The Manoeuvring Committee

Final Report and Recommendations to the 29th ITTC

1. INTRODUCTION

1.1 Membership

The 29th ITTC Manoeuvring Committee (MC) consisted of:

- Dr. Guillaume Delefortrie (Chair). Flanders Hydraulics Research (FHR), Belgium.
- Prof. Dr. Eduardo A. Tannuri (Secretary). Escola Politécnica da Universidade de São Paulo (USP), Brazil.
- Prof. Dr. Xide Cheng, Wuhan University of Technology, China.
- Prof. Dr. Sanghyun Kim. Inha University, South-Korea.
- Dr. Takashi Kishimoto. Akishima Laboratories Inc., Japan
- Dr. Zhi Leong, Australia Maritime College, Australia (since January 2019).
- Dr. Salvatore Mauro. INM, Italy (until October 2018).
- Ms. Janne Flensborg Otzen. FORCE Technology, Denmark.
- Dr. Zhiming Yuan. Universities of Glasgow and Strathclyde, UK.

1.2 Meetings

Three meetings have been held as follows:

- INM, Rome, Italy, January 22–24, 2018;
- Akishima Laboratories Inc., Tokyo, Japan, November 6–8, 2018;
- Universities of Glasgow and Strathclyde, Glasgow, UK, June 5–7, 2019, prior to OMAE 2019.

The fourth meeting was planned in 2020, subsequently in Wuhan (China), Seoul (South-Korea) and Ostend (Belgium), but could never happen due to the Covid-19 threat. Instead, video calls were used to finalize the present report. These video calls took place on April 1–3, 2020 (4th virtual meeting) and on January 7–8, 2021 (5th virtual meeting).

2. TASKS AND REPORT STRUCTURE

The following lists the tasks given to the 29th MC together with explanation on how the tasks have been executed.

1. Update the state-of-the-art for predicting the manoeuvring behaviour of ships, emphasizing developments since the 2017 ITTC Conference. The committee report should include sections on:
   a. the potential impact of new technological developments on the ITTC
   b. new experiment techniques and extrapolation methods
   c. the practical applications of computational methods to manoeuvring predictions and scaling, including CFD methods
   d. the need for R&D for improving methods of model experiments, numerical modelling and full-scale measurements
   e. the effects of free surface, roll, sinkage, heel and trim in numerical simulation of manoeuvring
   f. Include specifically, the prediction and testing of low speed manoeuvring to understand the impact of these types of manoeuvres in model testing.

The state of the art has been updated based on a comprehensive literature review spanning publications from 2017-2020. This is elaborated in section 3 of the present report, where the literature has been grouped in research in deep (unrestricted) or shallow (restricted) areas. A massive amount of literature on unmanned navigation and autopilots has been published, which is discussed in dedicated subsections.

2. During the first year, review ITTC Recommended Procedures relevant to manoeuvring, including CFD procedures, 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.

No new procedures have been proposed, but the changes to the existing procedures are discussed in section 4.1.

3. Coordinate and exchange information with the Specialist Committee on Ice with regard to the possible updating of ITTC Recommended Procedure 7.5-02-04-02.3, Manoeuvring in Ice.

Some preliminary work has been performed by the MC, however, the Specialist Committee on Ice did not require further input. More details are provided in section 4.2.

4. Update 7.5-02-06-03 2014 Validation of Manoeuvring Simulation Models, including verification, sensitivity analysis, results from the SIMMAN conferences and step by step validation of manoeuvring models.

The procedure has been updated. Details are provided in section 4.3.

5. Investigate the missing elements in the Procedure on Uncertainty Analysis for Manoeuvring Prediction Based on Captive Model Tests, such as the accuracy of carriage kinematics and the data filtering (noise). Update 7.5-02-06-04 if necessary according to the requirements of the ISO GUM.

The procedure has been updated by providing information on the mentioned missing links, discussed in section 7.1. The ISO GUM update is recommended for the 30th term as part of an integrated example. See section 4.4 for more information.

6. Update 7.5-02-06-02 Captive model test procedure to provide a definitive, agreed, method for each of the testing approaches.

