ITTC2024
30TH INTERNATIONAL TOWING TANK CONFERENCE
22–27 SEPTEMBER 2024 | HOBART TASMANIA AUSTRALIA

Report of the Manoeuvring Committee

1. INTRODUCTION

1.1 Membership and Meetings

The members of the Manoeuvring Committee (MC) of the 30th ITTC are:

- Prof. Dr. Xide Cheng (Chair). Wuhan University of Technology, CHINA
- Dr. Zhiming Yuan (Secretary). Universities of Glasgow and Strathclyde, UK
- Ms. Janne Flensborg Otzen. FORCE Technology, DENMARK
- Dr. Takashi Kishimoto. Akishima Laboratories (Mitsui Zosen) Inc, JAPAN
- Dr. Youngjae Sung. Hyundai Maritime Research Institute, REPUBLIC OF KOREA
- Dr. Maciej Reichel. Gdansk University of Technology, POLAND
- Dr. Dobrin V. Efremov. Bulgarian Ship Hydrodynamics Centre, BULGARIA
- Dr. Andrea Serani. National Research Council-Institute of Marine Engineering, ITALY
- Prof. Heather Peng. Memorial University Newfoundland, CANADA
- Dr. Shawn Aram. Naval Surface Warfare Center Carderock Division, USA
- Dr. Dong Jin Yeo. Korea Research Institute of Ships and Ocean Engineering, REPUBLIC OF KOREA

Four committee meetings have been held during the work period:

- The first meeting (online), January 10-12, 2022;
- The second meeting (online), 30th November - 1st December, 2022;
- The third meeting (in-person), 20-21 July, 2023, KRISO, Daejeon, Korean
- The fourth meeting (in-person), 9-11 January, 2024, Strathclyde, Glasgow, UK.

Due to COVID impacts, MC also held more than ten breakout online meetings during this term.

1.2 Tasks

The recommendations for the work of the Manoeuvring Committee as given by the 30th ITTC were as follows:

1) Update the state-of-the-art for predicting the manoeuvring behaviour of ships, emphasizing developments since the 2021 ITTC Conference. The committee report should include sections on:
   a. The potential impact of new technological developments on the ITTC, such as unmanned ship and autonomous navigation
   b. New experiment techniques and extrapolation methods
   c. The practical applications of computational methods to manoeuvring predictions and scaling, including CFD methods

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

2) During the first year, Recommended Procedures manoeuvring, and
 a. Identify any requirements for changes in the light of current practice and, if approved by the Advisory Council, update them,
 b. Identify the need for new procedures and outline the purpose and contents of these.

3) Update procedure 7.5-02-06-05 "Uncertainty Analysis for Free Running Model Tests" complying with current ITTC guidelines for uncertainty analysis. Cooperate closely with the Quality Systems Group.

4) Survey the state of the art of the development of autonomous navigation technology such as the application of artificial intelligence schemes, and investigate potential impact to ITTC, including the impact to autopilot of full-scale ships.

5) Update 7.5-02-06-02, "Captive Model Test", particularly with specific attention to the treatment of amplitudes, frequencies, and inertial coefficients and to have a single integrated example for uncertainty analysis, based on the SIMMAN results.

6) Update 7.5-02-06-03 "Validation of Manoeuvring Simulation Models", reflecting the outcome of SIMMAN and any other new developments.

7) Continue the work with underwater vehicles towards and complete the guidelines, extending to submarines and ROV's, if possible.

8) Update the guidelines proposed by Special Committee on Manoeuvring in Waves of the 29th term, collaborating with the Seakeeping Committee.

9) Support and collaborate with SIMMAN group for post processing and analysis of the submitted results and collect the benchmark data for the validation of numerical methods of ship manoeuvring, including the wave induced forces and moments in waves.

10) Validate the Level 2 - Minimum Power Assessment of the Draft Amendments to Guidelines (MEPC.1/Circ.850/Rev.3).

11) Collect benchmark data for
 a. Underwater vehicles
 b. Inland navigation
 c. Model-scale vessels with a documented full-scale variant

12) Survey the captive test in waves and collect the data of the hydrodynamic forces acting on the ship in waves, which can be used for the validation and application of simulation tools, including
 a. Oblique towing test data in waves
 b. Circular motion test data in waves
 a. PMM test data in waves
 b. Rudder force data in waves when ship is moving straight ahead

13) Investigate its implications on manoeuvrability of the effect of novel devices and clean fuel technology on available installed power, in wind and waves.

2. STATE OF THE ART

2.1 Experimental Measurements

2.1.1 Shallow, Restricted and Confined Waterways

Recent studies provide invaluable insights into various aspects of maritime navigation, including the effects of mud layers, ship-to-ship

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interactions, and the impact of canal and quay geometries on ship manoeuvrability. The following papers collectively contribute to a deeper understanding of the complexities involved in maritime transportation in specialized environments.

Delefortrie et al. (2022a) presented a focused study on the influence of fluid mud on ship squats. Through an extensive series of towing tank tests, the research demonstrates that the presence of a mud layer significantly increases squat, especially at smaller drift angles. The experimental results led to the development of a correction term for existing empirical squat prediction formulas, accounting for the unique impact of mud layers. This study is particularly relevant for navigating ships in environments with fluidized mud layers, providing essential insights for safe and efficient manoeuvring in such challenging conditions.

Böttner and Kondziella (2022) explored the dynamics of ship-to-ship interactions in shallow and confined waters. Their model test study reveals that the forces exerted on moored containerships by passing vessels increase more than quadratically with the speed of the passing ship, highlighting the significant impact of speed reduction in managing these interaction forces. The study also emphasizes the amplified longitudinal interaction forces due to the presence of a quay wall, with reduced sway forces. These findings are instrumental for improving the safety and management of ship movements in such challenging navigational environments, particularly given the trend towards larger vessels.

Ley et al. (2022) presented a comprehensive examination of the hydrodynamic interactions between passing and moored ships in confined canal environments. The research, utilizing scale model tests, focuses on the dynamic response of moored ships to passing vessels in a canal port setting. Key findings include the identification of significant rope tension forces on the moored ships, influenced by various factors such as the speed of the passing ship, rope stiffness, and pretension. The study reveals that the hydrodynamic forces induced by passing ships are considerable and must be factored into the design and operation of mooring systems in similar canal port scenarios.

Mehr et al. (2022) focused on the impact of water depth on the rolling behaviour of large vessels. The study utilizes model tests to determine how different water depths affect the roll natural period and damping coefficient. The findings indicate that for a depth-to-draft ratio greater than 2.0, changes in water depth do not significantly influence these parameters. However, when this ratio is less than 2.0, both the roll period and damping coefficient increase exponentially with decreasing water depth. This study offers crucial insights into ship stability and safety in shallow waters, a significant consideration for large commercial vessels operating in such environments.

Okuda et al. (2022) examined how the direction of propeller rotation (inward or outward) affects the manoeuvrability of twin-propeller and twin-rudder ships. The paper presents results from free-running model tests, including turning, zigzag, stopping, and crabbing manoeuvres in both deep and shallow water conditions. A key finding is that the propeller rotation direction significantly influences crabbing performance in shallow water. Specifically, ships with outward rotating propellers demonstrate better manoeuvrability in these conditions. This research provides valuable insights for the design and operation of twin-propeller, twin-rudder ships, particularly in terms of propeller rotation direction and its impact on manoeuvrability in shallow waters.

Verwilligen et al. (2022) presented a comprehensive analysis of the impact of bank effects on ship manoeuvrability in confined channels. The study combines model-scale towing tank tests with full-scale measurements to assess the influence of bank effects on a bulk carrier navigating through the Canal Ghent-Terneuzen. Key findings highlight the significant impact of canal

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geometry and bank presence on ship behaviour, including alterations in manoeuvring and squatting. The research underscores the importance of considering bank effects in the design and operation of navigation channels, especially for large vessels in confined waterways, to ensure safe and efficient maritime operations.

Delefortrie et al. (2022c) presented an in-depth exploration of how various barge configurations affect the manoeuvring behaviour of push convoys. Using a 6 Degrees of Freedom (DOF) manoeuvring model, the research evaluates multiple configurations for factors such as number of barges, draft, and position of the pusher in both deep and shallow waters. The findings from captive model tests, validated through fast time simulation runs and real-time simulations with experienced skippers, demonstrate that barge configuration significantly impacts manoeuvrability. These insights are essential for designing and operating inland waterways and push convoys.

Esferra et al. (2021) investigated the hydrodynamic interactions between passing and moored ships. The research, using scale model simulations, focuses on the Santos Port and explores the effects of different navigational conditions on the mooring lines of docked ships. The findings emphasize the significant strain on mooring systems induced by passing ships, especially in the right margin trajectory close to the dock. The study offers valuable insights into mooring system performance under varying conditions of ship passage, highlighting the critical need for effective mooring strategies in ports to ensure the safety and stability of docked vessels.

Hachiya et al. (2022) investigated the impacts of a false bottom in a towing tank on the hydrodynamic forces acting on a ship model. The research, conducted with a KCS model, reveals that in a false bottom setup, both lateral force and yaw moment are reduced compared to a true bottom setup, with the difference growing more pronounced at shallower depths. The study also proposes and preliminarily tests countermeasures against this false bottom effect, using computational fluid dynamics (CFD) simulations to assess their effectiveness. This research provides valuable insights for accurate hydrodynamic force measurements in ship model testing, particularly in shallow water environments.

Delefortrie et al. (2023) provided an in-depth analysis of shallow water effects on ship manoeuvrability using experimental fluid dynamics (EFD), focusing on cases from SIMMAN 2020. The study utilizes historical test data and new trials to understand the behaviour of ships like KVLCC2 and KCS in shallow waters. A major finding is the significant impact of underkeel clearance on ship performance, particularly in manoeuvres like zigzag tests. This research enhances the understanding of ship dynamics in shallow waters, offering valuable insights for navigation and design in such conditions.

The studies reviewed highlight the multifaceted challenges of navigating in shallow, restricted, and confined waterways. From the impact of environmental factors like mud layers and bank effects to the design considerations such as propeller direction and barge configurations, these papers underscore the need for a comprehensive approach to maritime navigation safety and efficiency. As shipping continues to evolve, understanding these complexities becomes ever more critical for the sustainable and safe operation of vessels in such specialized conditions.

2.1.2 Deep and Unrestricted Waterways

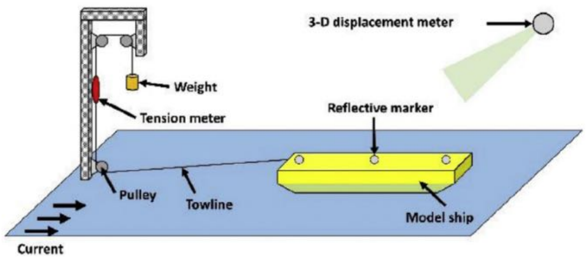
<u>Environmental effects</u>

Lu et al. (2023) assessed the manoeuvrability of a 7m KVLCC model numerically and experimentally. The tests presented by the authors were conducted under field conditions, and some random factors of the field environment were not considered into the mathematical model. This approach amplifies the idea, that the impacts of wind, wave and current should be integrated into the modular model to describe motion responses of different ship manoeuvrings in real sailing situations.

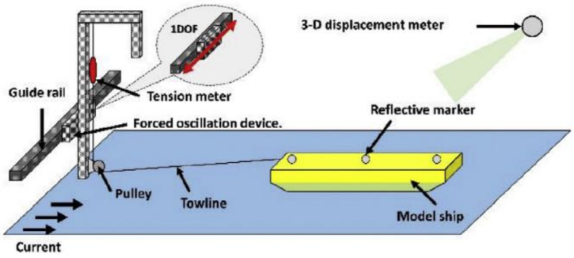
Yasukawa et al. (2022) investigated the influence of slight initial disturbances made by environmental factors, which occur immediately after the start of the stopping test, on the stopping performance by propeller reverse rotation. The authors additionally discussed the standard for acceptable initial disturbances. It was concluded that initial disturbances on track reach (RT) are closely related to the course stability of the ship. It is suggested that for analysed bulk carrier in course-unstable loading condition the absolute non-dimensional value of the initial yaw rate should be minimized, and the non-dimensional value of the initial lateral velocity component should be maintained at −0.02 to 0.02. In course-stable loading condition even if those values were exceeded the error in RT was minimal.

Testing procedures

Park et al. (2021b) presented a new method for testing of towing operation stability (see Figure 1). The authors introduced forced oscillation device changing frequency and amplitude. As an example, tugboat -FPSO configuration has been tested and results of towing- and course-stability have been checked. The authors investigated the influence of the length, trim condition and speed of the tug-barge set on the reaction of the towed FPSO.



(a)



(b)

Figure 1. Conventional (a) vs. new (b) experimental method for towing testing.

Kitagawa et al. (2022) described a methodology for carrying out the free-running model tests with correction for skin friction between full scale and model scale. An Auxiliary Thruster System (ATS) was introduced to minimise the scale effect on rudder effectiveness induced by the propeller loading condition, measured results of ship motion and surface pressures. The authors calculated the skin friction correction as recommended by ITTC ’78 and used this value as the target thrust of the ATS, that consisted of an aerodynamic ducted fan, a loadcell and a PC for controlling the exact value.

Mathematical modelling

Kryvyi and Miyusov (2021) presented multivariate regression analysis of mathematical models of hydrodynamic forces and moments. The authors suggest a unified approach to the construction of models of hydrodynamic forces and moment, based on multivariate regression analysis, using Fisher's and Student's criteria.

Yasukawa et al. (2021) presented a new method for improving the formula for the longitudinal inflow velocity component to the rudder used in the MMG modelling method. The authors pointed out that the original MMG model is applicable to estimating the rudder force, including the hull-rudder interaction force component, when the absolute values of the hull drift angle are smaller than 45°. In the region where the absolute values of the hull drift are larger than 45°, the flow straightening factor is not constant, and the MMG model cannot be applied.

For improving the original formula for longitudinal inflow velocity component to the rudder, a new formula was proposed by the authors.

Ma et al. (2021a) presented research on uncertainty analysis of Planar Motion Mechanism PMM model tests. The authors performed randomness analysis, stationarity analysis, normality analysis, and statistical convergence of the acquired data to assess their quality. Additionally, the uncertainty analysis (UA) method for the PMM tests performed in the circulating water channel was also developed by the authors.

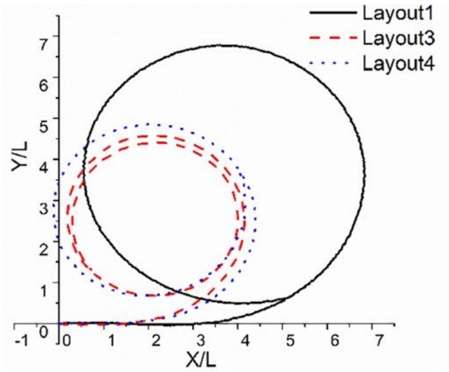
Sadati and Zeraatgar (2023) presented in their paper the tuning manoeuvre of the planning craft simulations carried out using 4+2DOF method in several operation modes such as semi-planning to semi-planning, planning to planning and planning to semi-planning. The hydrodynamic derivatives in the simulations were concluded from PMM tests in both the planning and semi-planning modes in a range of forward speeds.

Zhang et al. (2023) evaluated the manoeuvrability of a fast waterjet-propelled trimaran with three methods – CFD, EFD and MMG. The authors concluded that empirical hydrodynamic derivatives based MMG method produced the fastest results, but lacked accuracy in simulating a constant turning diameter, making it suitable for fast manoeuvring estimation and prediction during the design stage. Conversely, a direct force (moment)-based CFD model required more accurate input estimates to acquire acceptable simulated results. Meanwhile, a body force based CFD model considered more complex nonlinear impacts and was most similar to reality, achieving better agreement with the experimental results.

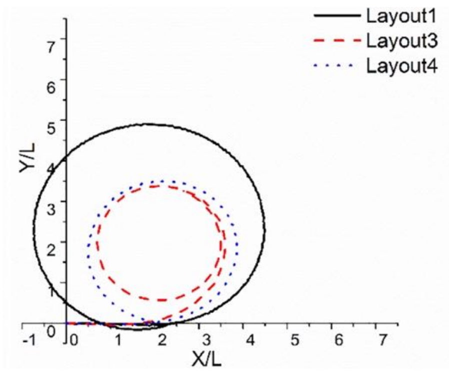
Nautical studies related manoeuvrability

Reichel (2021) presented the influence of propulsion-steering system on the position of pivot point on a large LNG carrier during standard manoeuvres. The author analysed two arrangements, i.e., twin-pod propulsion system and the conventional twin-propeller twin-rudder configuration. He pointed out that the pivot point for the same pod/rudder angles is much closer to midship for pod version than for ruder version.

Berg et al. (2021) presented manoeuvring analysis of a double-ended ferry based on CFD, PMM and full scale tests. An extremely important issue raised by the authors is that IMO standard manoeuvring tests are of little value for ship captains on double-ended ferries, and more data on low-speed manoeuvring is needed from safety of navigation point of view.



(a) δ=-15°



(b) δ=-25°

Figure 2. Turning trajectory with different layouts and rudder angles at F_r=0.353.

Jiang et al. (2022) investigated a self-propelled trimaran model powered by two waterjet impetus. The manoeuvrability of the trimaran is studied in self-propulsion navigation tests in a reservoir (open water). The turning and zig-zag manoeuvres with different layouts (i.e. side hull positions) and nozzle angles are carried out at various speeds. It is found that the position of

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the side hulls has an obvious influence on turning manoeuvres, as shown in Figure 2. A larger hull separation leads to a larger turning diameter. However, the effect of layout on zigzag manoeuvres is relatively weak.

Park et al. (2021a) investigated the course-keeping stability of a water-jet propelled planning boat through model- and full-scale experiments as well as model-scale CFD analysis. The results show that the flat and wide waterjet intake plane of the initially designed boat makes the course-keeping stability worse.

2.2 Numerical Simulations

2.2.1 Shallow, Restricted and Confined Waterways

The shallow, restricted and confined water definitions in the 28th Manoeuvring Committee are used in this report.

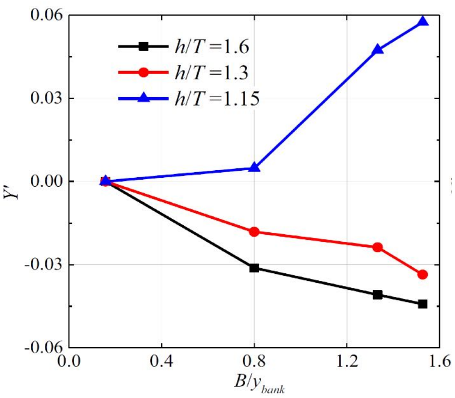


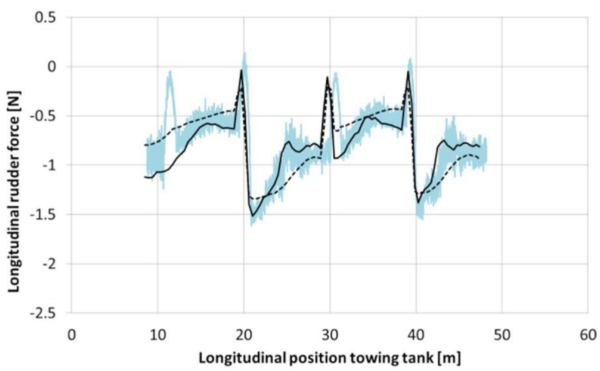
Figure 3. Non-dimensional sway force at different water depths for KCS at U = 0.73 m/s.

Liu et al. (2021) presented a CFD validation and analysis of ship-bank interaction for a model scale KRISO Container Ship (KCS) under extreme ship-bank distance conditions, water depth and ship speed. The predicted resistance and squat were compared with the model test data for depth to draft ratios of h/T = 1.3 and 1.6, and good agreement was achieved. However, the trim was over-predicted. It was found the sway force (Y') changes from attraction to repulsion force with an increase in the water depth, as seen from Figure 3. The magnitude of these parameters increases with a decrease in ship-bank distance (y_{bank}). Comparison of the results with and without free-surface modelling also indicated that the wave action is a key factor significantly influencing the hydrodynamic characteristic of the ship-bank interaction.

