{-2.972} K_b$$

$K_b = 1$ if $W/B \geq 9.61$,
$K_b = 3.1\,(W/B)^{-1/2}$ if $W/B < 9.61$.

Full scale squat measurements on a bulk carrier were reported by Nawrocki (1994).

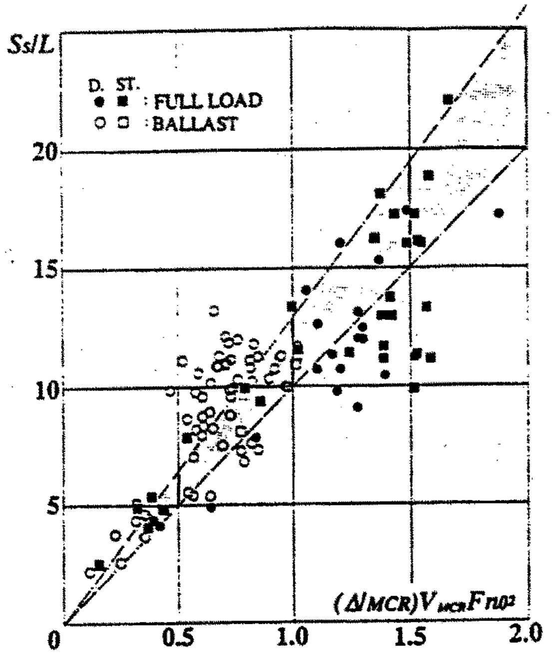

Figure 7.4 Results of Stopping Distance (Yoshimura & Kose 1995)

Empirical squat formulae for practical use. A review of practical methods for calculating squat was made by PIANC/IAPH WG30 (to be published in 1996).

Squat values calculated for a number of ships with different formulae show very important deviations (Figure 7.5). Thus, there appears to be an urgent need for clarification.

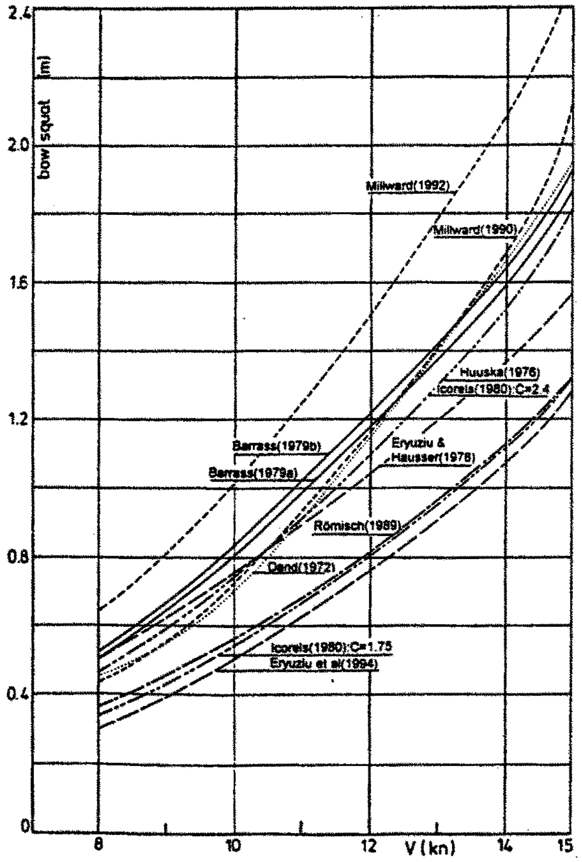

Figure 7.5 Bow Squat for 250 000 tdwt Tanker (L_{pp} = 330m; B = 50m; T = 20m; C_B = 0.85) h/T = 1.2 (PIANC/IAPH 1996)

Muddy areas. As discussed by Sellmeijer & van Oortmerssen (1983), Vantorre & Coen (1988), Brossard et al (1990b), Van Craenenbroeck et al (1991), mud layers affect squat due to two effects: interface undulations, depending on speed, and increased buoyancy, depending on the initial under keel clearance (UKC). In general, mud decreases squat effects, except for:

- low speed, relatively large positive UKC;
- higher speed (≥ 8 knots), negative UKC, thick layer of low density mud (low concentration gradient).