The procedure has been significantly updated. See section 4.4 for more details.

7. Assist with the organization of SIMMAN 2019. Use the output from this conference and others to develop a guideline for the setup, execution of benchmark tests and use of benchmark data for manoeuvring.

The MC has supported the SIMMAN organization (see section 5). As SIMMAN is postponed to the end of 2021 the output of this conference could not be used in the guideline. The guideline itself is discussed in 4.5.

8. Investigate the uncertainties associated with manoeuvring tests in shallow water including aspects such as structural strength of moveable bottoms, extent of gaps around the edges and the degree to which a fixed floor is level.

Section 7.2 is dedicated to the issues of the tests on shallow water. The MC has executed potential flow calculations to investigate the effects of gap extents.

9. Investigate the results from the previous ITTC questionnaire on captive model tests especially related to concerns over turbulence stimulation and full scale effects; update 7.5-02-06-02, if necessary, concerning this matter.

A new questionnaire has been setup and the results are discussed in section 7.3.

10. Liaise with Specialist Committees on Combined CFD/EFD Methods and Manoeuvring in Waves as required.

Contacts have been established with these committees. Specifically the Specialist Committee on Combined CFD/EFD reviewed our RANS procedures.

11. Develop guidelines for the model testing and sea trials of autonomous underwater vehicles (AUVs) (resistance, manoeuvring, propulsion and control, computational methods for the low Reynold’s Number flow around AUVs).

The original TOR as mentioned here was very broad and has been limited by the AC afterwards to the study of AUVs and the creation of guidelines for model testing and sea trials focusing at manoeuvring. This is elaborated in section 4 and section 6.

3. STATE OF THE ART

3.1 Deep Unrestricted Water

3.1.1 Experimental methods.

General. Bonci et al. (2017) investigated the effects of heel and drift angle on the hydrodynamic forces acting on a high-speed craft via captive model tests as shown in Figure 1 and numerical predictions using a 3-D potential flow method. The results between model tests and predictions were in a good agreement over a broad range of Fr, including semi-planing and planing conditions. The proposed prediction method is considered as a valuable and less-time consuming alternative to EFD techniques and more complex approaches such as RANS tools.

Figure 1: Model test run in heeled condition (Bonci et al., 2017)

Yasukawa et al. (2019) proposed a pragmatic extension to 4-DOF of the standardized 3-DOF MMG model. The roll moment was modelled using the vertical application lever of the sway force (acting on hull and rudder). The roll damping coefficients were derived from roll decay tests. Roll dependencies were added to the surge, sway and yaw moment expressions as well, including in the expression for the propeller wake and straightening coefficient of the rudder. The practicality here is that different roll dependent terms are predicted using new empirical formula derived from experimental tests with 4 ship models. The simulation model was then validated against free running model tests executed with variations of GM.

Yeo et al. (2018) performed captive model tests with the KCS hull to investigate the effect of a heel angle as shown in Figure 2. A number of manoeuvring simulations were conducted to apply the hydrodynamic derivatives obtained from the model tests. The results showed the difference in turning and zigzag characteristics according to heel angle.

Figure 2: Captive model test in heeled condition (Yeo et al., 2018)

Yun et al. (2018) reported results of free running model tests of the KCS hull form with CG variations, i.e., trimmed condition, heeled condition and smaller GM condition. The test results can be used as benchmark data sets for future simulation research.

Reichel (2020) adequately pointed out the challenges of podded ships to comply with the IMO Standards for Ship Manoeuvrability when the pod angle was used instead of the rudder angle (comparative steering angle). Based on manned model tests executed with a marginally unstable ship equipped with two pods at the Ship Handling Research and Training Centre in Poland, he demonstrated that remarkably smaller steering angles can be acceptable to fulfil the IMO turning criteria for podded ships.