Delefortrie et al. (2022b) developed a mathematical model to predict the force and moment on a rudder behind the propeller of KCS applicable to the ship manoeuvring in shallow and confined water. The coefficients of the mathematical model for the rudder force and moment were driven from the captive model tests conducted at Flanders Hydraulics Research. The tests were performed in full four quadrant conditions and for a full drift and yaw range a ship may experience in a harbour. The predicted rudder force was compared against measurement for all captive test conditions and good agreement was achieved, as presented in Table 1. Enhancement in rudder torque prediction was recommended. The predicted rudder forces were also compared with the force measurement of a free-running model test and good agreement was found with slight discrepancy for the lateral force, as demonstrated in Figure 4.

Table 1. Comparison between measured and modelled rudder force.

Ukc (%)	Longitudinal force (N)	Lateral force (N)
100	$F_{X,\mathrm{mod}} = 0.9485F_{X,\mathrm{meas}} - 0.0217$ $R^2 = 0.9416$	$F_{Y,\mathrm{mod}} = 0.9562F_{Y,\mathrm{meas}} + 0.0171$ $R^2 = 0.9509$
50	$F_{X,\mathrm{mod}} = 0.9340F_{X,\mathrm{meas}} - 0.0372$ $R^2 = 0.9148$	$F_{Y,\mathrm{mod}} = 0.9477F_{Y,\mathrm{meas}} + 0.0022$ $R^2 = 0.9454$
20	$F_{X,\mathrm{mod}} = 0.9430F_{X,\mathrm{meas}} - 0.0288$ $R^2 = 0.9338$	$F_{Y,\mathrm{mod}} = 0.9422F_{Y,\mathrm{meas}} - 0.0097$ $R^2 = 0.9427$
10	$F_{X,\mathrm{mod}} = 0.9066F_{X,\mathrm{meas}} - 0.0421$ $R^2 = 0.9112$	$F_{Y,\mathrm{mod}} = 0.9028F_{Y,\mathrm{meas}} + 0.006$ $R^2 = 0.9127$



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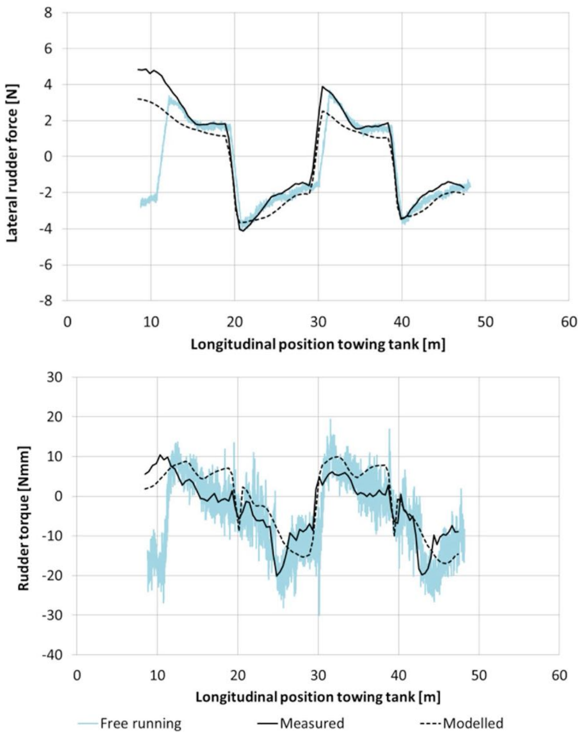

Figure 4. Comparison between modelled and measured rudder forces in a − 20/5 free-running tests, 50% under keel clearance (UKC).

The 6th International Conference on Ship Manoeuvring in Shallow and Confined Water (MASHON) was held in Glasgow, UK in 2022 and research in several shallow and confined water subjects was presented, as summarized below.

Most of the studies presented in the 6th MASHCON are based on CFD simulations. Zheng et al. (2022b) used STAR-CCM+ to investigate the unsteady hydrodynamic interaction of KCS parallel passing a moored Neo-Panamax container ship in port as a MASHCON benchmark case. The relative motions between the two ships were modelled with a dynamic overset mesh technique. For a UKC of 10%, similar trends between the CFD prediction and model test data were reported for hydrodynamic quantities and flow field details with some discrepancies at the early and late passing stages. Closer agreement between the two studies was found for a larger UKC of 50%. Yu et al. (2022) also performed viscous flow simulations of KCS passing Aframax tanker in shallow and confined water using an in-house CFD code. The spatial and temporal sensitivity analysis of the numerical approach for the stand-alone KCS showed convergence of the predicted heave and pitch motions to less than 5% relative difference to the model test. The predicted forces, motions and wave elevations during passing exhibited the same trends as the measured quantities. Kwon and Yeon (2022) used CFD to predict the ship-ship hydrodynamic interactions in a confined waterway. An overset gridding method was employed for movement of the passing ship, a KCS container ship, while the model was fixed in heave and pitch. The predicted forces and moments on the moored ships, a Neo-Panamax containership and an Aframax tanker were consistent with the MASHON 2022 benchmark data. The calculated dynamic pressure field and free surface elevation in the vicinity of the ships were also analysed, and it sheds light on the ship-ship interaction problem. It was shown that the pressure field generated by the Bernoulli effect around the passing ship influenced the moored ship, while the effect of moored ship on the passing ship was subtle. Yang and Moctar (2022) performed CFD simulations with a PMM of a KCS at a range of water depths to examine the shallow water effects on added mass and its frequency dependence. It was found that the hydrodynamic forces become highly non-linear when increasing the motion amplitude in shallow water (h/T = 1.2 and 1.5), while the effect of the motion amplitude was negligible in deep water. Frequency dependency of the yaw added mass coefficients in shallow water was also observed. For the PMM tests in shallow waters, small motion amplitudes at low frequencies were recommended. Kim et al. (2022a) performed CFD analysis of KCS free running manoeuvring in shallow waters with h/T = 1.2 – 4. Comparison of the predicted manoeuvre at a selected condition with model test data was satisfactory. It was shown that the standard turning circle parameters increase as the water depth decreases, with predicted transfer and tactical diameter being more than twice for h/T = 1.2 than those at deep water conditions.

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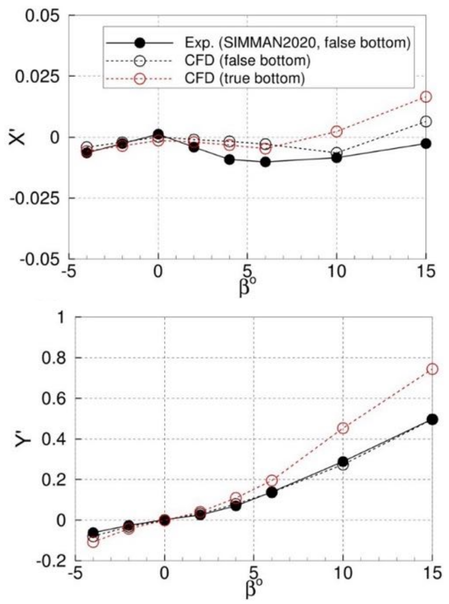
Potential flow method, empirical formulas and system identification based method were also used to tackle the issues occurs in confined waterways. Liu et al. (2022b) used a 3D potential flow solver, called MHydro which is based on the Rankine source panel method to model a KCS passing a Neo Panamax containership for water depth to draft of 1.5. Due to the unsteady nature of the problem, the code automatically re-meshed the entire computational domain. A three-time-level scheme was proposed in their study to investigate the contribution of the unsteady terms on the ship-ship hydrodynamic interaction. A satisfactory agreement between the prediction and model test data was obtained for the forces and wave elevations, while a great discrepancy was observed for the yaw moment. In addition, keeping the unsteady terms in the free surface conditions improved the prediction of unsteadiness in forces and waves for the most part of the passing. Liu et al. (2022c) also employed MHydro to simulate a ship entering a lock and showed the importance of the unsteadiness introduced by the free surface in predicting the hydrodynamic forces and waves in a lock. The potential flow method was also used by Lindberg and Vilmann (2022) to predict the hydrodynamic effects of ships in shallow and confined waters. The predicted squat and bank effects with this model for KCS and KVLCC2 operated in shallow water were compared against experiments and a satisfactory comparison was achieved. Miyauchi et al. (2021) developed a system-based mathematical model suitable for a berthing manoeuvre. System identification (SI) method was adopted for optimizing system parameters which reduced the amount of model tests compared to the captive model test approach. The results of the mathematical model based on the SI optimization approach showed a better agreement with the free running model test than the captive model approach.

Following the 2008 and 2014 workshops on the Verification and Validation of Ship Manoeuvring Simulation Methods, the SIMMAN 2020 workshop was held in 2023. The objective of these workshops is to assess the current simulation methods for ship manoeuvring, aid code development, establish best practices and guide industry. Two test cases including KVLCC2 and KCS were in shallow water ($h/T = 1.2$) condition. A summary of the selected papers on this topic is given below.

Sakamoto (2023) performed RANS validation and analysis for KCS under static drift and rudder configurations. The differences in hydrodynamic force prediction observed between false and true bottom condition indicated the importance of replicating the tank bottom in simulation for validation purpose. Hoydonck (2023) performed CFD simulations of KVLCC2 in shallow water under static drift and steady turn (Case 2.1) and predicted drag and lateral forces and yaw moment. A reasonably linear variation of the lateral force and yaw moment with the drift angle at low drift angle ($\beta \leq 6°$) was observed. The lateral force was higher for the wall resolved grid compared to the wall functions grid for $6° \leq \beta \leq 10°$. Pressure field around the hull in relation with the lateral force under the steady turn conditions was examined. Sensitivity of the predictions to the grid resolution was also investigated.



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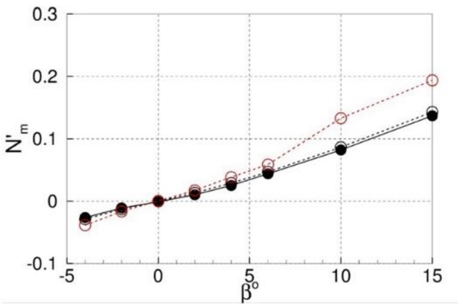


Figure 5. Experimental and computational results of surge force, sway force, and yaw moment acting on the KCS under static drift in shallow water (*h/T* = 1.2) with false bottom, the experimental data with true bottom.

False bottom problem, which has been highlighted in The 29th ITTC Manoeuvring Committee (2021) has been systematically studied by Sakamoto et al. (2023). An in-house viscous flow solver, NAGISA, was used to investigate the effect of a false bottom on a KCS model in shallow water (*h/T* = 1.2) under static drift and static rudder conditions. Figure 5 compares the predicted forces and yaw moment and model test under static drift conditions. The predicted loads with a false bottom correlate the measured quantities with an identical bottom configuration. However, the predicted hydrodynamic coefficients of the true bottom configuration deviate from those with the false bottom configuration at moderate to large drift angles. The study showed that even a gap size of 10% of the KCS length used for the false bottom was not sufficient to represent a true bottom. The forces and moments were not affected by the bottom configuration under the static rudder test. However, 7 – 10 % differences in the hull-rudder coefficients were observed between the results of the two bottom configurations. The authors extended this analysis to a pure yaw motion and found that the true bottom generated a smaller 1st harmonic amplitude of the total yaw moment than the false bottom. Significant differences were also observed for the linear hydrodynamic coefficients of the two bottom configurations. A local flow analysis provided insight into potential contributors to these differences. Asymmetric patterns of pressure distribution with respect to the centreline was observed on the tank bottom with a larger magnitude for the true bottom. Integration of bottom pressure quantifies the required mass for a false bottom unit, which can be helpful for design of a false bottom. Clear differences in the unsteady vortical structures during the yaw motion were also observed between the two tank bottoms, which could explain the discrepancies in the predicted hydrodynamic coefficients.

2.2.2 Deep and Unrestricted Waterways

Numerical simulations of ship manoeuvring in deep and unrestricted water typically involve solving the six-degree-of-freedom manoeuvring equation based on hydrodynamic coefficients. Chame and Tannuri (2023) adopted an open-source code OpenFOAM and conducted static drift tests on the model-scale bare hull of the KVLCC2. The predicted cross-flow drag coefficient and resistance force coefficient are all in good agreement with those from the literatures. The friction resistance coefficient showed a remarkable difference between model-scale and full-scale Reynolds numbers, as expected. The discrepancy between numerical and experimental of Y_v is 1.3% and 3.1% for model-scale and full-scale Reynolds numbers respectively. However, scale effects have a negligible effect on N_v.

Zhu and Kim (2023) adopted a CFD method to simulate the oblique towing test (OTT) and circular motion test (CMT) in deep water conditions. The simulated results show highly nonlinear behaviour at high rate of turns. In CFD numerical setups, more refined boundary meshes are required to capture the boundary flow.

Lu et al. (2022) proposed an integrated CFD and empirical manoeuvring model to predict the manoeuvrability of a twin-propeller twin-rudder (TPTR) inland vessels. This model was validated against free-running model test data of a 64TEU TPTR inland container. By comparing their simulation results to the experiments, it shows that applied CFD methods can help to increase the modelling accuracy, and the integrated manoeuvring model can roughly fit main characteristics of different motion parameters during manoeuvring motions.

There are more applications of CFD methods to directly simulate the self-propelled manoeuvring motions of ships. Propeller modelling is one of the key elements for analysis of hull-propeller-rudder interactions. Two major techniques, namely the direct or actual propeller (AP) method and the body force model, have been widely used by researchers in ship hydrodynamic community.

Oud and Toxopeus (2022) proposed a solution based on a single grid setup with consistent boundary conditions and incorporating a body force wake damping zone to accurate computation of hydrodynamic loads on ships during steady yaw manoeuvres. Their method could solve challenges when a ship encounters its own wake when rotating (see Figure 6), leading to an effective, fast, and accurate method to compute hydrodynamic loads of a ship in steady yaw manoeuvres.

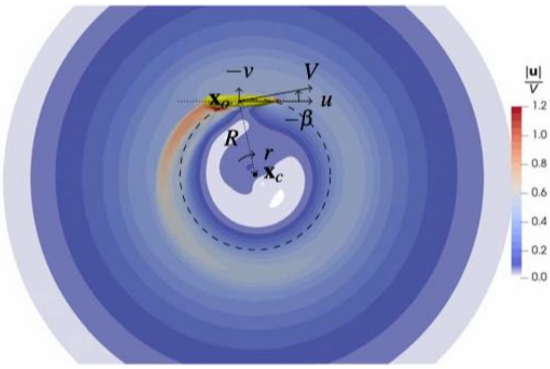
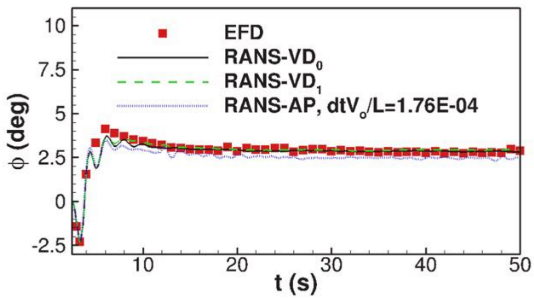
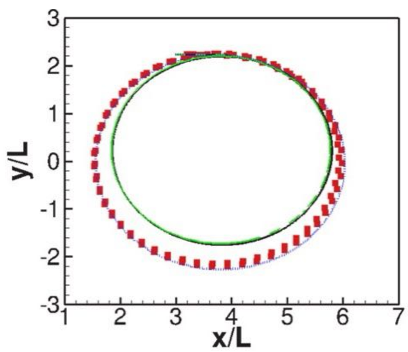


Figure 6. Velocity contours resulting from a steady computation of a rotational manoeuvre with drift in shallow water.

Aram and Mucha (2023) conducted turning circle simulation of the ONRT model with rudder angles of 25° and 35° and 20° zig-zag manoeuvre at F_r = 0.2. They utilized two distinct propeller models: a body force model rooted in open-water propeller testing and a discretized propeller model. The predicted manoeuvring characteristics were compared against the model test data. The actual propeller (AP) model showed a closer agreement to the experiments compared to the virtual disk (VD) model. Although all propeller models offered an excellent agreement to the model test for the time history of motions and velocities in the transient phase of the turning manoeuvre, the VD models deviated more from the experiment in the steady turn phase compared to the AP model, as shown in Figure 7. Their findings revealed that the absence of propeller side force in the body force model contributes significantly to its inferior accuracy when compared to the discretized propeller model. However, AP model is about 36 times more expense than VD model in terms of computational cost.



(a) Roll angle



(b) Trajectory

Figure 7. Time history of ship manoeuvring characteristics in port turn with 25° rudder angle.

It is important to note that recently there are more studies focusing on the application of intelligent methods, such as Neural Network, to predict the hydrodynamic characteristics. Support vector machine (SVM) based on a grey box model is one of the most commonly used methods. Based on the MMG model, Mei and Shi

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(2023) proposed a 4-DOF grey-box model to predict ship manoeuvring motions. The results show that the fidelity of the model is high when the disturbance level is low and decreases with the increase of the disturbance level. Compared with black-box model, the grey-box model can reflect the physics of ship manoeuvring motions, and it is convenient to observe the changes of specific parameters under different disturbances. It should be noted that this grey-box model only involves one-time identification modelling. It cannot be applied to real-time modelling of ship motion when ship parameters are subject to change, for instance, under different loading conditions.

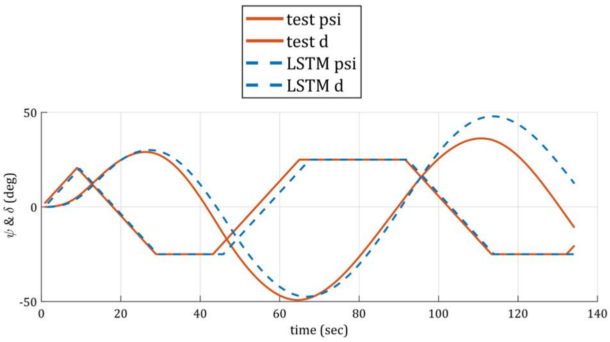

Figure 8. Predicted result of 10°/5° zig-zag test using LSTM deep neural network.

Another widely used method is the neural network method. Jiang et al. (2022) proposed a novel system identification scheme based on long–short-term-memory (LSTM) deep neural network to obtain the multi-input multi-output (MIMO) model of ship manoeuvre motions. As shown in Figure 8, the comparison between the simulated and predicted results demonstrates that the LSTM neural network is capable of identifying the mathematical model of ship manoeuvring motion. In particular, the robustness to noise of the LSTM model is validated by learning the model of manoeuvring motion using the training data artificially contaminated with Gauss white noise of different levels. The results show that the proposed identification modelling method has promising anti-noise performance. It should be noted only artificially contaminated data from the simulated manoeuvres are used to train the LSTM. For such data-based method, real data from model tests or even full-scale trials are urgently needed.

Jeon et al. (2022a) proposed a 4-DoF dynamics model to predict the manoeuvring motion of a warship in both intact and damaged conditions. The asymmetric manoeuvring characteristics of starboard and port turning motions under the damaged condition were successfully captured by their model, as shown in Figure 9. However, it is very challenging to address the simultaneous drifting phenomenon. Their method relies on captive model test results, and it cannot solve the multicollinearity caused by high correlation between motion variables. If there are no captive model test results, it is recommended to first estimate the hydrodynamic derivatives using empirical formulas and CFD simulations, and then perform system identification.