7.6 The Use of Escort Tugs

Escort tugs capable of rendering assistance to disabled tankers at high speed have been the subject of intense investigation. Modern omni-directional drive tugs are suitable vessels for escort duty given their superior manoeuvring capabilities. The Voith Water Tractor and the omni-directional stern drive tug are the two accepted configurations.

Tug performance at high speed depends heavily on forces acting on the tug's hull as well as those generated by the thrusters. Hydrodynamic aspects relating to the performance of stern drive tugs have been investigated by Renilson et al, (1992). Detailed investigations have been carried out by Hutchison et al, (1993), into the capabilities of the Voith Water Tractor.

Investigations into stern drive and tractor tug capabilities for escort duty have been presented by Hendy & Freathy (1993) where a dynamic model was used to examine the behaviour of the tug in extreme situations. The performance of stern drive tugs and their role in shiphandling have been investigated by Brandner & Renilson, (1993) & (1994).

Predictions of stern drive tug performance have also been presented by Sas et al, (1993).

Gale et al. (1994) have presented some simple analyses and results from model tests for a modified omni-directional stern drive tug with a bulbous bow.

8 EVOLUTION OF MODEL TESTING METHODS

8.1 Introduction

The manoeuvrability testing methods are under continuous but not very rapid development. The more recent publications on new testing methods seem to concentrate on procedures that are simpler and less expensive than the traditional captive (PMM) model tests. Some authors have suggested new ways of conducting and analyzing captive model tests, others have suggested methods to replace the captive model tests.

8.2 New Captive Test Procedures

Rhee et al. (1993) have analyzed PMM test data by the Recursive Least-Square system identification method instead of the more traditional methods. By introducing special combined PMM motions all hydrodynamic derivatives can be estimated with good accuracy from only six test records.

Another way of economising on a traditional captive model test program involves the use of fully automatized PMM equipment, as described by Vantorre (1994b).

Hashizume & Matsui (1994) have presented test results from a PMM installed in a circulating water tunnel with a cross section of 4.0 m by 1.6 m. Hydrodynamic coefficients obtained for a Series 60 hull deviate less than 10% from those obtained in a towing tank.

Lee et al. (1993) have studied the transient manoeuvring test method. Instead of the traditional PMM, they use a simplified hydraulically driven PMM to give the short impulse motion needed to cover all frequencies in one test run of about 2-3 seconds duration. The results for a Series 60 model compare very well with traditional PMM results.

8.3 New Non-Captive Test Procedures

Burcher & Zhang (1995) have developed a method to determine the manoeuvrability characteristics from tow line tests. The purpose has been to replace more expensive and time consuming methods. The authors have not dealt with the problem of how to include a propeller working at the self-propulsion point in the towline procedure.

Montero et al. (1993) have developed another oscillating model test procedure where the oscillatory sway and yaw motion is induced by an oscillatory motion of the rudder. The model is pivoting around a fixed point in the fore end of the vessel.

9. RECOMMENDED STANDARD PMM TEST PROCEDURE

9.1 Introduction

The PMM test is employed as one of the captive model test techniques to determine the hydrodynamic coefficients for a mathematical model of ship manoeuvring motion. An example of standard procedures for this test is presented, together with recommendations to obtain reliable results from these tests. It should be noted that this is not the only means of obtaining those hydrodynamic coefficients.

The procedure described here is to be used for surface ships only, where Froude scaling is applied. In this PMM test procedure a modular type of mathematical model is assumed for the hydrodynamic coefficients describing the hull and rudder forces.

9.2 Experimental technique

Model dimensions. The scale of the model should be selected not to be less than the generally accepted existing standards. (Note that scale effects in manoeuvring are not yet fully understood. Two of the recommendations of the Manoeuvrability Committee involve investigations into scale effect.)

Tank dimensions. The tank should be wide enough to avoid interference between the model and the tank walls. For shallow water tests the water depth should be scaled correctly, and for the case of deep water it should be deep enough to be free from shallow water effects.

Model inspection. The model should be inspected, prior to testing, for its principal dimensions, hull configuration, model mass, centre of gravity position, moments of inertia etc.

Model speed. Model speed should be chosen using the Froude scaling law.