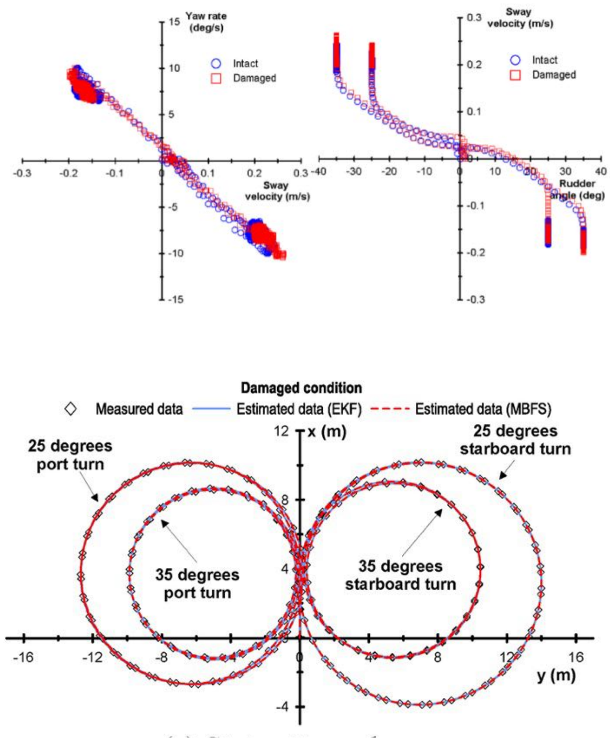

Figure 9. Measured and estimated trajectories of a warship under damaged conditions in a 25° turning motion.

Wakita et al. (2022) proposed a new system identification method to predict low-speed manoeuvres by using RNN and free running model tests. They compared two RNN models and

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found the prediction accuracy of the RNN that ignores the memory before a certain time was better than the "standard" RNN. To reduce the adverse effect of the noise included in the measurement data, a loss function was used, which has been proved to significantly improve the NN's prediction accuracy. It should be noted that the prediction accuracy of their method is strongly depended on the dataset, in particular the amount of data and types of manoeuvres in the data set. RNN is also used by Hao et al. (2022) to predict the ship manoeuvring motion of a KCS.

Based on full-scale trial data, Meng et al. (2022) developed a parameter identification scheme by using a Support Vector Regression (SVR) and a Modified Grey Wolf Optimizer (MGWO) to identify the response mathematical model and 4 DOF nonlinear whole-ship mathematical model of vessel YUKUN. Their prediction of ship motion state show that the MGWO algorithm has strong search and optimization ability. In the case that the reference values obtained by SVR are not accurate, MGWO algorithm can be used to identify accurate parameters of the mathematical model of ship manoeuvring motions.

Apart from CFD and data-based methods, mathematical models still play an important role in ship manoeuvring prediction. Barrera et al. (2021) developed a mathematical formulation to predict the actuation of vector tugs during docking, steering, and braking manoeuvres. The results show the proposed model can improve the realism of vector tug towing force prediction and positioning during maritime simulators manoeuvres. However, the model does not take into consideration of thruster-to-thruster interactions. As a result, it imposes an error of about 30% on the towing force prediction.

Daidola (2022) investigated the effects of hull roughness on ship manoeuvring characteristics. The hydrodynamic derivatives in ship manoeuvring motion equations are modified to incorporate roughness of the hull and rudder. By calculating turning motions of single screw cargo ships, it is found that the turning radius increases with time. After 25 years, the turning radius of a range of vessel sizes is in the range of 2.5–4.6% over which would be predicted for a smooth model,

Cura Hochbaum et al. (2022) proposed a mathematical model to predict the manoeuvrability of planning vessels in calm water considering all six degrees of freedom. All hydrodynamic coefficients of the used mathematical model were obtained from RANS simulations. A key advantage of their method is the ability to predict manoeuvres in vanishing CPU time once all coefficients have been determined. This allows for predicting new manoeuvres or easily repeat one with changed parameters, as well as to analyse the stability of chosen motion modes.

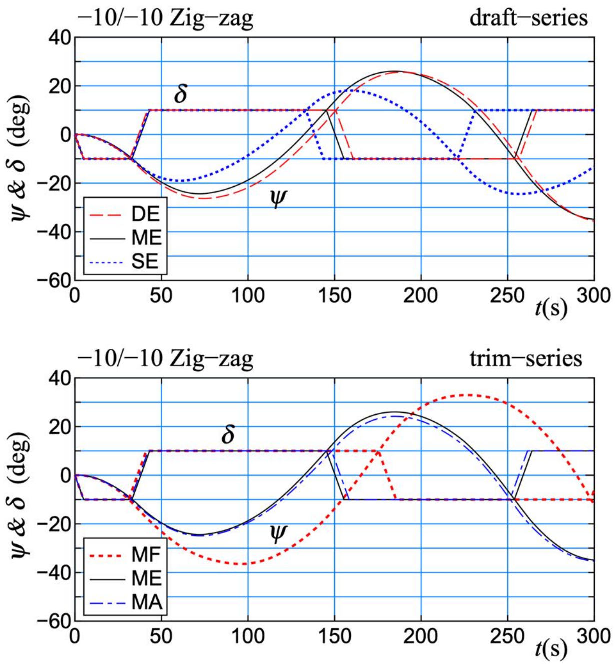

Figure 10. Time histories of ψ and δ in zig-zag manoeuvres under different loading conditions. ME: middle even; MF: middle fore-trim; MA: middle aft-trim; SE: shallow even; DE: deep even.

The MMG model is used by Yasukawa et al. (2023) to investigate how changes in the loading conditions affect ship manoeuvring. Five loading conditions with different displacements and trims were set in the vicinity of the full load condition for a container ship. It is found when the aft trim is attached to the ship, the course stability is improved, and the overshoot angle in the zig-zag manoeuvre is reduced. On the other hand, when the draft is deeper or when the bow trim is attached, the turning performance is improved, as shown in Figure 10, but the course stability deteriorates, and the overshoot angle often does not meet the IMO manoeuvrability criteria. It was concluded that the course stability of the container ship is significantly influenced by the loading condition.

3. BENCHMARK DATA

The main development in the field of benchmark data for manoeuvring prediction in the recent years has been connected to SIMMAN2020 concerning both captive and free running data in captive and free running mode in both calm deep water, calm shallow water and in waves. At the recent SIMMAN conference the focus was placed on the three hulls: KVLCC2, KCS and ONRT.

Besides SIMMAN, captive shallow water benchmark data have also been published for the 6th MASHCON, with focus on the effects of passing ships on moored ships.

3.1 SIMMAN2020

SIMMAN2020 was held in July 2023 in Seoul, South Korea, with the objective to obtain, assess and discuss the state of art in manoeuvring prediction techniques. The workshop was made as a follow up and continuation of the SIMMAN2014 and SIMMAN2008 workshops and like the past events, the purpose is still to benchmark the capabilities of manoeuvring prediction methods through comparisons with towing tank results.

Although the workshop was held in 2023, all submissions to the workshop were created in 2019 or earlier, with the latest submissions in January 2020. Due to the worldwide pandemic, the SIMMAN2020 workshop, which was planned for April 2020, was postponed to 2023. The delay turned out to influence the data analysis and the reporting and thereby changing the way in which the workshop was going to be organised. In 2021 the SIMMAN committee decided to issue the result as triple volume books, based on the results of SIMMAN2020 (Quadvlieg et al., 2023, 2024), instead of just a conference with presentations. Since all results were generated in 2019, the workshop was still called SIMMAN2020, as it reflects the state-of-the-art in 2020 and not in 2023. If submissions were allowed to be redone in 2023, due to increased insights, progresses in code development, increase of computer power, and increase of user experience, etc., the results might have been different.

The SIMMAN2020 test cases are a tanker, a container ship, and a surface combatant hull form like SIMMAN2008 and SIMMAN2014. The tanker and the container ships are still represented by the KVLCC2 tanker and the KCS container ship, whereas the 5415M surface combatant has been replaced by the ONR Tumble home (ONRT). The ONRT is a well-established surface combatant hull form like the 5415M and used in past CFD workshops and NATO-AVT. The KVLCC2 is kept as a reference ship due to the low Froude number and the high GM, which simplifies the problem as both the free surface and heel motion may be neglected. The KCS is kept as a reference ship because of the relatively strong heel-to-yaw coupling affecting the manoeuvring characteristics of the ship. The ship is tested at a very low GM (0.6m in full scale), which makes the ship a particularly interesting case when it comes to 4DOF motions. The ONR Tumblehome model 5613 (ONRT) is a preliminary design of a modern surface combatant and was introduced instead of 5415M to include new test cases for the participants. The benchmark data sets of the ONRT are all new model tests and includes both captive tests and free running model tests (FRMT).

For both the KCS and the ONRT the FRMT tests were carried out in calm water as well as regular waves. The full overview of all test cases in seen in Table 2.

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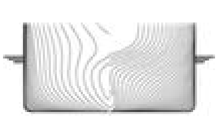
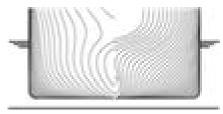
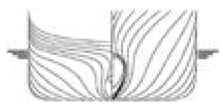
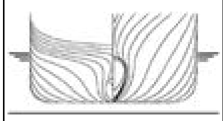
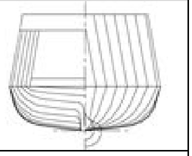
Table 2 Overview of test cases.

		Case 1 KVLCC2-deep	**Case 2 KVLCC2-shallow**	**Case 3 KCS-deep**	**Case 4 KCS-shallow**	**Case 5 ONRT**
						
Calm water	Captive forces and moments	Case 1-1 1-1-1: pure drift 1-1-2: drift with yaw	Case 2-1 2-1-1: pure drift 2-1-2: yaw with drift	Case 3-1 3-1-1: pure drift 3-1-2: drift with yaw	Case 4-1 4-1-1: pure drift 4-1-2: yaw with drift	Case 5-1 5-1-1: pure drift
		EXP by HMRI	EXP by BSHC	EXP by JMU	EXP by KRISO	EXP by SNU
Calm water	Trajecto-ries	Case 1-2 1-2-2: 20/20 ZZ (SB) 1-2-3: 35 TC (PS)	Case 2-2 2-2-2: 20/5 ZZ (PS) 2-2-3: 35 TC (PS)	Case 3-2 3-2-2: 20/20 ZZ (PS) 3-2-3: 10/10 ZZ (PS) 3-2-4: 35 TC (PS) 3-2-5: 20/20 ZZ (SB)	Case 4-2 4-2-2: 20/5 ZZ (PS) 4-2-3: 35 TC (PS)	Case 5-2 5-2-2: 20/20 ZZ (SB) 5-2-3: 35 TC (PS)
		EXP by MARIN	EXP by FHR/MARIN	EXP by MARIN	EXP by MARIN	EXP by IIHR
Waves	Trajecto-ries			Case 3-3 3-3-1: 35 TC (SB) calm w 3-3-2: 35 TC (SB) waves		Case 5-3 5-3-2: 35 TC (PS) waves
				EXP by HU		EXP by IIHR

SIMMAN2020 worked on two paths similar to SIMMAN2014:

- Captive forces and moments, where the focus is prediction of forces and moments for selected and well-defined cases using the force reconstruction method.

- Trajectories, where focus is prediction of trajectories of well-defined manoeuvres, which also includes turning circles in regular waves.

Based on the experience from SIMMAN2014 the following changes were introduced for SIMMAN2020 compared to SIMMAN2014 (and SIMMAN2008).

SIMMAN2020 used the force reconstruction as a measure for the quality of force and moment predictions. I.e. the submissions by the participant were not compared to individual tested point, but to an entire set of captive tests, which allows to make a simplified mathematical model. Previous SIMMAN workshops focused on a very selected point (such as only 1 drift angle), but the capabilities for predicting forces and moments have improved so much since the first SIMMAN workshop, that a range of drift angles and yaw rates are easily prescribed, which allowed for this different approach compared to previous workshops. The methodology to make this comparison was designed and made prior to the SIMMAN2020 workshop. The cases for the forces and moments were simplified as much as possible (only drift angles and yaw rate, no rudder angles, no RPM changes) to prevent misunderstandings and limit the uncertainties from the benchmark test cases. The total number of cases was minimized to increase the number of submissions per test case, i.e. only deep water and $h/T = 1.2$ was included, without considering intermediate water depths. A second measure to increase the number of submissions per test case was to apply a staircase approach for the test cases. It was only possible to make a submission for the complicated case if a submission is also made for the simple case. The comparisons for the free running model tests were partly blind in the sense that the FRMT data in calm water that was re-measured after SIMMAN2014 along with the data in waves was not provided to the participants prior to the workshop.

3.1.1 Prediction of forces and moments

Forces and moments are submitted for specific combinations of drift angle β and non-dimensional rotational velocity r'. All cases are defined with a rudder angle of zero. This means that the submissions are insufficient so make a simulation model, but the data is enough to make a decent fit of the hull forces with the rudder at zero. Three of the four cases have an acting propeller (case 1-1, 2-1 and 4-1), and one case is without propeller (case 3-1).

To make a base model for the comparison, a set of experiments was used, as obtained from one of the model basins around the world. Through these experimental points, a mathematical model is fitted. This model has the following shape for all cases:

$$X' = X_0' \cdot u'|u'| + X_{vv}' \cdot v'^2 + X_{vvvv}' \cdot v'^4 + X_{rr}' \cdot r'^2 + X_{vr}' \cdot v'r'$$

$$Y' = Y_v' \cdot v' + Y_{v|v|}' \cdot v'|v'| + Y_r' \cdot r' + Y_{r|r|}' \cdot r'|r'| + Y_{vvr}' \cdot v'^2 r' + Y_{vrr}' \cdot v' r'^2$$

$$K' = K_v' \cdot v' + K_{v|v|}' \cdot v'|v'| + K_r' \cdot r' + K_{r|r|}' \cdot r'|r'| + K_{vvr}' \cdot v'^2 r' + K_{vrr}' \cdot v' r'^2$$

$$N' = N_v' \cdot v' + N_{v|v|}' \cdot v'|v'| + N_r' \cdot r' + N_{r|r|}' \cdot r'|r'| + N_{vvr}' \cdot v'^2 r' + N_{vrr}' \cdot v' r'^2$$

The values of these coefficients X_0' through N_{vrr}' were determined by a least squared method and the quality of the fit was determined by the R^2 method.

An example of a fit of the experimental value, together with the obtained values for the coefficients is shown in Figure 11. The figure shows:

- the individual experimental data points (blue dots).
- the fit through the data points as determined using the least square fitting (blue drawn line).
- the light blue shaded area around the line indicates the 2 x standard deviations above and below the line.
- the values of the coefficients that describe this fit.
- the value of R^2.
- the standard deviation between the fit and the points.

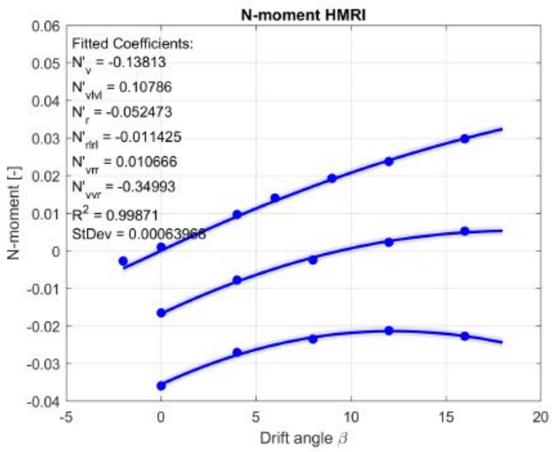


Figure 11. Uncertainty of the experiment in deep water with the KVLCC2.

Similar fit of the mathematical model was done for all the submissions. Just like for the experiments, it is possible to determine the R^2 for the fit of the submissions, which represents the quality of the fit.

The presently selected approach (the force reconstruction) is a new development engineered while performing the analysis for SIMMAN2020. The time needed to engineer the methodology was kindly provided by the delays caused by worldwide pandemic. The method is that:

– From the individual forces and moments for given drift angles and rotation rates a fit is created.
– This fit is compared against a fit from the experiments on a point-by-point basis.
– This is then summarised in a joint error per series.

For all cases, it was observed that the pure drift cases were well captured by the majority of CFD submissions, both in deep and shallow water. The average submission error $E\%D$ was 6.5% in deep water and 10.1% in shallow water. The

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submissions revealed a need for further improvements and investigations regarding rotation in especially shallow water, with an average error $E\%D$ of 16.2% in deep water and 26.2% in shallow water for combined yaw with drift or combined drift with yaw. For CFD submissions, it was unclear whether a distinction could be seen between free-to-heave-and-sink versus fully-captive, double body versus free surface, the choice of code, turbulence models, amount of grid cells, domain size and the different ways of modelling propellers.

Although the method of force reconstruction may be improved further, it is suggested in future work to gather experience with the present approach, as it appears to give a better overview of the capabilities than the approach used in the previous SIMMANs (2008 and 2014) which was based on individual data points. Furthermore, it is recommended to design one case for the next SIMMAN, which would focus on the prediction of flow separation during a manoeuvre, which can hopefully be compared to flow field data of separated flow. This might shed light on the recommended CFD settings to predict flow separation and hopefully achieve a better prediction accuracy for high drift angles and yaw rates. A much more thorough description of the validation approach and examination of the captive results is available in the final proceedings of SIMMAN2020 (Quadvlieg et al., 2024).

3.1.2 Prediction of trajectories in calm water and in waves

For the trajectory part of SIMMAN2020, it was chosen to compare data reduction and key characteristics, but not trajectories. For calm water manoeuvres in deep and shallow water, and for manoeuvres in waves, a set of key characteristics was defined and used. For all manoeuvres, it remains of interest to look at time traces of the velocities and the positions but to use the key characteristics to quantify the prediction errors.

Calm and deep water. For the calm water test cases, the focus on key characteristics and not the trajectories themselves proved to provide good insight into the capabilities to predict trajectories. The intention of the analysis was to obtain insight in:

1) A subgroup analysis, which resulted in the assessment of the capabilities of the different simulation methods also concerning the performance in deep water versus shallow water and calm water versus waves.
2) Status, quality, and suitability of the experiments.
3) Assessment of different hull forms.
4) Assessment of different manoeuvres.
5) Assessment of the data reduction and analysis procedures.
6) Assessment of effects CFD modelling: degrees of freedom, turbulence modelling, propeller models, free surface/double body flow, handling of wall functions etc.

In SIMMAN2014 the approach of considering the scatter in the results, alongside the prediction error, were introduced, i.e., the standard deviation σ of the submitted values S_i and errors in % of the mean value and experimental benchmark data D, respectively. The error averages $\bar{E}$ and standard deviations σ_E were also assessed using absolute value, which was found to provide a good assessment of prediction capability. Therefore, the same mind setting was continued in SIMMAN2020.

The error averages are interesting, as a small value of $\bar{E}$ indicates that the average of all submissions is close to the experiments. The spreading in the prediction error, which should also be small, is indicated by two variables in the SIMMAN2020 analysis: the standard deviation of all errors σ_E and the average of the absolute value of all errors $\overline{|E|}$. The advantage of the characteristic $\overline{|E|}$, is that it combines the average error and the standard deviation in one. $\overline{|E|} > \bar{E}$ will always apply, so the value of $\overline{|E|}$ will immediately reveal the quality of a (sub) group of predictions.

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In SIMMAN2014 only the KVLCC2 had enough submissions to draw any conclusions, i.e. the KVLCC2 was selected to review the progress of the calm water manoeuvres between 2014 and 2020. The results of SIMMAN2008 were too scattered to make any clear error definition, and therefore these results are not included in the present review. To make a fair comparison to SIMMAN2014 (Quadvlieg et al., 2014), the values of advance AD and tactical diameter TD have been used, as well as the values for the first and second overshoot angle. The other derived characteristics are not considered, as they were not part of the analysis in 2014. The summary of the overall error for KVLCC2 from 2020 and 2014 is given in Table 3.

Table 3. Comparison of the prediction error for KVLCC2 in deep water.

	SIMMAN2020	SIMMAN2014
Zigzag error	16 %	27 %
Turning circle error	7 %	6 %
Overall	11 %	16 %

The comparison shows that the zigzag errors are reduced by about almost 40% (from 27% to 16%), whereas the turning circle errors are similar. I.e. overall, this shows that the average prediction error has reduced from 2014 to 2020 (based on the KVLCC2).

Looking at all the hulls for SIMMAN2020, the conclusions for the overall average were seen to be the same as for each hull form. The empirical methods have about 2 x larger $\overline{|E\%D|}$ and $\overline{\sigma_{|E\%D|}}$ than those from the whole ship models, modular mathematical models and CFD, where the latter three all have similar capability.

Calm and shallow water. For the KVLCC2 and the KCS, manoeuvres were asked in calm and shallow water at *h/T*=1.2 for four cases: a zigzag test and a 35 turning circle manoeuvre for the two ships. The average submission error $\overline{|E\%D|}$ and the standard deviation of the error $\overline{\sigma_{|E\%D|}}$ per method was evaluated by using a similar method in the deep and calm water test cases.

For the experimental reference data, the uncertainty $U_D\%D$ was seen to be more than twice larger than that in deep water. The prediction errors $\overline{|E\%D|}$ were seen to be nearly 4 times larger than those in deep water, and the standard deviation $\overline{\sigma_{|E\%D|}}$ more than 6 times larger.

The number of submissions for the shallow water test cases is much lower than that for the deep water cases (25 in shallow water versus 111 in deep water). The reduction of the amount of test cases in shallow water compared to SIMMAN2014 (from 42 to 4) led to more submissions per case, but still, the number of submissions were insufficient to make a meaningful subgroup analysis. Looking at trends though, the subgroup analysis for the shallow water cases was similar to those for the deep water cases: the empirical methods have about 2 x larger $\overline{|E\%D|}$ and $\overline{\sigma_{|E\%D|}}$ than those from the whole ship models, modular mathematical models and CFD, where the latter three all have similar capability. The number of submissions has increased from 2014 towards 2020, but given the criticality of manoeuvring in shallow water, this topic should deserve more attention.

Waves. Besides calm water test cases, new test cases in waves were introduced for SIMMAN2020.

Turning circles in regular waves were carried out with both the KCS and the ONRT. The turning circle manoeuvre was simulated for at least 3 full turns, i.e., the models turn at least 1080 degrees with regards to the original heading. The analysis of the prediction in waves was divided into three aspects:

1) The drift-away characteristics due to the 2nd order wave forces.

2) The impact of the wave on the manoeuvring characteristics: the rate of turn, drift angle and roll angle are depending on the wave heading direction and consequently, there is a variation in these parameters as function of the local angle wave heading.

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3) The prediction of wave frequent motions (the 1st order motions) in surge, sway, heave, roll, pitch and yaw.

For each of the three aspects new key characteristics were derived.

The drift-away characteristics are evaluated based on the drift distance H_D and the drift direction μ_D.

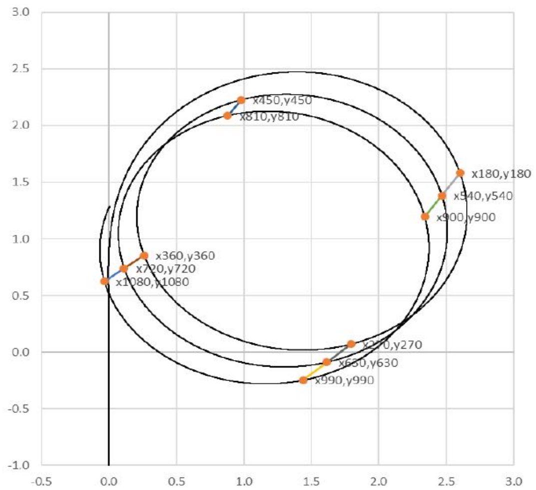

Figure 12. The drift-away characteristics.

The drift distance is calculated by the following two steps:

1) The drift distance of the individual points defined as the drift distance during 1 turn from 180° to 540°and up to 720° to 1080° (see Figure 12):

$$H_{D540-180} = \sqrt{(x_{540} - x_{180})^2 + (y_{540} - y_{180})^2}$$
...
$$H_{D1080-720} = \sqrt{(x_{1080} - x_{720})^2 + (y_{1080} - y_{720})^2}$$

2) The average drift distance H_D defined by:

$$H_D = average(H_{D540-180}, H_{D630-270}, H_{D720-360}, H_{D810-450}, H_{D900-540}, H_{D990-630}, H_{D1080-720})$$

The drift direction is calculated by the following two steps:

1) The drift direction of the individual points defined as the drift direction during 1 turn from 180° to 540°and up to 720° to 1080°:

$$\mu_{D540-180} = atan2(x_{540} - x_{180}, y_{540} - y_{180})$$
...
$$\mu_{D1080-720} = atan2(x_{1080} - x_{720}, y_{1080} - y_{720})$$

2) The average drift direction μ_D defined as:

$$\mu_D = average(\mu_{D540-180}, \mu_{D630-270}, \mu_{D720-360}, \mu_{D810-450}, \mu_{D900-540}, \mu_{D990-630}, \mu_{D1080-720})$$

In waves the speed of the ship will change depending on the wave direction. This is different from the calm water cases where the ship will turn with the same velocity at every sector of a steady turn. I.e. it is of interest to plot the speed, and other parameters to see the change of the values in each of the sectors as defined in Figure 13.

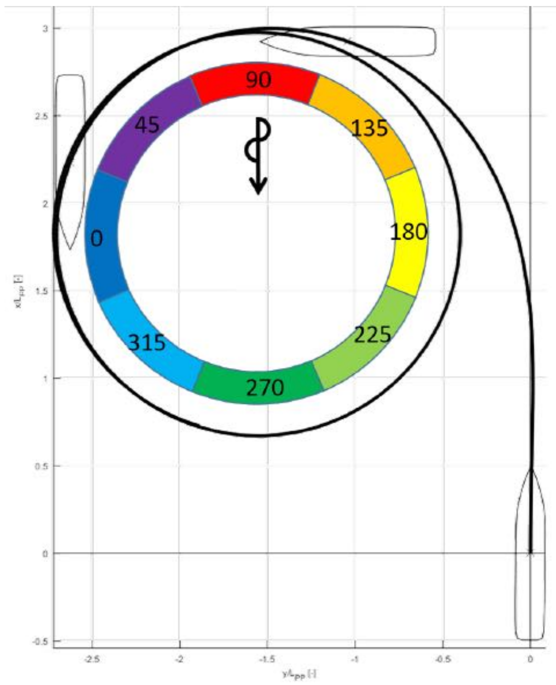

Figure 13. Sectors and colours used to describe the turning circles in waves.

The parameters of interest when evaluating the impact of the waves on the manoeuvring characteristics are the average speed loss V/V_0, the average non-dimensional rate of turn r', the average drift angle β, and the average roll angle ϕ and how they change in waves compared to the corresponding calm water values.

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The average values are determined for every single sector of the circle, e.g.:

r'_{270}, $(V/V_0)_{270}$, β_{270} and μ_{270} are found by averaging between heading 247.5° and 292.5°, etc.

The change in waves is then found by averaging per sector per turn, i.e.:

$$r'_{w0} = \frac{average(r'_{180}, r'_{540}, r'_{900})}{r'_C}$$

Similar for r'_{w45} to r'_{w315}, with $w180$ representing head sea following the standard coordinate system of seakeeping. An example for the rate of turn is seen in Figure 14.

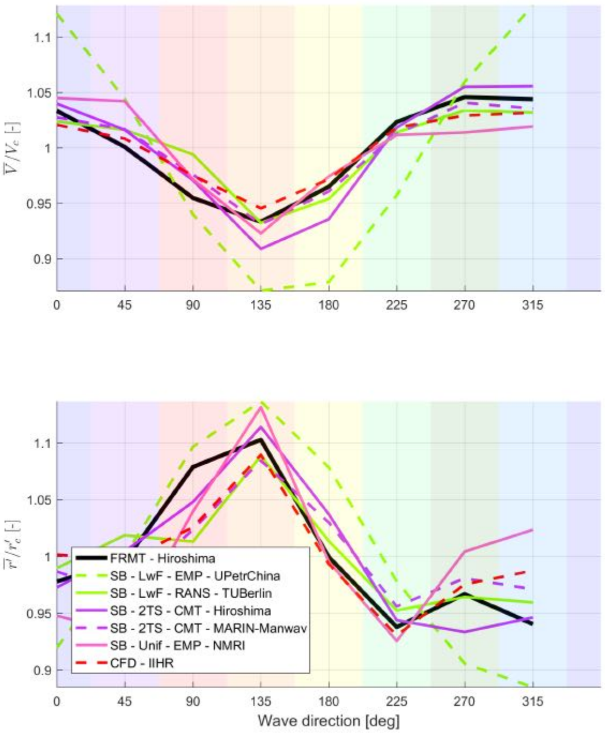

Figure 14. Example of change of rate in turn in waves.

The impact factor is then defined as the highest difference minus the lowest difference, e.g.:

$$\frac{r'_{w135} - r'_{w225}}{r'_C}$$

The same is repeated for V/V_0, β, and ϕ.

In addition to these values the turning ability in general were also analysed characterised by:

- Additional needed thrust, rpm_w/rpm_C
- Average nondimensional rate of turn (for 2 turns), r'_w
- Average speed loss, $\left(\frac{V}{V_0}\right)_w / \frac{V_C}{V_0}$
- Average drift angle, β_w/β_C

In the analysis of the wave frequent motions, only the heave, pitch and roll motion are analysed. Because the ship is moving in regular waves, and the speed is variable, the encounter frequency changes with the ship velocity and the instantaneous wave direction.

The analysis is therefore carried out for each sector in the turn (see Figure 13), by determining the standard deviation of the motion over the period in time where the wave direction is within each sector respectively.

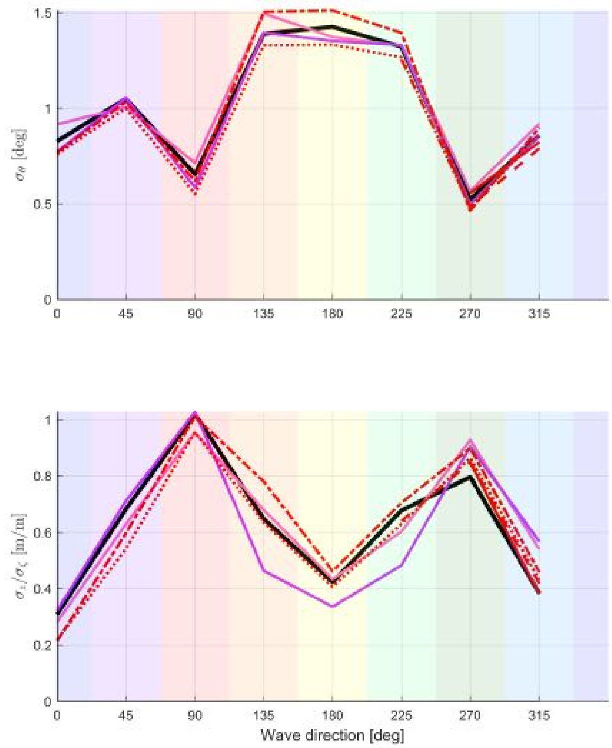

Figure 15. Example of the wave frequent motions per sector.

The values of the standard deviation of the heave motions will be divided by the standard

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deviation of the wave height σ_ζ, to obtain a non-dimensional value σ_z/σ_ζ. Besides the standard deviates for heave, roll and pitch, also the average heel angle $\bar{\phi}$ and the range of heel angles $\phi_{max} - \phi_{min}$ within each sector were evaluated for each wave sector. An example of the wave frequent motion parameters plotted against the heading of the waves are shown in Figure 15.

The results of the turning circles in waves are comparable to those for calm water in the sense that the number of submissions is similar to those of the other individual deep water trajectory test cases, and the U_D, $\overline{|E\%D|}$ and $\overline{\sigma_{|E\%D|}}$ values are like those for calm water. Thus, similar conclusions can be made concerning the uncertainties for waves vs. calm water manoeuvres, although the errors are somewhat larger, i.e., 17.5%D vs. 14.1%D respectively.

For code development, it would be good to have available insight in the forces on a ship while performing manoeuvring motions. For another ship, the SR108, such experiments were reported by Yasukawa and Faizul (2006). It is therefore recommended to the international community to perform similar experiments for KVLCC2, KCS or ONRT.

Considering the number of papers and global (academic) attention for manoeuvring in waves, the amount of 10 submissions at SIMMAN2020 is quite small and not in agreement with the general amount of academic attention.

The detailed evaluation of all the derived key parameters, the description of the validation approach and the examination of the trajectory results are available in the final proceedings of SIMMAN2020 (Quadvlieg et al., 2023).

3.1.3 Overall conclusions and recommendations

In general, a good progress was seen in the prediction capability. The predictions errors defined in 2020 were smaller than the prediction errors in 2014, though it was only properly statistically documented for the deep water cases.

The amount of test cases has decreased significantly from about 84 trajectory cases in SIMMAN2008, 66 cases in SIMMAN2014 to 14 trajectory cases in 2020. The decreasing of the amount of test cases in SIMMAN has led to more focus and sound conclusions.

A quantitative increase of submissions using time domain CFD simulations has increased throughout the years of SIMMAN, but still the present amount of free running CFD submissions is insufficient to give guidance regarding preferred turbulence models, wall functions, grid size, grid refinement techniques, etc. Future test cases ought to consider this aspect as well.

It is recommended to keep KVLCC2, KCS and ONRT. There is no need to change this as there are plenty of developments to be dealt with for these ships. Unless there is a ship for which full scale data will become available, it will be beneficial to stay with these three unrestricted ships. It is however recommended to include the propeller thrust and the rudder forces in the analysis.

The developments of analyses as initiated in this edition of SIMMAN are considered worthwhile to keep. The proposed key characteristics seem manageable and provide a good insight in the capabilities if the simulations. Likewise, it is recommended to keep the present error determination for captive forces for consistency and to gain experience with the method.

It is recommended to promote the research in shallow water. At the SIMMAN2020 workshop it was seen that less submissions were made for shallow water, and that both the experimental error and the prediction errors were larger than for the deep water cases.

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3.2 UV, Inland Navigation, Model-Scale Vessels

Van Zwijnsvoorde et al. (2022) presented findings of a study that is part of the 6th MASHCON conference, focusing on port manoeuvres and passing ship effects on moored ships. These interactions are crucial as they involve large magnitude forces and long period excitations that can affect a ship's mooring system and potentially lead to unsafe situations.

The research is conducted under the PESCA (Passing Effects in Shallow and Confined Areas) project, where captive model tests were executed at FHR's towing tank for manoeuvres in confined waters in cooperation with UGent. The tests involved the KCS as the passing ship, and a Neo-Panamax container ship (C0P) and an Aframax tanker (T0Y) as moored ships. The Aframax tanker was moored in two configurations: along the tank wall (quay configuration) and connected to a measurement frame in the tank (jetty configuration), which represents open water mooring. This study provides data for understanding the dynamics of ship interaction in confined and shallow waters, particularly in high blockage areas. The results, scaled down to 1:80, offer valuable insights for the validation and verification of various research methodologies in this field.

4. AUTONOMOUS, NOVEL DEVICE AND CLEAN FUEL

Maritime autonomous surface ships (MASS) are a growing area of interest, with significant ongoing research and development. With high levels of autonomy, it can reduce operational costs, improve safety, and increase efficiency. Motivated by these advantages, many companies have incorporated artificial intelligence (AI) and autonomy technologies into their business operations and developed their first generation of MASS prototypes. The most widely known protypes include:

1) Yara Birkeland (see Figure 16 (a)) designed by Norwegian companies Yara and Kongsberg Maritime. It is an all-electric autonomous container ship, which was put into commercial operation in Porsgrunn in 2022.

2) Mayflower Autonomous Ship (see Figure 16 (b)), developed by ProMare with support from IBM. In 2022, it crossed the Atlantic Ocean from Plymouth UK, arrived in Plymouth, Massachusetts.

3) Soleil, developed by Nippon Foundation, Mitsubishi Shipbuilding, and Shin Nihonkai Ferry. This very large vehicle-carrying ferry (223 meters long) successfully completed an autonomous 240-kilometer return voyage from Fukuoka to the Iyonada sea.

4) USNS Apalachicola (EPF 13), developed by Austal. EPFs are designed to operate in shallow waterways and are capable of a wide range of activities. it has been delivered to US Navy in 2023 after several successful sea trials to assess its autonomous capabilities.

(a) Yara Birkeland

(b) Mayflower Autonomous Ship

Figure 16. MASS prototypes.

More MASS prototypes are under development. More importantly, the clean fuel technologies are integrated into autonomous ships. It is clear that the maritime shipping is heading towards autonomy and zero-emission era.

The published research papers on MASS also witness a significant increase over the past decade. Most of these works are focused on developing methods/algorithms for path planning/tracking that can reduce the risk of collisions, groundings, and stranding accidents at sea, as well as costs and time expenditure. Vagale et al. (2021a, 2021b) conducted a critical review of path planning and collision avoidance for autonomous surface vehicles. It was found that the artificial intelligence is an enabling technology for autonomous surface vehicles, with methods such as evolutionary algorithms, artificial potential fields, fast marching methods, and many others becoming increasingly popular for solving problems such as path planning and collision avoidance. However, there is no unified way to evaluate the performance of different algorithms. Real-world field tests are needed to evaluate the actual performance of the developed algorithms in various scenarios.

It is a very challenging issue to standardize the sea trial procedure for MASS. For traditional surface ships, the procedures for tank testing or sea trials are well established. The manoeuvrability of a ship, which is mainly determined by its hydrodynamic performance, can be evaluated and compared in a fair manner by conducting standard manoeuvring tests, regardless of ship types and sizes. However, when it refers to the MASS, its autonomous performance is not only determined by the ship's hydrodynamics, but also by its control system that consists of three main modules: Guidance, Navigation and Control (GNC). To evaluate the effectiveness of the control system, the testing of autonomous ships may need to be conducted in specific test areas with both land-based and on-board technological infrastructure that can be used for navigation, communication, and monitoring. Over the past decade, several countries, including UK, Norway, Finland, Belgium, and the USA, have developed specific testing areas for autonomous ships. There are also some existing guidelines for MASS trials, including IMO's Interim Guidelines for MASS (International Maritime Organization, 2019), the EU Operational Guidelines for Trials of (Trials of MASS, 2020) UK Industry Conduct Principles and Code of Practice for (Maritime UK, 2023) , etc. However, there are no standard tests proposed for autonomy, and types of tests between the sites may differ significantly. As pointed by Bellingmo et al. (2022), plans and results from autonomous tests are not unified and shared. It is hard to compare results from different tests. It is important to standardize and document autonomous tests to accelerate the technology and regulatory development.

As a ITTC technical committee, Manoeuvring Committee seeks to evaluate the importance of MASS trials and feasibility of conducting standard tests. Some key questions should be considered before recommendations are provided:

1) How will the existing procedures/guideline for conventional ships be used for MASS tests?
2) How to define the autonomy capacity/ ability?
3) What type of standard tests to evaluate each ability defined in 2)?
4) How to perform the tests?
5) What are the results to be documented from standard tests?
6) How can these testing results be served as inputs to develop the regulations by maritime authorities?

The autonomous shipping sector is still at an early stage. To answer the above questions, it requires to consult with different stakeholders, including maritime authorities, infrastructure owners, service providers, classification, clusters, and research and education stakeholders. This will be one of the terms of reference of the 31st ITTC.

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4.1 Course Planning, Following and Tracking

This subject and its closely related topics, including berthing, formation control, and obstacle avoidance (as detailed in section 4.2), have seen a substantial volume of literature published over the last decade. Importantly, the quality of these articles varies considerably, with most of them lacking essential experimental validations. Notably, only the most significant contributions in the field are considered in this report. It should be emphasized that special consideration is deserved by the topic of AI assistant autonomy.

Course planning and path optimization are fundamental research topics in autonomous ship's navigation. Wu et al. (2021) proposed a multi-scale visibility graph method for long-voyage route planning of autonomous ships, addressing the issues of slow planning and poor route accuracy. The method involved extracting obstacle data from electronic charts, establishing multi-scale visibility graph models, and using a local planning window approach to reduce complexity and search time. The results showed that the proposed method could greatly reduce the complexity of visibility graph models and shorten the search time, improving the efficiency and accuracy of ship route planning.