Model setup. The model is usually connected to the PMM such that it is free in heave and pitch, and fixed in roll. Great care must be taken when aligning the model and this should be checked before and after the tests.

For some tests, the model may be free to roll, or roll may be forced. Note that if measurements concerning roll are required, or if roll is not fixed, the vertical centre of gravity and the moment of inertia about the X axis are to be modelled correctly.

The loading condition of the model, (fore and aft draft) should be checked before and after the tests.

Calibration. Calibration of all sensors and the movement of driving units should be carried out immediately before and immediately after the tests. The capacity of load cells should be chosen to be appropriate to the loads expected.

Test method for hull forces. The following tests may generally be carried out for hull forces:

(A) oblique towing test;

(B) pure sway test;

(C) pure yawing test; and

(D) yawing with drift test.

In tests (B), (C) and (D), the circular frequency of oscillation should be selected to be free from frequency dependence, both for the hydrodynamic forces and the natural frequency of the carriage and measuring equipment and the water in the tank.

In addition, the lateral amplitude should be selected to be less than that which causes interference of the model with the tank walls. The data sampling rate and filter details should be determined on the basis of the oscillation frequency, together with considerations of the primary noise frequencies.

In tests (A) and (D), the drift angle should be varied from 0 degrees to the maximum drift angle, which may be determined according to the purpose of the tests, at an appropriate interval. The maximum drift angle should not exceed that which causes interference of the model with the tank walls.

In tests (C) and (D), the amplitude of yaw rate should be varied from 0 to the maximum yaw rate at an appropriate interval. The maximum yaw rate should be determined taking the above limitation for the circular frequency of oscillation and the lateral amplitude into consideration.

Test method for rudder forces. The tests for the rudder forces may generally be carried out by changing rudder angles and propeller loadings (propeller rpm) in straight and oblique tow with a model with propeller(s) and rudder(s) as follows:

(E) straight towing test with rudder deflection; and

(F) oblique towing test with rudder deflection.

In tests (E) and (F), rudder should be deflected from 0 degrees to the maximum rudder angle, which may be determined according to the purpose of the tests, at an appropriate interval for both port and starboard. In test (F) drift angles to both port and starboard should be tested to check for possible asymmetry effects caused by the propeller.

Number of oscillations. In tests (B), (C), and (D) the number of oscillations should be determined to be large enough to obtain reliable results, noting that data in the transient regions of starting and stopping should not be used in the analysis.

Record of results. The measured real time data should be recorded. It is recommended that real-time analysis be made immediately after each test in order to check for obvious errors in the data.

9.3 Analysis procedure

Visual inspection. Immediately after each run the data should be inspected in the time domain to check for obvious errors such as: transients caused by recording too soon after starting; additional unknown sources of noise; or the overloading or failure of one or more sensors.

Analysis of hull forces. Detailed analysis should be carried out with the use of the stored data. This can be carried out after all the tests are finished. The hydrodynamic coefficients should be obtained on the basis of the mathematical model to be utilised for manoeuvring simulations. While there exist many different possible analysis methods, the following procedures may generally be employed:

- coefficients for sway velocity from test (A);
- coefficients for yaw rate from test (C);
- coefficients for sway velocity and yaw rate from test (D); and
- Inertia coefficients from tests (B) and (C).

The frequency dependence on hydrodynamic forces should be checked, and it should be ensured that the coefficients are equivalent to those at zero frequency. Where possible this can be done by comparing with the results from the static tests.

Analysis of rudder forces. Detailed analysis should be carried out with the use of the stored data. This can be carried out after all the tests are finished. The hydrodynamic coefficients should be obtained on the basis of the mathematical model to be utilised for manoeuvring simulations. While there exist many different possible analysis methods, the following procedures may generally be employed:

- coefficients of the forces induced on a ship hull due to rudder deflection from test (E); and
- coefficients for the effective inflow angle into the rudder from test (F).

Number of oscillations or time interval to be analysed. The numerical accuracy may generally be improved by increasing the number of oscillations (tests (B), (C) and (D)) or the measuring length or time interval (tests (A), (E) and (F)). In analysis of these tests the number of oscillations and/or the time interval should be selected so as to obtain reliable hydrodynamic coefficients. Transients due to starting, stopping or changing conditions should not be included in the data to be analysed.