Hinostroza et al. (2021) presented experimental results of the cooperative operation of two autonomous surface vehicles (ASVs) navigating in a complex marine environment. The ASVs were equipped with algorithms for motion planning, path-following, and motion control, and the experiments were conducted to validate the developed. Li et al. (2022) presented a dynamic path planning method for unmanned ships in a multi-object environment, integrating ship manoeuvrability, COLREGS, and good seamanship to ensure safe navigation. The proposed method utilized the multi-layer Morphin adaptive search tree algorithm to build an environment model, calculate collision avoidance ranges, and optimize the ship's trajectory. Through a case study and comparison with traditional artificial potential field models, the method demonstrated its applicability and potential in autonomous navigation for unmanned ships. Krell et al. (2022) presented a novel approach to path planning for ASVs using Particle Swarm Optimization (PSO) and Visibility Graphs. The goal was to generate energy-efficient routes based on water current forecasts and to incorporate reward-based planning to increase the scientific return of the mission. Ma et al. (2022b) presented a new coverage path planning algorithm for unmanned surface mapping vehicles (USMVs) to improve the efficiency and accuracy of underwater topographic mapping. The algorithm overcame the limitations of local optimization and incorporated task decomposition and map dynamic updating to achieve significant improvements in path length, number of turns, unit number, and coverage. The effectiveness of the algorithm was validated through simulations and mapping experiments. Zhang et al. (2022c) proposed a time-optimal path planning algorithm based on the MMG manoeuvring model and spatial reformulation of dynamic model. The path planning is implemented by Model Predictive Control (MPC). Extend Kalman Filter is used to minimise real-time disturbances.

Path Following and Trajectory Tracking are key performance criteria for ship manoeuvring Choe and Furukawa (2019) introduced an automatic track keeping algorithm consisting of a waypoint switching system and a rudder control system, as shown in Figure 17. The effectiveness of the algorithm was verified by the fact that the ship can closely follow the desired track under realistic environmental conditions.

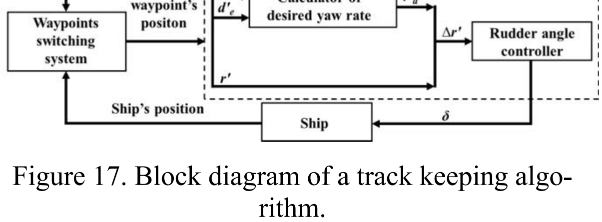

Figure 17. Block diagram of a track keeping algorithm.

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Huang et al. (2021b) proposed an observer-based motion control system for an approach ship in a process of underway replenishment, addressing the challenge of maintaining a certain distance between the guide ship and the approach ship. The control strategy utilized a leader-follower approach, an extended state observer, and the command filter backstepping method to achieve trajectory tracking without velocity measurements. Simulation results demonstrated the effectiveness of the proposed method. Nie et al. (2021) presented a finite-time output feedback path following control strategy for underactuated marine surface vehicles (MSVs) with unknown velocity, dynamics, and external disturbances. The strategy utilized a finite-time extended state observer (FTESO) to accurately observe the unknown velocity and disturbances and constructed finite-time output feedback controllers to achieve precise path tracking performance. Simulation results demonstrated the effectiveness of the proposed strategy. Min and Zhang (2021) proposed a concise robust track-keeping control strategy for ships using a multi-technique improved LOS guidance system, which included a robust course-keeping controller and a nonlinear feedback technique. The strategy addressed the limitations of parameterized LOS guidance and enhanced the track-keeping effect through the introduction of three techniques. Simulation results demonstrated the superiority of the proposed strategy in both dynamic and static performance, making it significant for enhancing ship's autonomous navigation.

Zheng et al. (2022) proposed a soft actor-critic based control strategy for unmanned surface vessels (USVs) to achieve path tracking under wind and wave disturbances. The authors utilized a three-degree-of-freedom manipulative modelling group (MMG) model to represent the USV's dynamics and designed a linear active disturbance rejection controller (LADRC) combined with SAC algorithm for adaptive control (see Figure 18). The effectiveness of the proposed method was validated through simulation experiments.

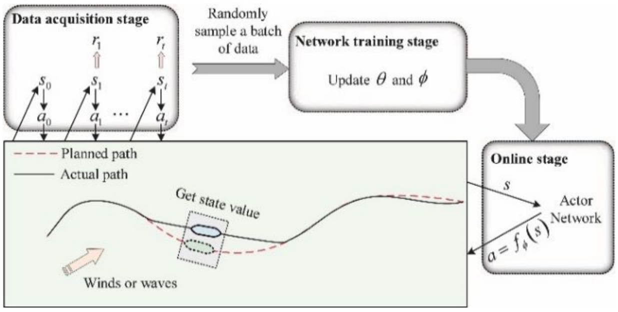

Figure 18. Schematic diagram of process of USV path tracking LADRC controller based on SAC optimization.

Qu et al. (2021) addressed the path-following control problem of USVs with unknown dynamics and unmeasured velocities. The main contributions of this work included the design of a finite-time velocity observer (FVO) to estimate velocities, the proposal of a heading-surge (HS) guidance scheme, and the use of a wavelet neural network (WNN) and adaptive techniques to accurately estimate unknown dynamics. Zhang et al. (2022b) proposed a novel robust adaptive fault-tolerant control algorithm for USVs using a multiplied event-triggered mechanism. The algorithm addressed challenges such as gain uncertainty, actuator faults, and limited communication resources, and was validated through simulations and physical experiments. Chen et al. (2021) introduced a new tracking controller for ship manoeuvring in shallow or confined water and compared it with an existing model-based tracking controller. The performance of the new controller was evaluated through simulation studies, demonstrating advantages such as improved speed control and reduced computational cost. Wang et al. (2022b) proposed an Antenna Mutation Beetle Swarm Predictive (AMBS-P) algorithm for path-following of underactuated cargo ships with unknown dynamics, using data gathered during operation to improve the model and path-following performance.

The path-following control of a ship by pushing using a single autonomous tugboat (see Figure 19) is studied by Choi (2023); Sawada et al. (2021a). The contact between the ship and tugboat is assumed to be a point contact, and the contact point does not slip. The simulation results show that the proposed control method causes the ship to follow the given straight-line paths correctly without slipping at the contact point.

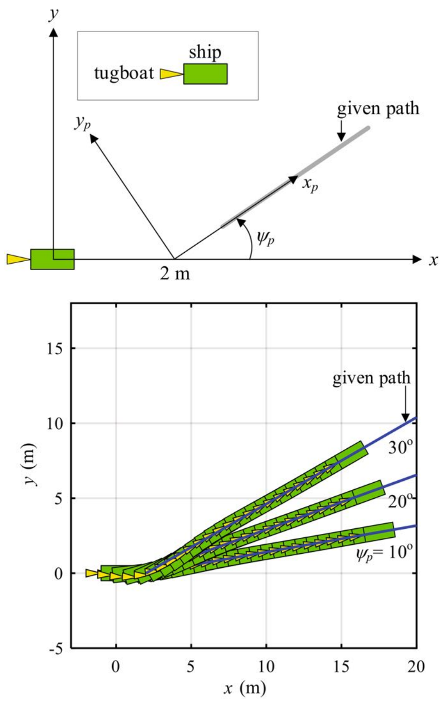

Figure 19. Simulation results of path-following of a ship pushed by a tugboat at different path angles.

Experimental tests were conducted by He et al. (2023) to validate their proposed model predictive controller (MPC) for surface ships' path following. It is concluded that the MPC could achieve a high tracking accuracy, smooth track transition, insensitive parameter setting and strong robustness in the presence of inherent model uncertainty, despite the simplifications made for practicality. Kim et al. (2023a) investigated the path following performance of a ship operating at low forward speeds in adverse weather conditions based on CFD modelling. It is found that increasing the propulsive power could achieve a better path following performance, while the impact of the propulsion power on path following in quartering waves is less important. Zhang et al. (2024a) proposed a manoeuvring model under waves for autonomous ships. Second-order wave loads are introduced to MMG model the simulate the manoeuvring operation with wave load and a turning motion of ship manoeuvring is validated compared with experimental test. Two control strategies were proposed to track the planned path with an MPC control algorithm.

4.2 Berthing, Formation Control and Obstacle Avoidance

Automatic Berthing is a crucial technical challenge that involves advanced technology in autonomous ship's manoeuvring.

Sawada et al. (2023) proposed the 2 DoF controller for automatic berthing under wind disturbances based on the path following control algorithm originally developed in Sawada et al. (2021a). The authors implemented this algorithm in a programmable logic controller (PLC) and conducted performance verification by installing it on an experimental ship (see Figure 20). After analysing the impact of wind disturbances on path following, the newly developed control algorithm for automatic berthing demonstrated high performance even under disturbances, as confirmed through validation on the experimental ship.

Figure 20. Experimental Ship "Shinpo".

Maki et al. (2021) proposed an automatic method to generate take-off and landing pier paths. Many merchant ships equipped with fixed-pitch propellers do not engage in manoeuvres that involve repeatedly reversing propeller during berthing operation. Therefore, the proposed algorithm limited the number of times of

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switching to once. An optimization was performed through covariance matrix adaption evolution strategy (CMA-ES). The proposed method enabled the acquisition of a more realistic take-off/landing path.

A novel ASV-centric Berthing assistance system (BAS) is proposed by Wang et al. (2024a) for the real-time calculation of navigable regions and idle berths during the berthing process. Applying a 3D-LiDAR, this method provides:

1) Localisation - estimating precise vessel position data through a simultaneous localisation and mapping algorithm with LiDAR and RTK data).

2) Details of navigable region - segmenting point clouds based on horizontal emission angles and identifies the nearest points within each segment. By employing a fitting algorithm, multiple lines are fitted, and those are selected to establish the berth line (Figure 21).

3) Idle berth information - determined based on the nearest point cloud passed by the fitted berth line.

4) Berthing state parameters (berthing distance, berthing speed, approaching angle and yaw rate)

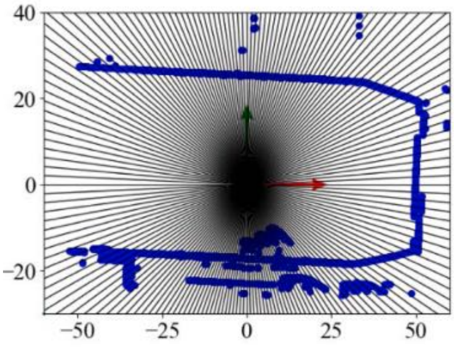

Figure 21. Point cloud segmentation map.

Formation Control is a significant challenge for technological development of autonomous ships, which requires complex manoeuvring operation.

Huang et al. (2021b) proposed a leader-follower motion control strategy to realize the synchronized control of two ships engaged in underway replenishment operation (UNREP). It was based on the command filtered adaptive backstepping approach combined with a novel extended-state observers to design the motion controller of the follower ship including model uncertainties and external disturbances with hydrodynamic interactions and effects of the highline cable. Simulations were performed on two scaled model ships to demonstrate the effectiveness of the proposed motion control strategy and the results showed the follower ship precisely tracks the desired trajectory and the relative positioning between the leader-follower ships were maintained near expectations, which guaranteed the safety of the UNREP operation.

Tan et al. (2021) proposed a hybrid behaviour-based (HB) method to achieve the coordination control of multiple USVs in the dynamic environment. Kalman filter algorithm is incorporated into the HB method to predict states of other ships based on their previous AIS information and to filter the signal noise. The objective of this paper was to achieve the rendezvous issue, formation keeping and obstacle avoidance for multiple USVs at the same time by considering the model uncertainty and the feature of the AIS broadcasting mechanism. Three numerical simulations were performed to validate the effectiveness of the HB method and results showed that the multiple USVs maintained a relatively stable formation while following the desired path sailing to the goal without colliding with each other, static obstacle or other moving ships.

Zhang et al. (2021a) also proposed a formation control system of USVs. This study employed event-triggered robust neural control, in which state variables and control inputs were updated when reaching certain threshold values. The proposed system is characterized by its capability to reduce the communication load between the controller and the actuator. The validity of the system was also demonstrated through extensive simulations considering disturbances (Figure 22).

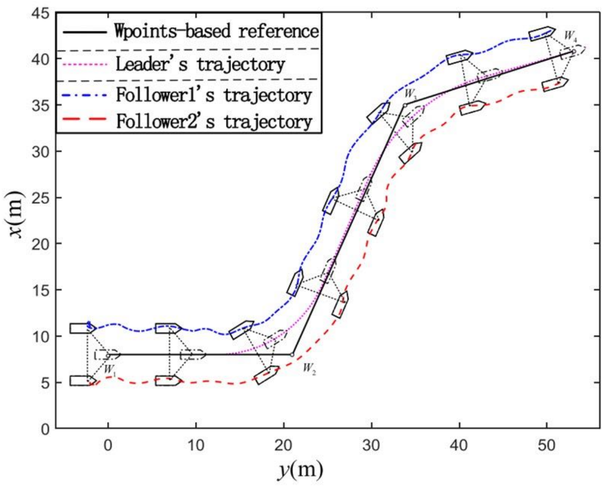

Figure 22. Comparison of the formation trajectory.

Obstacle Avoidance is key technology for ensuring the safety of autonomous ships. In collision avoidance manoeuvres, compliance with COLREG is a fundamental premise, but how to incorporate this into avoidance algorithm is a highly important aspect in the technological development of this field.

Hagen et al. (2023) proposed a method for representing the COLREG steering and sailing rules with concise mathematical expressions and conducting quantitative safety evaluations. Their findings may become crucial components in the development of this field.

Sawada et al. (2021b) proposed a method for the automatic collision avoidance based on deep reinforcement learning (DRL) approach. The proposed DRL was established by implementing a reward function, which considers efficient avoiding and the COLREG. Risk assessments were performed with setting the obstacle zone defined by speed and distance of own ship and other ships. The proposed method was successfully validated through the scenario sets of the Imazu problem.

Lyu et al. (2024) proposed a unique method applying environmental potential field modelling to express static obstacles combined with a dynamic obstacle modelling method for target ships considering COLREGs. The first-order Nomoto model was adopted to consider dynamic response of ships to input rudder angle in their simulations. Though frequent and unnecessary steerage and fluctuated trajectories are observed in simulation studies, it was shown that reasonable paths were obtained to avoid collision with static obstacles and target ships in various scenarios.

Wang et al. (2023) proposed a collision avoidance method for unmanned surface vehicles when navigating restricted waters. In global path planning phase, a genetic algorithm was applied to pursue the path series with the least energy consumption and the shortest distance, with the fitness function designed to favour the exploration of as straight a path as possible. In local path planning phase, obstacle avoidance was conducted using dynamic window approach applying a simplified COLREG. Simulations for several scenarios involving changes in velocity demonstrated that the proposed algorithm exhibited high performance. As another example of research considering COLREG and energy efficiency (Seo et al., 2023).

Wang et al. (2021a) proposed an improved genetic algorithm to solve the problem of multiple USVs collaborative collision avoidance. The authors prepared a multiple USVs model of motion and sensors, established encounter scenarios and formulated corresponding collision avoidance strategies (Figure 23) and calculated the motion parameters and risk of collision to determine whether to take avoidance measures. Furthermore, the authors designed simulation cases to verify the effectiveness of the proposed collision avoidance planning with and without communication. The results showed that the proposed method enabled to plan the current best path of collision avoidance for multiple USVs in complex environment and had good stability and smooth trajectories. Compared

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with the conventional genetic algorithm, the improved algorithm effectively reduced the number of iterations, running time, and standard deviation, and improved the success rate.

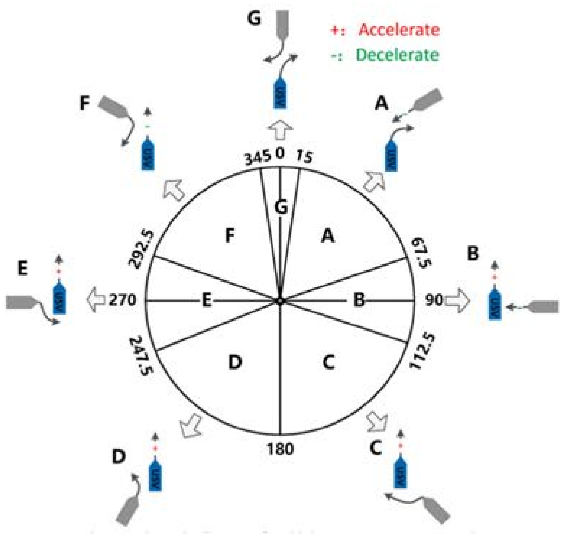

Figure 23. Schematic diagram of multiple USVs encounter scenarios.

Wang et al. (2021b) proposed a model to detect other vessels that might obstruct a ship's course. Considering scenarios involving multiple vessels, the authors combined a two-step approach: first, analysing the traffic situation and classifying cases based on relative motion, followed by inferring the operational intentions of the other vessels. The first step involves evaluating the traffic situation by multiplying the collision risk matrix and encounter situation matrix between each pair of vessels. The second step infers the intentions of each vessel from the traffic situation, incorporating fuzzy logic methods. The authors demonstrated the method by using real operational data.

Yuan et al. (2021) proposed a dynamic risk-informed collision awareness approach for real-time operating conditions to show the safe navigable space and the collision risk caused by current velocity, course, position of encountered obstacles. It was established by modifying NLVO method. The improved method called Uncertainty Non-Linear Velocity Obstacles (UNLVO) that enables to take the dynamic and uncertain characteristics of ship motion patterns into consideration and make real-time risk visualization. Simulations on multi-ship encounter scenarios were thoroughly conducted to validate the method. Compared with DCPA and TCPA, UNLVO provided more accurate predictions in expressing collision risk, and generated a uniform and acceptable risk evaluation.

Jia et al. (2023) proposed a RAGAN (Risk Aware Generative Adversarial Network) model to predict multi-ship's trajectories in encountering and avoiding situations. The trajectory prediction by RAGAN is derived from analysing encounter situations and collision risks among traffic ships based on AIS data and estimating the subsequent vessel behaviour. It is expected that RAGAN enhances situational awareness and provides valuable insights for decision-making in maritime operations.

Wang et al. (2024b) addressed the problem of automatically generating simulation scenarios to validate collision avoidance algorithms in ship navigation issues. In the generation process, real AIS data is incorporated, and the following steps are followed:

1) Analyse encounter situations after handling anomalies or missing data;
2) Evaluate importance based on both occurrence frequency and severity;
3) Generate simulation scenarios deemed important after excluding those with low severity;

Creating scenarios to validate collision avoidance algorithms is laborious, so this kind of studies is expected to be useful in the future.

4.3 Novel Device and Clean Fuel Technology

4.3.1 Novel Devices

Generation of greenhouse gases, CO2 and other toxic substances that are proven to contribute to the climate change, have been rising continuously in the last few decades. A 2010 report by the Office of the European Union indicated that the ship operations (Jaramillo, 2016) contribute to 3 – 5 % of CO2 emissions. Adverse effects of climate change on human and wildlife have urged international organizations to take actions towards reducing the emissions of the toxic gases. Among them is the International Maritime Organization (IMO), which has set requirements for ships contracted from 2013 to be 10% more efficient by 2015, 20% more efficient by 2020 and 30% more efficient from 2025. To meet this target, potential applicability of various methods such as energy saving devices and clean fuel technology have been investigated in the recent years. In this section, the effect of adapting some of the low emission technologies and novel devices on the ship manoeuvrability will be discussed.

Energy Saving Devices (ESDs). Stark et al. (2022) categorized the energy saving devices to five groups based on their locations on ships as shown in Figure 24: hull resistance reduction measures, propeller/hub modifications, propeller flow conditioning devices, renewable energy-assisted propulsion, and manoeuvring energy-saving devices.

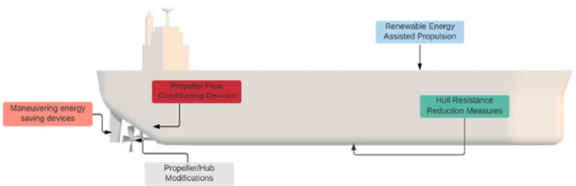

Figure 24. Applicability of Energy Saving Devices based on their location on the vessel.

Hull Resistance Reduction Measures. The hull resistance could consume a significant percentage of fuel. Therefore, the hydrodynamic community has been examining various techniques to reduce the hull resistance. One of the methods for lowering the fuel consumption is to attach a fixed hydrofoil called Hull Vane (HV) below the waterline and to the transom of a vessel. HV was originally invented by Peter Van Oossanen in 1992, first patented in 2002 and has been widely investigated for various ship types with reported fuel reduction between 3 to 10% for merchant ships. Hou et al. (2020) generated the lift by the foil to reduces the pitching motion and consequently wave resistance, corrects trim, reduces the stern wake generation, and generates additional thrust. Despite potential benefits of HV on the fuel saving, it can cause adverse effects on manoeuvrability of ships. Full scale sea trials on a 55 m Fast Supply Intervention Vessel, Karina, retrofitted with a HV showed a reduction in engine power requirement by 15%. However, Uithof et al. (2014) indicated the manoeuvrability tests turning circle was slightly increased which was caused by an increase in the directional stability by the struts used to connect the HV to the hull.

Propeller/Hub Modifications. Energy saving of marine vessels can also be achieved through geometry modifications of the propeller and hub. Various methods have been investigated to improve propeller performance from the power requirement standpoint. Contracted and Loaded Tip (CLT) propeller is a novel propeller design, where the blade tip is modified to act as a winglet and reduce the interactions between flow on the pressure and suction side of the blade. A survey study by (Gennaro and Gonzalez-Adalid, 2012) on the CLT propeller application to 280 ships of different types indicated the following improvements: 5-8% higher efficiency which results in fuel savings, lower emissions and greater range, reduction in cavitation and tip vortex and consequently lower noise and vibrations, greater thrust and better manoeuvrability.

Hub modifications have shown to be an effective way to save energy, but direct effect of this modification on the ship manoeuvring performance has not been reported yet.

Propeller Flow Conditioning Devices (PFCDs). PFCDs are used slightly upstream of the propellers to adjust the propeller inflow with the purpose of improving the propeller performance. Several PFCDs have been examined and fuel saving between 5 to 12% have been reported. Among these devices is the pre-swirl duct, where Sasaki and Aono (1997) investigated and indicated 5% power savings based on

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the sea trials, as well as reduction in the hull vibrations and enhancement in the manoeuvring characteristics. In another effort, Kishimoto et al. (2016) performed a series of tank tests on a Japan Bulk Carrier (JBC) with two different model scales to examine the effect of a stern duct shown in Figure 25 on the propulsion efficiency. The study showed significant improvement in propulsion efficiency with no adverse effects on the manoeuvring performance.

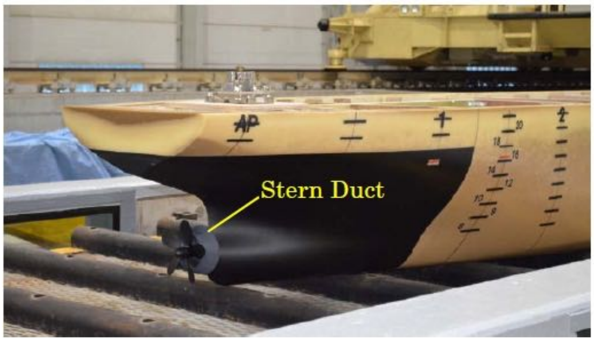

Figure 25. Stern duct on Japan Bulk Carrier.

Renewable Energy Assisted Propulsion. Clean energies such as wind and solar power have gained attention in the recent years as potential alternatives to the conventional energy sources. Despite significant advantage of these energy resources for reducing fuel consumption, their potential benefits for enhancing manoeuvring performance of marine vessels have not been reported in the public domain.

Manoeuvring Energy Saving Devices. The rudder not only serves as a steering and course keeping device, but also plays an important role in recovering the energy of the propeller wake. Therefore, proper design of rudders can reduce the power requirement for propulsion system. Three types of rudders including twisted rudder, gate rudder, and Hebel rudder are discussed in this section and each aims to reduce the energy expenditure.

1) Twisted Rudders

Rudders operate behind the slipstream of propellers and can experience large inflow angles varying along the rudder span. Large inflow angle typically causes the cavitation and consequently erosion of the rudder surface, which increases maintenance cost, rudder drag, lift in the case of massive flow separation on the suction side caused by cavitation, and introduces hull vibration and noise. The concept of twisted rudders based on rotation of rudder cross sections along the span was originally introduced by. Shen et al. (1997) and is aimed at elimination or reduction in rudder cavitation. Their experimental study in the U.S. Navy Large Cavitation Cannel (LCC) showed a wider cavitation inception envelope for the twisted rudder compared to the non-twisted rudder. However, the lift slopes of the twisted and non-twisted rudders were close, which indicates that the effectiveness of the turning manoeuvre is compatible between the two designs.

The X-Twisted rudder was originally designed by Hyundai Heavy Industries, where the leading edge of the rudder is continuously twisted along the span. Ahn et al. (2012) compared the hydrodynamic characteristics of an X-Twisted rudder (Figure 26) and a semi-balanced rudder. The manoeuvring model tests showed overall improvement in manoeuvrability of a TEU class container carrier with the X-Twisted rudder and in particular a well-balanced manoeuvre between the port and starboard.

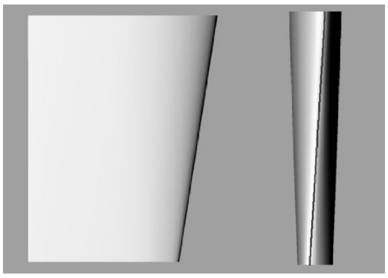

Figure 26. Drawing of X-Twisted rudder.

Calcagni et al. (2014) performed CFD comparative analysis of untwisted and twisted rudders on a single screw tanker operated at constant speed and at a range of rudder angles between 0 to 20 degrees. Computational results were also compared against experimental data. The predicted side force and yaw moment produced by untwisted and twisted rudders were comparable, which indicated that the manoeuvring performance of the ship was not affected by changing the rudder design. However, the twisted rudder reduced the suction pressure peak occurring on the rudder surface, and as a result, the cavitation was mitigated.

Sukas et al. (2021) examined the effect of a twisted rudder on the manoeuvring performance of a model scale Duisburg Test Case (DTC) hull. Both system-based and direct CFD methods were adopted in this study. Numerical results showed that the twisted rudder generated significant asymmetry in the flow, where the starboard turning with twisted rudder was close to turning with a normal rudder. Meanwhile, a significant reduction in steady turning diameter was reported for the port turn. Part of the reported asymmetry was caused by the rotational direction of the propeller. In general, the manoeuvring ability of the ship seemed better to port side than the starboard turning.

2) Gate Rudders

Figure 27. Gate rudder system of Shigenobu.

Figure 27 shows a gate rudder, where unlike the traditional designs, the two rudders are positioned astride of the propeller. The gate rudder was initially designed and patented by Kuribayashi in Japan in 2012. In 2020, Wartsila licensed the technology for marketing and development, by Sasaki et al. (2018). The European Union (EU) granted a team of researchers at the University of Strathclyde in 2020 under the Horizon 2020 Research and Innovation Framework Program to demonstrate the retrofit of the system for short sea shipping operations, explore the technology for oceangoing shipping operations, and evaluate it for fuel savings and manoeuvrability improvement of commercial ships.

One of the unique features of the gate rudder is its ability to act as a duct and increase the propeller thrust, which can remarkably reduce the energy consumptions and emissions of the ships particularly within coastal and port areas. The independent movement of the two rudders offers a more flexible steering and sideway movements compared to the conventional designs. The rudders can be retrofitted to the existing ships, as well as integrated to other fuel saving devices. Compared to the traditional rudder systems, gate rudders are in general quieter, reduce hull wake, and can reduce the propeller damage by the environment.

The gate rudder for the first time was tested on a 2400 GT container ship called “Shigenobu” in 2017 in Japan. Fukazawa et al. (2018) compared it to her sister ship “Sakura” equipped with the conventional rudders, a trial report indicated 14% energy savings with the gate rudder system in calm water. Sasaki et al. (2019) performed evaluation of two ships in rough weather in the northeast coast of Japan showed a higher reduction of 30% in fuel consumption with the gate rudder system.

The sudden or significant speed loss introduces a large turning rate and change in the ship direction, which poses adverse effects on the ship stability and safety of operation. Recent investigation on the turning capability showed that the gate rudder offers remarkably safe turning ability without excessive speed loss. The speed of a gate rudder ship at the same turning rate and the same tactical diameter is 20-30% greater than a ship with conventional rudder.

Joint sea trial of Sakura and Shigenobu conducted in following quartering wave and wind indicated that the gate rudder produced significant damping effect on the ship motions during their running period on the same track. The yawing and rolling amplitudes of Shigenobu were about half of Sakura14. The joint sea trial was also conducted for crabbing mode and pivot turn. By the combination of two rudder angles, 55° and 110°, Shigenobu proved a superiority in berthing using a pivot turn and a crabbing in the extremely narrow port.

3) Hebel Rudders

Dereszewski et al. (2021) presented a new type of rudder called Hebel rudder shown in Figure 28. The blade is divided into two parallel parts and the general idea is to use the accelerated flow between the blades to generate additional steering force.

Figure 28. Hebel rudder.

The Hebel rudder has been tested in full scale on a small trawler and the manoeuvring test results were compared with those carried out with standard NACA profile. The results showed much better turning ability of the tested trawler with the Hebel rudder than with a standard rudder, especially for small rudder deflections. However, the authors didn't mention the overall test conditions. Following the ITTC procedures, more tests may be required to draw a more general conclusion regarding the performance of the proposed rudder.

4.3.2 Clean Fuel Technology

Along with development of the energy saving devices, the shipping industry has been investigating the technology readiness level and potential adoption of the zero-emission technology such as ammonia, hydrogen, and batteries to reduce the production of greenhouse gases. One of the existing hurdles with clean fuel technology is the higher cost of its production compared to traditional fuel. Nuclear power is one of the zero-emission technologies. However, the significant cost required for preparing the infrastructure has made it less attractive for commercial shipping. Another challenge for transition to clean fuel is the dependence of the technology to the type of vessel, travel distance and cargo choice. For example, Sims et al. (2014) show that batteries are an environmentally friendly choice in cases powered by renewable energy sources such as wind or solar but it can only be employed for driving light vessels over a short distance. Green ammonia is another zero-emission technology with no carbon content but it can release NOx during the use which is highly toxic.

Green hydrogen, which can be produced from renewable energy sources such as wind, is one of the strongest candidates for the clean shipping in the future. One of the current challenges with this technology is the storage space requirement due to the low energy density, as well as higher production cost relative to traditional fuel. There are safety concerns with the fuel as well, since it is highly flammable and could be explosive, and difficult to detect leaks due to it being colourless and odourless. Despite existing challenges, a few projects have demonstrated the viability of hydrogen fuel propulsion systems for maritime application. Hydroville was the first passenger shuttle certified in 2017 to operate with hydrogen fuel on a hybrid hydrogen-diesel engine. The FLAGSHIP project was co-funded by the European Union (EU) is deploying two commercially operated hydrogen fuel cell vessels in 2023. The demo vessels include a new build in France (Zulu) and a retrofit in Netherland (FPS Waal). Zulu operates on compressed hydrogen produced from electrolysis. The propulsion system for FPS Waal consists of PEM fuel cells, battery packs, an electric motor and hydrogen storage with the total power ~ 1.2 MW. HyShip is another EU funded project which is in the process of building a cargo vessel for commercial operation equipped with liquid hydrogen, a 1 MWh battery pack and 3 MW proton exchange membrane fuel cells. With the EU

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support, DFDS, a Danish company plans to build a large ferry designed for 1,800 passengers in collaboration with external partners. The ferry named Europa (Europa Seaways) is powered by electricity from a hydrogen fuel cell, where the green hydrogen will be produced by a projected offshore wind energy-powered electrolyser plant.

The main limitation of fuel cells is an adverse effect of transient loads on their lifetime and performance. Unsteady loads occur in various conditions such as ship manoeuvring, propeller cavitation, and ship operation in strong winds and high sea states. Further investigation into the problem and pursuing potential solutions for propulsion system such as power management systems and combination of fuel cells with batteries are recommended. Despite growing investment in fuel cells, the impact of these technologies on ships' manoeuvrability is not well studied. The current studies are mainly focused on propulsion. One of the suggested topics for the future investigation would be to determine the minimum propulsion power requirement supplied by the clean fuels to maintain the manoeuvrability of ships in adverse conditions.

5. MANOEUVRING IN WAVES

5.1 Experimental

Free running model tests in waves. Free running model tests allow a more realistic simulation of a ship's behaviour in waves. The model is not constrained or artificially guided, enabling it to respond freely to wave-induced motions, providing insights into the actual performance of the ship in dynamic sea conditions. The results obtained from the free running model tests serve as valuable validation data for computer simulation models.

Stern et al. (2022) performed the experimental and the numerical turning circles test in waves. They found the physics of turning circles in waves can be best explained using inverse dynamics: wave induced motions (mainly, pitch and heave) result in oscillating X and Y forces (mainly, added resistance X_H/X_w, and side forces Y_H/Y_w), which produce the oscillating u, v, drift angle (hull vortices), and propeller and rudder loads; all of which combine as the time mean and unsteady responses, and wave drift direction and distance.

Suzuki et al. (2023) investigated the rudder effectiveness and the engine limits effects in short waves by conducting course-keeping manoeuvres in regular waves. Duct-fan-type auxiliary thruster was used to allow various rudder effective conditions. They found that the rudder effectiveness for the full-scale ship and (smaller) engine outputs increase the time-averaged values of the ship speed reduction and the drift angle from head to beam waves. This implies that the full-scale ship is more susceptible to waves than the model-scale ship. The difference in the rudder effectiveness affects the time-averaged rudder angle (i.e. check helm), although definite wavelength-independent trends are not observed.

Captive model tests in waves. Captive model tests in waves have been performed to investigate the forces and moment induced by waves. In case of static straight or oblique tests, in which the incident wave direction is fixed, both the first and the second order wave forces can be obtained by fitting and averaging.

Suzuki et al. (2023) investigated the effects of the steady wave force variations generated by oblique motions. Oblique tests in regular short waves with various combination of towing speed and drift angles were performed to measure the steady wave forces. They observed that the steady wave forces in short waves are affected by not only the ship advancing speed but also the oblique motion. The steady wave sway forces at a positive drift angle becomes smaller than those at zero drift angle, and the steady wave yaw moment increases in the negative direction when the drift angle increases under such wave conditions.

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5.2 Numerical

Mean wave force methods. Oladele et al. (2023) developed an integrated time-domain seakeeping and manoeuvring model for the self-propelled ONR Tumblehome vessel in waves. Memory effects due to radiated waves and incident wave forces are incorporated into a 4DOF (surge/sway/yaw/roll) lumped-parameter model for manoeuvring in calm water to simulate the manoeuvring of the ship in waves. The proposed combined manoeuvring/ seakeeping model is validated against available experimental results on the self-propelled ONRT model using zigzag tests in head and following waves.

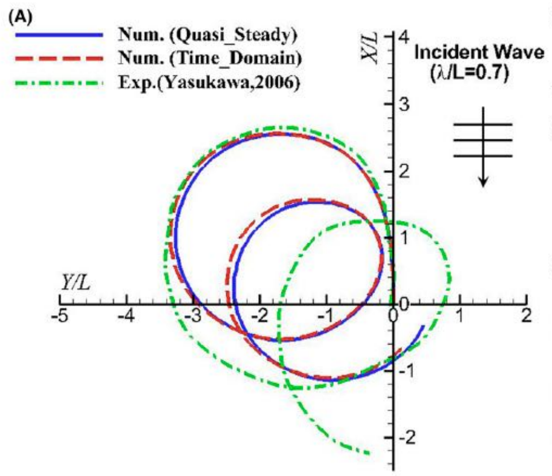

Figure 29. Results of the port side 35 turning manoeuvres of a S-175 model in regular waves of *l/L*=0.7, χ = 180°.

Zhang et al. (2022d) added wave drift loads obtained from the potential flow theory to the MMG model to account for the wave effects on ship manoeuvring. Two numerical methods were proposed to handle the coupled manoeuvring and seakeeping problem, a time domain approach and a quasi-steady method. A time-domain seakeeping computation was conducted that parallels to the manoeuvring simulation for the time domain approach. For the quasi-steady method, the wave drift loads were evaluated using a frequency domain method. The free turning of a S-175 container ship in regular waves were validated with experimental data. The results of the quasi-steady method and the time domain approach show good agreements (see Figure 29).

Two-time scale methods. Zhang et al. (2022a) proposed numerical simulation of ship manoeuvrability in irregular wave based on Taylor Expansion Boundary Element Method (TEBEM) with two-time scale model. The added resistance in wave was calculated first and followed by the free turning trajectory of KVLCC2 with different sea states. The comparison with available model test results shows good agreement (see Figure 30).

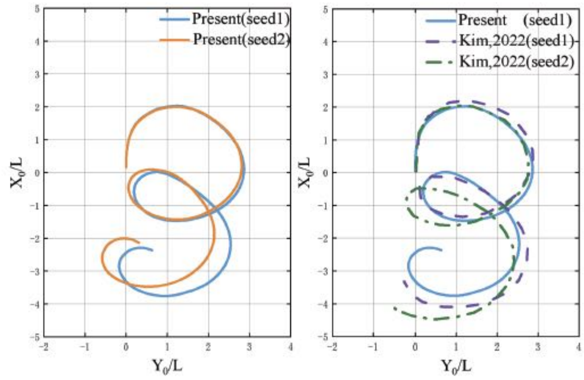

Figure 30. +35° turns with 5.54 RPS sea state 6.

Ma et al. (2022a) compared the two-time-scale method and the unified method on manoeuvrability in waves. The turning circle, heading angle and roll motion of a S-175 container ship in regular waves obtained from the two methods were compared with experiments. It was concluded that the two-time-scale method and the unified method can predict the ship turning circle and motions satisfactorily even though there are some differences between the simulated results and the experimental ones in short wavelength conditions.

TEMPEST is a time-domain potential-flow code developed at NSWCCD to predict the ship manoeuvring in waves using blended method as reported by Aram and Wundrow (2022). Manoeuvring forces due to linear circulatory lift are modelled by a low-aspect ratio wing theory and are parameterized by user supplied calm-

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water stability derivatives. Sectional coefficients account for nonlinear cross-flow drag induced manoeuvring forces. The TEMPEST results are validated against model data and high fidelity free-running simulations (Star-CCM+ setup with overset grids and actuator disk) for turning circle manoeuvres in calm water and regular waves for the ONRT. The rudder inflow condition calculated from captive double-body simulations does not accurately account for hull-propeller-rudder interactions, which apparently influences the prediction of manoeuvring characteristics by TEMPEST.

Hybrid numerical framework. White et al. (2022) proposed a hybrid numerical framework for simulation of ship manoeuvring in waves. A combination of CFD and a linear time-domain boundary element method, and a propeller-force model are developed for efficient computation of the total hydrodynamic forces. This approach is distinguished from previous two-time-scale approaches in that the manoeuvring forces are computed from a viscous DB RANS computation rather than a mathematical manoeuvring model. It demonstrates that the hybrid method offers an efficiency gain by at least a factor of 10 using a VOF method with free-surface capturing. The comparable accuracy and reduced computational expense highlight the hybrid method as an attractive option for prediction of ship manoeuvring performance in waves.

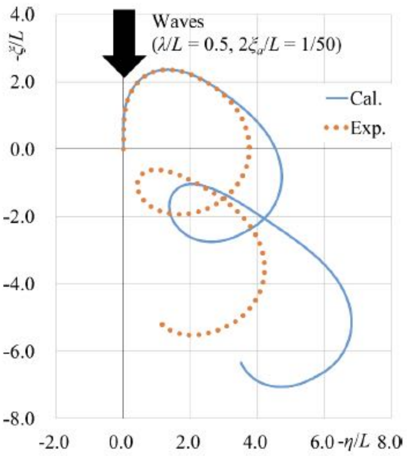

Figure 31. Comparison of 35° turning trajectories in regular waves for KVLCC1 (λ/L = 0.5, $2\zeta a/L$ = 1/50).

Unified methods. Suzuki et al. (2021) proposed a modified unified method to directly solve 6-DOF ship motions, without separating the motions according to frequency. To validate the proposed method, free-running model tests for KVLCC1 and KCS hull have been conducted. Comparisons for the regular waves (λ/L = 0.5, $2\zeta a/L$ = 1/50) for KVLCC1 show that the drifting directions of the estimated trajectories roughly agree with those of the FRMTs (Figure 31); however, the proposed mathematical model overestimates the drifting distance in wavelengths. The modified unified method can estimate the manoeuvring characteristics (e.g., mean ship speed, drift angle, and check helm) for course-keeping manoeuvres and turning trajectories, as well as 6-DOF ship motions induced by waves.