9.4 Prediction procedure

The simulation of ship manoeuvring motion may generally be performed by making use of the mathematical model with which the test results are analysed, with the use of the hydrodynamic coefficients obtained through the process described above.

9.5 Documentation

The following should be documented and included in the test report:

Experimental technique.

(1) Model: Model dimensions, including rudder and propeller; mass; coordinate(s) of centre of gravity; moment(s) of inertia; method of turbulence stimulation; and details of appendages;

(2) Tank: Tank dimensions; water depth indicating the ratio of water depth to model draft; and water temperature;

(3) Model setup: Condition of model restraint for heave, pitch and roll modes, including details of forced roll, if applicable;

(4) Measurement: Measuring equipment; maximum capacity of load cell(s); and filter characteristics;

(5) Hull force tests: Test type; model speed; time of oblique towing test; number of oscillations in oscillatory tests; circular frequency of oscillation together with proof of avoidance of resonance with the natural frequency of the carriage measuring equipment, and the water in the tank; maximum drift angle; maximum yaw rate; and maximum lateral amplitude;

(6) Rudder force tests: Test type; model speed; time of straight/oblique towing test with rudder deflection; maximum rudder angle; and propeller rpm variation with model speed;

(7) Recording: Recording equipment; including sample time; and digitising rate; and

(8) Calibration: Details of all calibrations conducted; including information on linearity and repeatability of all sensors.

Analysis procedure

(1) Hull force analysis: Method of hull force analysis; hull force coefficients, together with the mathematical model with which measured data was analysed; number of oscillations in oscillatory tests used for analysis; circular frequency of oscillation

indicating that the coefficients are equivalent to those at zero frequency; data sampling rate; and filtering technique; and

(2) Rudder force analysis: Method of rudder force analysis; and hydrodynamic coefficients for rudder forces, together with the mathematical model with which the measured data were analysed.

10. CONCLUSIONS OF THE COMMITTEE

Prediction of forces. No accurate methods for predicting hull forces in deep and shallow water, or hull/propeller/rudder interaction are available at present, although many developments, such as CFD, are potentially able to do so. The influence of essential design features, such as stern shape, is not yet fully understood.

Although in some cases it is possible to adequately predict the manoeuvring characteristics, without recourse to model experiments, of vessels which meet the IMO standard, at this time there is some difficulty predicting the manoeuvring characteristics of sub-standard vessels.

Simulation of dynamics. There is no tendency towards uniformity of simulation models. Each member organisation appears to have its own mathematical model which it deems adequate for its own purposes.

The need for inclusion of the roll equation into the model for special cases such as high speed displacement craft and manoeuvring in waves has been recognised. More work needs to be done on roll coupling.

Non-conventional craft. There is more work being carried out on high speed craft than before. However, this tends to be applied to specific vessel developments; at this stage, general data are not sufficiently available.

Validation, scale effects and full scale trials. There is a need for more accurate full scale data for validation purposes, particularly at the full load condition.

Scale effects are not yet fully understood. Methods based on model tests appear to underestimate turning circle diameters and zig-zag overshoot angles by about 0-10% as compared to full scale trials.

Ship operation and safety, IMO standards. Ship simulators are being extensively used, in conjunction with pilots, for ship safety studies, including investigations involving human factors, ECDIS, and other means of displaying navigational data.

Significant developments are being made using control theory.

Behaviour in restricted water, including squat and the effect of a muddy bottom, is not yet very well understood. This is of particular importance for studies concerning design and safety of harbours and waterways.

New criteria have been proposed for special cases. Although the IMO interim standards have received some criticism, it is generally felt that they should not be changed until more experience using them has been obtained. The adoption of IMO standards has increased the level of safety by increasing the amount of research into manoeuvrability of conventional ships. However, it should be noted that these criteria do not apply to high speed ships.

The recent adoption of escort tugs has lead to increased research into the manoeuvrability of vessels fitted with omni-directional drive thrusters.

Model testing techniques Although a number of new testing methods have been proposed recently and may show promise in the future, to date none have achieved widespread acceptance. Further work needs to be done in this area.

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