Paramesh and Suresh (2021) applied a unified seakeeping and manoeuvring model with a PID controller for path following of a KVLCC2 tanker in regular waves. The second order wave mean drift forces are calculated based on Salvesen's method and the wave exciting forces/moments and the restoring forces in the vertical planes are calculated for the exact wetted surface area. Through a set of pre-defined way-points using LOS algorithm, the largest cross track error of 0.78L is observed for port and starboard turn. This deviation is mainly due to the large drift force in sway and yaw when the ship is in oblique sea condition.

Yao et al. (2021) proposed the pure low-frequency and pure high-frequency ship motion equations in regular waves for ship manoeuvring prediction in waves. These motion equations, in which the inertia forces due to two coupled high-frequency motions were derived, were the modified versions of the traditional motion equations, e.g. the equations solved in the two-time scale methods. The predicted results based on the solution of the pure low-frequency ship motion equations reached a very high accuracy (see Figure 32).

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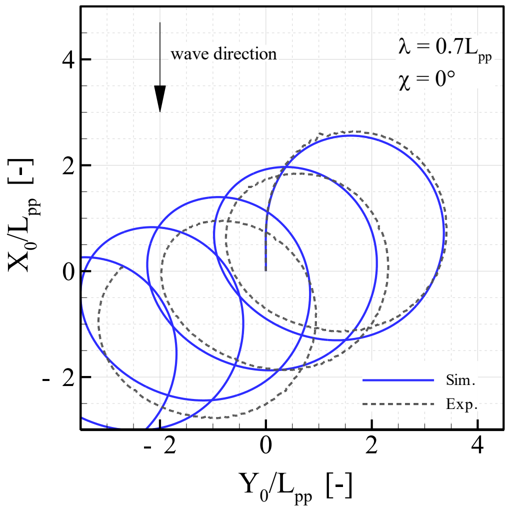

Figure 32. Comparison of the experimental turning trajectory with the precited one based on the solution of the pure low-frequency ship motion equations for S-175 in regular waves.

CFD based direct simulation methods. Ma et al. (2021b) performed the planar motion mechanism (PMM) tests on a containership S175 in regular waves systematically using CFD method for the first time. The hydrodynamic derivatives in waves of the target model are obtained by simulations in following waves or the surf-riding condition. The overset grid combined with Euler overlay method are useful and efficient. It is shown that wave effect on the hydrodynamic derivatives is significant.

5.3 Minimum Power Requirement

Overview. Since the introduction of the Energy Efficiency Design Index (EEDI), there was a concern that one of the most effective ways of reducing EEDI is simply by choosing a smaller main engine or main propulsion motor. However, it is required to keep sufficient propulsion power for operations in adverse weather conditions. At MEPC.232(65) (2013), Interim Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions were developed to avoid construction of extremely under-powered ships. At MEPC 71/INF.28 (2017), it was agreed to extend the application period of the Interim Guidelines towards phase 2 of EEDI regulation. The application date of Phase 3 is approaching, and finalisation of the Guidelines was the urgent matter. At MEPC.1/Circ.850/Rev.3 (2021), amendments to Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions were adopted. The amendments include changes to the definition of adverse weather conditions, new default values for thrust deduction factor and wake fraction, and two newly recommended semi-empirical methods for estimating the added resistance in waves in the new "minimum power assessment" method. MEPC 76 also agreed to further consider the concept of shaft/engine power limitation as measures to comply with both EEDI and minimum propulsion power requirements at MEPC 77.

Major amendments. The amendments are detailed in MEPC76/5/1 (2021). The major revisions include the following aspects:

1) Revised definition of adverse conditions (wave and wind conditions) which is now harsher, as seen from Table 4.

Table 4. Comparison of definition of adverse sea conditions.

	Existing	Revised
Wind speed [m/s]	15.7~19.0	19.0~22.6
Hs [m]	4.0~4.5	4.5~6.0

2) The "Simplified Assessment" method in 2013 Interim Guidelines is replaced by a new "Minimum Power Assessment" method, which examines the "maximum total resistance in the longitudinal ship direction over wind and wave directions from head to 30 degrees off-bow".
3) The navigational speed of the ship for assessment is defined to 2 knots.
4) Default conservative estimates of the thrust deduction factor t and wake fraction w are changed to t = 0.1 and w = 0.15, respectively. This change of t will lead to significant change of the required thrust. And apparently, the resultant hull efficiency η_H will also change.

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5) Several practical methods recommended for the prediction of added resistance in waves to facilitate the assessment.
6) Introduction of added rudder resistance due to manoeuvring in seaway.

With the amendments referring to higher sea states and lower ship speed, the added resistance in waves will practically dominate the prediction of the required power in adverse condition. Liu et al. (2022b) reviewed the revised Guidelines and found an inconsistency in the recommended methods for the added resistance prediction on typical tankers and bulk carriers. The proposed simple formula in the Guidelines is too simple, as it uses only the main ship particulars *L*, *B* and *d* in the calculation. Hence, for ships with the same main dimensions, but of different hull forms, the method will always lead to the same values and, it gives very low values for larger ship sizes. They also found that, due to the revision of the default thrust, deduction factor *t*, the required thrust has been decreased, which finally leads to a relaxed/reduced torque and power requirement.

Mao and Zhan (2022) developed a manoeuvring-seakeeping unified model of ship motions in waves to simulate the course-keeping manoeuvres of KVLCC2. The course-keeping ability in different wave directions with different autopilot parameters, as well as a MCR limit of engine, were discussed. The level-3 comprehensive assessment of minimum propulsion power (MPP) was compared with the level-1 and level-2 results according to MPP Guidelines. It was found that the level-2 simplified assessment is not enough to simulate the safe manoeuvrability of ships. The level-3 assessment by time-domain method should be adopted for the course-keeping ability simulation of ships in adverse conditions.

Sui et al. (2022) investigated the influence of propeller pitch and the PTO/PTI on ship propulsion and manoeuvring performance in adverse sea condition through simulation. The engine could more easily exceed the thermal loading limit at high propeller pitches and overspeed at low pitches. A shaft generator, PTO, will narrow the ship thrust/velocity envelope and reduce the operational safety at adverse weather condition. On the other hand, PTI extends the ship thrust envelope and results in better operational safety of both the engine and ship.

6. UNDERWATER VEHICHLES

6.1 Manoeuvring Hydrodynamics of UV

Numerical Methods. CFD tools have been widely used for self-propelled simulations of underwater vehicles' (UV) manoeuvring motion. There are a lot of works about a standard submarine model Joubert BB2. Carrica et al. (2021a) presented a study of a 10/10 vertical zigzag manoeuvre of the generic submarine Joubert BB2. Its manoeuvring characteristics, such as depth, pitch, pitch rate, vertical drift, vertical velocity, absolute velocity, and propeller thrust and torque coefficients were analysed at 6, 10 and 15 knots. The results show the overshoots in pitch and depth increase with the UV speed, and the velocity decreases rapidly, but the dimensionless pitch rate is only mildly affected. The average thrust and torque coefficients decrease as the speed increases, but the amplitude of the fluctuations increases.

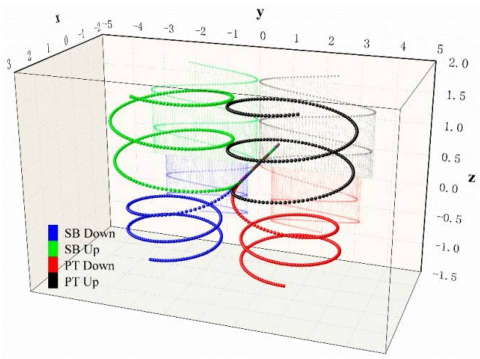

Figure 33. 3D trajectories for the space spiral manoeuvres.

Han et al. (2021) focused on analysing Joubert BB2's turning capabilities during both ascending and descending motions. Their analy-

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sis encompassed both steady turning manoeuvres and complex space spiral manoeuvres, as shown in Figure 33. The findings reveal that the turning motion significantly impacts the submarine's depth and pitch attitude, with a notable "stern heavier" phenomenon observed post steering. Notably, underwater turning can serve dual purposes for a submarine: reducing braking speed and limiting dangerous depths.

Skejic and Faltinsen (2022) predicted the manoeuvring behaviour of Joubert BB2 with particularly focusing on its sail design configuration in the horizontal plane under authentic seaway conditions. They employed a pre-selected Tabain's wind wave energy spectrum to describe the irregular wave field at specified geographical locations. Their simulations examined the submerged submarine's manoeuvring behaviour in a deep-water seaway as it executed turning circle (see Figure 34) and zig-zag manoeuvres at pre-determined periscope depths. Furthermore, this study introduces a novel 3 DOF combined manoeuvring and seakeeping two-time scale model, built upon a modular concept, to enhance the accuracy and comprehensiveness of the predictions.

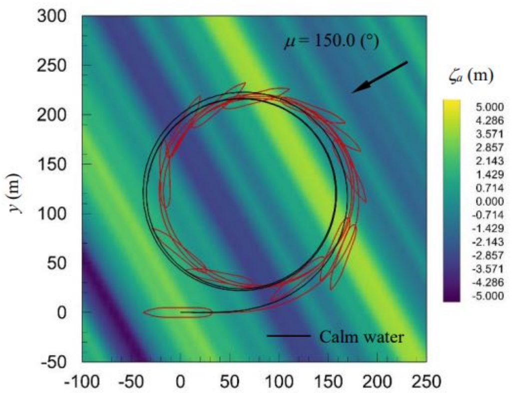

Figure 34. 20° port turning circular manoeuvre of Joubert BB2 at an approach speed of 10 knots.

Carrica et al. (2021b) conducted an extensive study involving a 20-degree turning manoeuvre, controlled vertically through the stern planes, as well as a 20/20 zig-zag manoeuvre, where both the sail and stern planes were vertically controlled, as shown in Figure 35. Both manoeuvres were executed at a standard speed of 10 knots. Additionally, a 20-degree rise manoeuvre was performed with horizontal control at 12 knots. The findings indicate that computational fluid dynamics accurately predicts the motions and speeds of the submarine under free-sailing conditions. However, replicating controller commands proved to be challenging. Notably, the computational results for the rise manoeuvre with surfacing closely aligned with experimental data, encompassing even the crash-back manoeuvre designed to halt the submarine's motion.

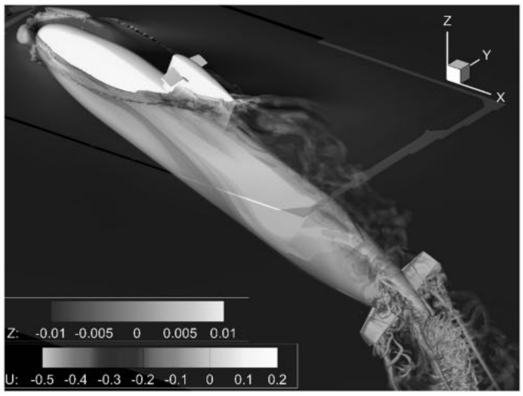

Figure 35. A submarine manoeuvres at a large pitch angle after breaking the surface. Vortical structures are shown as isosurfaces of Q = 3000 coloured with axial velocity.

Jeon et al. (2022b) predicted the dynamic characteristics of an X-rudder submarine. The near surface manoeuvres were analysed, and the jamming cases of control planes were discussed. The prediction results show the X-rudder submarine can execute standard manoeuvres when only one control plane is functional.

Kim et al. (2022b) investigated capability of a coefficient-based model to predict the stern dipping of a submarine during a turning motion. A simplified method was introduced to examine the influence of sail's position on stern dipping. It was found that the out-of-plane loads were very large when the sail was located further aft along the hull.

Arslan and Kefeli (2022) conducted 3-DoF numerical simulations a SUV, focusing on the

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changes in cavitator's pitch deflection, angle of attack, control surface angle, and pitch rates. The simulation results demonstrated that hydrodynamic analyses of vehicles exhibiting supercavitation can be accurately conducted under both cruising and manoeuvring conditions, and the hydrodynamic characteristics of an SUV can be thoroughly examined using validated CFD analysis models.

Doyle et al. (2022) employed RANS CFD methods to calculate the forces and moments arising from the presence of the sail. Their findings revealed the generation of normal forces and pitching moments was attributed to the interaction between the sail vortex system and the flow along the hull. It is also found that while the in-plane forces and moments were accurately predicted, the out-of-plane force and moment were significantly overestimated at high angles of drift.

Amini Foroushani and Sabzpooshani (2021) proposed a method to estimate the variation of hydrodynamic coefficients of UVs with low Reynolds number. They conducted rotational arm tests on a standard UV model, DARPA SUBOFF, to simulate the rotational linear damping hydrodynamic coefficients. Numerical results are used for deriving proper functions to estimate hydrodynamic coefficients. It was concluded that it is more appropriate to use fitted functions instead of constant values especially at low Reynolds numbers.

Experimental Methods. Zhang et al. (2021) carried out the tests by a drag method to obtain different inflow rates with 0° attack angle under different gliding speeds at 0.25 m/s, 0.5 m/s, 0.75 m/s, 1 m/s, and 1.25 m/s. The results showed the theoretical values were in good agreement with the experimental values, and the error was controlled at about 5%.

Khan et al. (2022) conducted wind tunnel tests to meticulously investigate the distribution of surface pressure over the SUBOFF hull form at elevated angles of incidence. The data collected from this comprehensive study will serve as a valuable adjunct to computational and experimental research on turbulent flows over submerged bodies, encompassing a broad spectrum of angles of incidence.

Wei et al. (2022) developed a numerical prediction method for the emergency ascent of a submarine with flow holes in calm water based on a RANS method, which was then validated by physical tests, as shown in Figure 36. The ascent motion was shown to be influenced by buoyancies, longitudinal and vertical positions of the centre of gravity, and diving depths.

Figure 36. Underwater trailer.

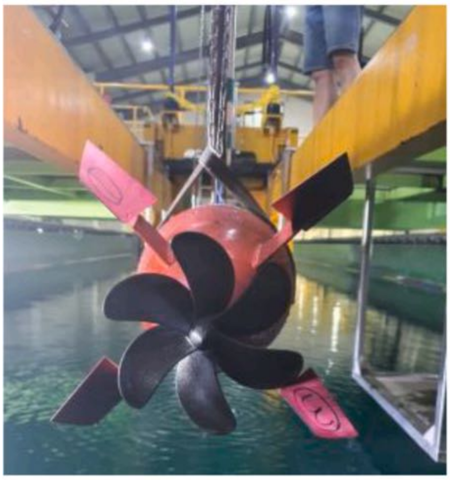

Figure 37. Snapshot of the effective elevator angle $\delta s = 40°$.

Kim et al. (2023a) carried out a series of captive model tests of the BB2 model with a scale ratio of 35.1, as shown in Figure 37. Combination tests including a horizontal static drift with rudder test and pure yaw with rudder were performed in the model basin at Pusan National University, and a mathematical model was constructed based on hydrodynamic coefficients obtained from captive tests. The key parameters, including the tactical diameter and transfer, are

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well predicted by using this mathematical model. However, the initial rate of turning shows significant discrepancy against the free-running model experiment due to the estimation error of the added mass in the sway or yaw motions.

Novel technology. It is noteworthy that some novel model-free approaches have been recently implemented to predict the hydrodynamic characteristics of underwater vehicles. Mai et al. (2023) developed a novel empirical formula for the hydrodynamic derivatives of a submarine using multiple regression analysis. They derived estimation formulae through based on CFD simulations, and then applied it to calculate the hydrodynamic derivatives of BB2 and a 2,000 tons submarine. Good agreement indicates that the established empirical formulae can be extended to submarines in general at the designing phase.

Thurman and Somero (2022) employed machine learning algorithms to establish prediction models for force and moment coefficients of axisymmetric bodies of revolution. They conducted a uniform experimental design encompassing 50 design points across five factors. A comprehensive test dataset was created to ensure that the prediction models were not overfitted to the training data and could accurately predict arbitrary geometries and inflow conditions within the experimental design region. This approach allows for a thorough assessment of the impact of varying geometric parameters on each force and moment coefficient.

6.2 UV control

The control system of an underwater vehicle is the key technology and the main indicator for measuring the performance of an UV. In case of the control of UVs, robustness and reliability are the most emphasized aspects.

The purpose of those research of the control of UV can be categorized into the following:

- to design a controller of a single underwater vehicle (Borlaug et al., 2021; Chen et al., 2022; Herman, 2021; Huang et al., 2021a), (Ma et al., 2023; Tran et al., 2021; Wang et al., 2022a; Zhang et al., 2021b; Zhang et al., 2024b; Zhang et al., 2024c; Zhu et al., 2024);
- to design a control system of a heterogeneous multiple autonomous vehicles including UVs (Sato et al., 2023; Weng et al., 2022; Xia et al., 2021);
- to investigate robust and reliable controller design operating under error factors like model uncertainties, under-actuations, and unknown environmental disturbances (Borlaug et al., 2021; Chen et al., 2022; Huang et al., 2021a; Tran et al., 2021; Wang et al., 2022a; Xia et al., 2021; Zhang et al., 2021b; Zhang et al., 2024b; Zhang et al., 2024c; Zhu et al., 2024);
- to design a controller of a multi-articulated, non-streamline shaped underwater robot (Borlaug et al., 2021);

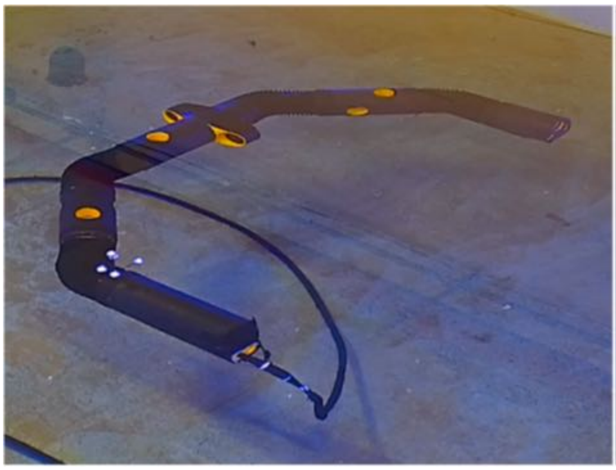

Figure 38. The Eelume vehicle with reflective markers attached at the base.

Borlaug et al. (2021) presented a trajectory tracking method for an articulated intervention autonomous underwater vehicle (AIAUV), as seen from Figure 38. For coping with hydrodynamic and hydrostatic parameter uncertainties, uncertain thruster characteristics, unknown dis-

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turbances, and unmodelled dynamic effects, super-twisting algorithm with adaptive gains and a generalized super-twisting algorithm were adopted for trajectory tracking of the position and orientation. A higher-order sliding mode observer was used for estimating the linear and angular velocities, for the case that velocity measurements were not available. To verify the algorithm applicability, comprehensive simulations and experiments were conducted.

Chen et al. (2022) investigated the fixed-time trajectory tracking problem of a small autonomous underwater vehicle (AUV) in the Trans-Atlantic Geotraverse (TAG) active mound with ocean current, unknown disturbances, model uncertainties, actuator faults, and input saturations. A high-order adaptive extended state observer, a continuous fixed-time sliding mode manifold, and an adaptive fault-tolerant trajectory tracking control law with an auxiliary dynamic system were used. The designed algorithm was verified through numerical simulations over the virtually generated topography of the TAG mound.

Herman (2021) presented a preliminary UV trajectory controller design method. The controller, which is applicable for fully actuated vehicles, contains the system dynamics in the control gains. Two examples of numerical simulations of underwater vehicle model were provided to suggest the effectiveness of the approach.

Huang et al. (2021a) dealt with the adaptive trajectory tracking control problem for an underactuated UV, to cope with unmodeled hydrodynamics, ocean disturbances and input quantization. The command filter-based backstepping design and minimum learning parameter algorithm were used for the controller design to avoid the adverse effect of explosion of complexity and computational complexity inherent in neural network. A mapping function was applied to transform the constrained control problem into the unconstrained one. Numerical simulations were conducted to verify advantage and effectiveness of the designed controller.

Ma et al. (2023) dealt with the position keeping process of an UV concept, subsea shuttle tanker (SST) for the offloading process. A linear quadratic regulator was designed for station-keeping in stochastic current. Numerical simulations were conducted to show that the designed control system could keep position during offloading process.

Tran et al. (2021) presented a study of depth controller design of a hybrid torpedo type AUV in the presence of model uncertainty and propeller torque's effect. They suggested a nonlinear disturbance observer (NDO) to deal with the linearization errors and uncertain components in the depth-plane model. The backstepping technique was adopted to design a depth controller. To verify the effectiveness, feasibility, and stability of the designed controller, numerical simulations were carried out by changing 20~30% of model parameter.

Wang et al. (2022a) presented heading control of an AUV by using the robust sliding mode control method. Control parameters were tuned by an automatic tuning method through a continuous hybrid model-based and model-free reinforcement learning method based on the deterministic policy gradient. To demonstrate the robustness and effectiveness of their approach, numerical simulations and sea trials were presented.

Zhang et al. (2021b) proposed an approach-angle-based three-dimensional path-following control scheme for an underactuated AUV with unknown actuator saturation and environmental disturbance. A path-following error dynamic model was derived based on the principle of relative motion which was followed by the design of approach-angle-based guidance law. A control law was designed based on the Lyapunov theory, backstepping technique, and fuzzy logic system approximation method. Numerical simulations, including straight path following and spatial helix path following, were presented to verify the effectiveness and robustness of the proposed control scheme.

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Zhang et al. (2024b) addressed the issue of learning from suboptimal demonstrations and suggested a model-free reinforcement learning method. They integrated a recurrent neural network into the policy network, based on a soft actor-critic, to capture the relationship between states and actions. Simulations with two reference trajectories were suggested for validation.

Zhang et al. (2024c) investigated a rotation-matrix-based finite-time trajectory tracking problem for AUVs in the presence of output constraints, input quantization, and uncertainties. To satisfy the finite-time stability of AUV tracking control and the output constraints imposed by introducing the new attitude error vector, a finite-time command-filtered backstepping controller was proposed based on the asymmetrical time-varying barrier Lyapunov function, and a second-order auxiliary dynamic system was proposed to estimate the negative effects of input quantization errors. An adaptive finite-time disturbance observer was also developed to estimate the lumped uncertainties without prior information on the bounds of the uncertainties. Through numerical simulations, they argued the effectiveness of the control scheme.

Zhu et al. (2024) proposed an adaptive sliding mode tracking control method with a nonlinear disturbance observer to solve the trajectory tracking problem of the underwater vehicle-manipulator system (UVMS) in the presence of large dynamic uncertainties and severe external disturbances. They employed an adaptive control law, an improved fractional-order sliding mode, and a nonlinear disturbance observer to achieve tracking performance of the UVMS. Tracking accuracy, system stability, and interference attenuation under the application of external disturbances were suggested through numerical simulations and experiments.

Sato et al. (2023) presented a basic formation control system that enables various AUV control with minimal software and hardware modifications to autonomous surface vehicle (ASV) and AUVs, for controlling a group of heterogeneous AUVs with different design concepts when operating multiple AUVs simultaneously. Designed control system was successfully tested in actual sea conditions. Four AUVs and one ASV from different manufacturers were used in the sea trials. The basic formation control system kept all AUVs within acoustic communication range and successfully acquired seafloor topographic data. The tests demonstrated the capability of basic formation control with heterogeneously navigated AUVs.

Weng et al. (2022) proposed a method for maintaining the relative position and orientation between AUVs, for establishing a line-of-sight underwater communication link to realize high data rate optical communication in ocean exploration. The policy that could suppress external disturbances and optimize the link establishment efficiency was searched using a reinforcement learning algorithm. To evaluate the performance of the proposed method, a hovering AUV was used to conduct the link establishment experiments. The reinforcement learning policy trained in a simulation environment, then the policy was tested in real sea environments. Based on field experiment results, the performance of the link establishment policy was evaluated.

Xia et al. (2021) dealt with three-dimensional (3-D) formation control of multiple underactuated AUVs with a multi-time-scale structure under uncertain nonlinearities and environmental disturbances. A double-layer independent position-velocity fixed topology was adopted to overcome the drawback of narrow bandwidth of underwater communication. An extended high-gain observer was used to cope with uncertain nonlinearities and environmental disturbances. An integral sliding mode controller was used for formation control of multiple AUVs. Numerical simulations were presented to verify the control performance.

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7. PROCEDURES

7.1 General and Minor Changes

The MC reviewed the procedures and guidelines under its responsibility and made updates to the following six procedures and guidelines:

- 7.5-02-06-02 Captive Model Test Procedure.
- 7.5-02-06-03 Validation of Manoeuvring Simulation Models.
- 7.5-02-06-05 Uncertainty Analysis for Free Running Model Tests.
- 7.5-02-06-06 Benchmark Data for Validation of Manoeuvring Predictions.
- 7.5-04-02-02 UV Full Scale Manoeuvring Trials.

The MC made minor changes to the following procedures:

- 7.5-02-06-04 Uncertainty Analysis for Manoeuvring Predictions based on Captive Manoeuvring Tests. Minor English corrections were carried out.
- 7.5-02-06-07 Captive Model Test for Underwater Vehicles. Minor changes were made for the implementation of steady straight-line tests.
- 7.5-03-04-01 Guideline on Use of RANS Tools for Manoeuvring Prediction. Minor updates of the list of nomenclature, and minor English corrections were carried out.
- 7.5-03-04-02 Validation and Verification of RANS Solutions in the prediction of Manoeuvring Capabilities. Some minor changes were made for format, gramma, etc.
- 7.5-04-02-01 Full Scale Manoeuvring Trials. Some minor changes are made for format, gramma. Minor English corrections were carried out.

The procedures of manoeuvring in waves are implemented into two existing procedures:
- 7.5-02-06-01 Free Running Model Tests.
- 7.5-02-06-02 Captive Model Test.

7.2 Uncertainty Analysis for Free Running Model Tests

The purpose of the guideline 7.5-02-06-05 ‘Uncertainty Analysis for Free Running Model Tests’ is to provide guidance for ITTC members to perform UA of a model scale free running model test following the ITTC Procedures 7.5-02-06-01, ‘Free running model tests’.

The guideline outlines the factors that should be considered in conducting free running model tests, focusing on elements that may impact the test results’ uncertainty. It also discusses the basic approach to quantifying uncertainty in tests results.

No newer material dealing with UA was found with respect to free running model tests. Thus, 30th ITTC MC made some cosmetic corrections and added ‘List of Symbols’ to the guideline in accordance with 30th QSG’s instructions.

7.3 Captive Model Test Procedure

A major change has been introduced to procedure 7.5-02-06-02 ‘Captive Model Test”. This procedure has been updated with testing details in waves, such as wave parameters, waiting time, loading conditions, etc.

Some minor changes on alternative steering devices have been introduced to define the suggested operational parameters of these devices for captive model testing. Furthermore, a list of necessary documentation on alternative devices used during the tests is proposed.

Additional information on hexapods and on movable bottom have been introduced to the procedure. Finally, the list of symbols has been updated according to the ITTC Symbols List

7.4 Guideline for Manoeuvring in Waves

The aim of the guideline “Manoeuvring in waves” is to addresses the necessary steps and documentation for the manoeuvring model tests

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in waves, including captive and free-running model tests.

One of the tasks given to MC was to survey two guidelines for manoeuvring in waves submitted by the Specialist Committee on Manoeuvring in Waves (SC-MW) of 29th ITTC, and to make draft guidelines for manoeuvring in waves based on the given references.

After surveying the reference guidelines, the 30th ITTC MC found that there are many similarities between the guideline for manoeuvring in waves and the guideline for manoeuvring in calm sea condition. Therefore, the 30th ITTC MC and AC agreed to merge the guidelines for manoeuvring in waves, which were originally prepared by the Specialist Committee on Manoeuvring in Waves (SC-MW) of 29th ITTC, with the guidelines for manoeuvring in calm condition.

Merging of two guidelines was conducted based on the following conditions:

- Use simple and effective representation for merging.
- Keep the original meanings.
- Procedures should be described as precisely as possible.
- Separate descriptions should be added for the parameters that are used only in waves tests.

The merged guidelines have been reviewed by the 30th ITTC Seakeeping Committee (SC) and 30th ITTC AC to incorporate any revision requests.

7.5 Guideline for UV

In the 29th ITTC, two new guidelines were proposed for captive model test and full-scale manoeuvring trials for underwater vehicles. in this ITTC, MC continues to work towards the completion of these two guidelines.

Minor changes have been made to 7.5-02-06-07 Captive Model Test for Underwater Vehicles, including the implementation of steady straight-line tests. Compared to surface ships, the Froude number is less important for underwater vehicles. The scaling effects for conducting UV captive tests are discussed and included in the update guideline, and the non-depersonalization of hydrodynamic derivatives is removed.

Major changes have been made to UV Full Scale Manoeuvring Trials (7.5-04-02-02). MC decided to make this guideline focused on unmanned UVs. It is very challenging to include the manned UVs, e.g. submarines, into this procedure. There are very limited literatures available on submarine full scale tests. The information on full scale test procedure is very sensitive. Each country may have its own procedure. It will be challenging to propose a standard testing procedure for submarines without collaborations among different nations and institutions. Even though we propose standard trials for submarines, these procedures are less likely to be applied by these countries/institutions.

The current guideline is focused on AUVs and ROVs. Their performance is determined by both hydrodynamics and autonomy system. It is noted that the 2021 version focuses too much on the control tests, which are hard to be standardized. Even in ITTC 7.5-04-02-01, full scale manoeuvring trials, the procedures are proposed for standard manoeuvring tests for surface ships, and no intension was made there to test the autonomy. Therefore, in this guideline, MC proposes to focus on standard manoeuvring trials, leaving the autonomy and control system tests for future tasks. The tests for autonomy are replaced by 8 standard manoeuvring trials. MC also defines the following 11 manoeuvrability for AUVs and ROVs:

1. horizontal inherent dynamic stability
2. vertical inherent dynamic stability
3. course-keeping ability
4. depth-keeping ability
5. course-changing ability
6. depth-changing ability

7. yaw checking ability
8. pitch checking ability
9. turning ability in horizontal plane
10. horizontal stopping ability
11. vertical stopping ability.

To evaluate the above 11 manoeuvrability, 8 standard tests are recommended as following:

Table 5. Standard manoeuvring tests for AUVs and ROVs.

Type of Tests		Manoeuvrability to be checked
1	Turning Circle Test	9
2	Zig-zag Test	5,6,7,8
3	Spiral Test	1,3
4	Pull-out Test	1,2
5	Stopping Test	10,11
6	Stopping Inertia Test	10,11
7	Thruster Test	5,6,7,8,9
8	Crabbing Test	5,6

The executions of the above 8 manoeuvres are updated accordingly in 7.5-04-02-02.

8. CONCLUSIONS

Experimental tests. MC has reviewed the literatures regarding the development of new methods, trends, and challenges in experimental hydrodynamics. Although more attention is put in manoeuvrability in waves, some issues on calm water manoeuvring tests are still to be solved. One of the issues is the correction of manoeuvring model test results with consideration of environmental factors. Especially the influence of wind should be considered as an important factor. Other yet unsolved topics include the scale effect in manoeuvring model tests. This is however extremely challenging due to lack of sufficient full scale data.

Low-speed manoeuvre is another challenging topic which has attracted many attentions. It is usually accompanied with the shallow and narrow water problem. This topic is extremely important in case of developing navigational simulators, in which the ship behaviour in muddy areas and ship-to-ship interactions are two focused areas. Model test data on ship-bottom, ship-bank and ship-ship problems have been well documented in literatures over the last few years.

Uncertainty analyses of experimental tests, especially captive model tests, is also a challenging topic in manoeuvring tests. New UA methods have been proposed, for instance in SIMMAN2020 workshop. They need to be carefully reviewed and assessed before they can be implemented into general procedures.

Numerical manoeuvring simulations. There is a growing interest in applying high-fidelity numerical approaches such as CFD for manoeuvring predictions. The majority of CFD studies have employed RANS as a practical turbulence modelling approach, providing reasonable accuracy. However, free-running manoeuvring perdition remains a computational challenge and is currently infeasible for application at the design phase and not practical for evaluating ship manoeuvring performance. Consequently, high-fidelity computations have primarily been used for captive model manoeuvring predictions to inform reduced order manoeuvring models.

Benchmarking the numerical models continues to be an active area of research. The uncertainty in the numerical predictions is generally greater in shallow and restricted water than deep, unconfined water, Future efforts should focus on improving numerical models to reduce uncertainty, leveraging CFD to deepen our understanding of the underlying flow physics in ship manoeuvring, and utilizing this knowledge to enhance reduced-order manoeuvring models. Application of ML&AI technologies should be considered for improving the models.

Benchmark data. The SIMMAN 2020 workshop has given a large amount of new valuable benchmark data for validation. Besides additional and updated data for the KVLCC2 and the

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KCS, the workshop introduced the surface combatant ONRT as a replacement for the 5415M. The benchmark data sets of the ONRT were all new and included both captive tests and free running model tests. Besides the calm water data in deep and shallow water, free running model tests (e.g. turning circles) in regular waves were also introduced for both the KCS and the ONRT.

The overall results from the workshop showed a good progress in the prediction capability. The prediction errors defined in 2020 were smaller than those in 2014, though it was only properly statistically documented for the deep-water cases. The amount of time domain CFD simulations submissions increases significantly compared to past workshops, though it is still an insufficient amount to give sound guidance and recommendations.

Based on the outcome of SIMMAN2020, it is recommended to keep the focus on KVLCC2, KCS and ONRT for future workshops unless a ship with open full scale data becomes available and to include propeller thrust and rudder forces in analysis, which were not considered in SIMMAN2020. It is also recommended to promote research in shallow water as the errors in general were larger than those in deep water cases.

In parallel with SIMMAN, a limited set of benchmark data has also been released in connection with the 6th MASHCON. The dataset contained captive shallow water benchmark data with focus on the effects of a passing ship (KCS) on two different moored ships (a Neo-Panamax container ship (C0P) and an Aframax tanker (T0Y)).

Autonomous, novel device and clean fuel. The number of the published paper on autonomous ships increases rapidly over the past decades. There are numerous methods/algorithms developed for ship path planning/following/tracking, collision avoidance, formation control, and berthing manoeuvres. Most of these works are mainly focused on simulations without sufficient validations of their proposed control algorithms. There are no widely accepted benchmark autonomous ship model or manoeuvring scenarios to compare the performance of the control strategy. Efforts are required to put forward benchmark models and standardize the testing scenarios to accelerate the technology and regulatory development for autonomous ships.

Zero-carbon shipping is another hot topic in maritime community. There are many zero-emission technologies, such as ammonia, hydrogen, and batteries, being proposed and validated by the shipping companies and research institutes to reduce the production of greenhouse gases. Novel devices, such as wind assist devices, novel rudders, have been proposed to reduce ship resistance, hence saving energy. Most of these studies are focused on propulsion. The impact of these technologies on ship manoeuvring are not well understood.

Manoeuvring in waves. There is no new PMM test in wave results published in this period. Only a few oblique towing tests in waves were available. The steady drift in regular waves for steady wave forces have been conducted in Actual Sea Model Basin for KVLCC1, under three wave frequencies with different drift angles and speeds. A series of steady drift tests in oblique waves to measure surge and sway wave drift forces and yaw drift moment acting on KVLCC2 have been performed in KRISO. On the other hand, several free-running model tests (FRMT) in wave are available during this term (the 30th) of ITTC. Trajectories of self-propelled ship with 35 degree turning circle for KCS and ONRT have been published in SIMMAN2020. Zig-zag model tests were performed on an unmanned wave glider.

In numerical simulation of manoeuvring in wave, mean wave force method is still attractive due to its simplicity. Two-time scale methods and Unified methods have been widely used to predict the manoeuvrability of ships in waves.

Direct CFD simulations of ship manoeuvring in waves continue to draw broad attention. Self-propulsion and turning circle motions in

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waves can be simulated using an overset method. However, due to the high computational cost and longer simulation time, direct CFD manoeuvring simulations in irregular waves are still changeling. A new combination of CFD, a linear time-domain boundary element method, and a propeller-force model are developed for efficient computation of the total hydrodynamic force. Another new direction for manoeuvring in wave is data-driven hybrid machine learning architectures to improve knowledge and forecasting capabilities for ships operating in waves.

Underwater vehicles. There have been a large number of publications on underwater vehicles during this term (the 30th) of ITTC, which include the studies on hydrodynamic design, interaction between UV and environment, appendages, path following, trajectory tracking, station keeping etc. Discussions are highlighted on UVs' hydrodynamic performance, flow field and control algorithms. However, the manoeuvrability of UVs is not clearly defined, and the manoeuvres presented in these studies are very scattered. Not like surface ships, the mathematical model of UVs' 3D manoeuvring motion has not been well established and progressed over the past few decades. The existing model is very complicated due to the cross-coupling terms in hydrodynamic derivatives, which largely hindered the application of this model in UV community. It also hinders the development of captive model test technologies for UVs, particularly for those with asymmetrical geometry in horizontal plane. Although CFD technology has been widely used to predict the hydrodynamic forces and simulate the free running manoeuvring motions of UVs, there is very limited benchmark data to validate and verify the CFD predictions. There is an urgent demand from UV community to put tother some joint efforts to benchmark UV models and test procedures.

Procedures. The MC reviewed the procedures and guidelines under its responsibility. A symbol list is added to all the procedures and guidelines. Major updates and improvements were made to:

- 7.5-02-06-03 Validation of Manoeuvring Simulation Models
- 7.5-03-04-02 Validation and Verification of RANS Solutions in the Prediction of Manoeuvring Capabilities
- 7.5-04-02-02 UV Full Scale Manoeuvring Trials

No new procedures and guidelines are developed in this term. However, the guidelines developed by the 29th ITTC specialist committee on manoeuvring in waves are merged to the following to general procedures:

- 7.5-02-06-01 Free Running Model Tests
- 7.5-02-06-02 Captive Model Test

9. RECOMMENDATIONS

The 30th ITTC Manoeuvring Committee recommends the following:

Update procedure 7.5-02-06-02 Captive Model Test with regards to hexapod tests.

Review the uncertainty analysis by SIMMAN 2020. If needed, procedure 7.5-02-06-04 Uncertainty Analysis for Manoeuvring Predictions based on Captive Manoeuvring Tests, will be updated to incorporate the outcome of SIMMAN 2020.

Update procedure 7.5-03-04-01 Guideline on Use of RANS Tools for Manoeuvring Prediction, update the numerical simulation procedure for calm water, add the guideline for simulations in waves, replace the example on simulation based on derivatives (calm water), add an example of direct manoeuvring simulation in waves.

Update procedure 7.5-03-04-02 Validation and Verification of RANS Solutions in the Prediction of Manoeuvring Capabilities, evaluate the feasibility of adding an example of manoeuvring in waves.

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Update 7.5-02-06-03 Validation of Manoeuvring Simulation Models, reflecting the outcome of SIMMAN and any other new developments.

Liaise with the authorities/organizations/associations on marine autonomous, evaluate the feasibility to propose standard manoeuvring trials for MASS.

Collect benchmark data for surface and underwater vehicles include these benchmark data in 7.5-02-06-06 Benchmark Data for Validation of Manoeuvring Predictions.

Liaise with Full-Scale Ship Performance Committee, review and collect benchmark data for full-scale manoeuvring tests.

Review the guidelines for low-speed manoeuvring tests and full-scale manoeuvring trials, if needed, update 7.5-02-06-01 Free Running Model Tests and 7.5-04-02-01 Full Scale Manoeuvring Trials by implementing the low-speed tests and/or bow thruster test procedures.

Investigate the novel propulsion/steering technologies, e.g. wind-assisted propulsion devices, and evaluate their impacts on ship manoeuvrability.

Survey the AI and data-based technology and their application to ship manoeuvring.

Keep updated on the ongoing discussions regarding amendments to the IMO Manoeuvring Standard and investigate the effects on tank tests and simulations.

The Manoeuvring Committee recommends to the Full Conference to adopt the updates to the procedures and the newly created guidelines.

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