<u>Innovations.</u> Measurements applying new test devices have been reported. Ortolani and Dubbioso (2019) developed two novel transducer setups that allow to monitor the in-plane loads of a propeller and the loads in 6-DOF developed by a single blade respectively. CFD and PIV were used to compare the transducers' measurements in a selection of manoeuvring conditions. The authors highlighted that such setups were scarcely described in literature and they could potentially be valuable inputs to understand the phenomena affecting the performance of a propeller behind a ship hull and their induced loads on ship structures and manoeuvrability.

A valuable report to explore the mechanism of flow separation was published by Lee and Jones (2018), who conducted multiple pressure measurements around a slender body with drift angles in a uniform flow. They thoroughly investigated the pressure field on the body surface and compared the locus of the flow separation with results of the flow visualization. Such research is of importance to update various estimation methods for the flow field and the hydrodynamic forces acting on a ship's hull, subject to large manoeuvring motion, which is characterized by highly non-linear effects (Figure 3).

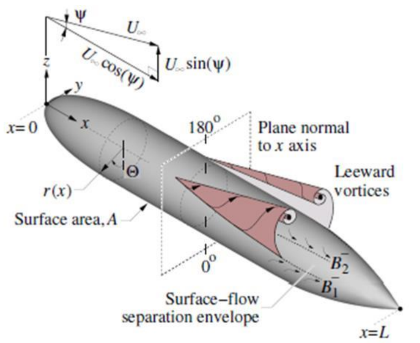


Figure 3: Flow separation on an inclined slender body in translation (Lee and Jones., 2018)

Iseki (2019) proposed a real-time identification procedure to estimate linear hydrodynamic derivatives based on on-board monitoring data regarding wind and ship's manoeuvres. Furthermore, by applying those results, the manoeuvrable range and limit in wind disturbance were shown (Figure 4). Although some derivatives of the estimation were unstable, the result of the proposed method shows the possibility to obtain feedback for ship design from on-board monitoring data.

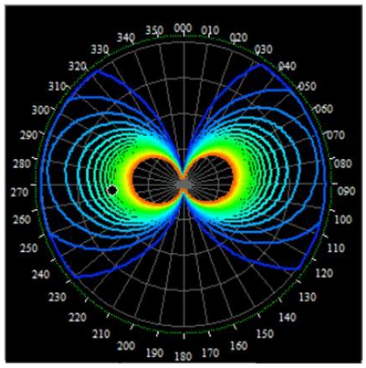


Figure 4: Manoeuvrable range in wind (Iseki, 2019)

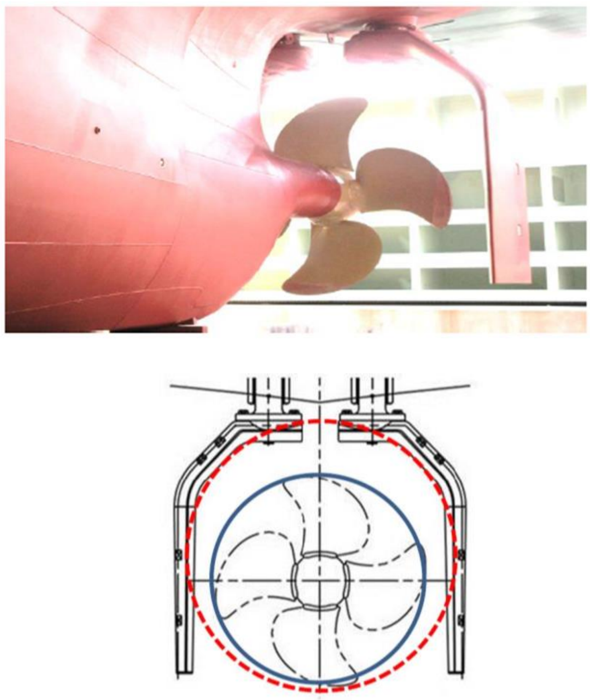


Figure 5: Gate Rudder (Sasaki et al., 2019)

Sasaki et al. (2019) investigated the performance of the world first Gate Rudder system installed on a container ship "Shigenobu". The Gate Rudder can be categorized as a new type of ducted propeller, i.e., open type ducted propeller as distinct from conventional ducted propeller (Figure 5). Comparing the full-scale data analyses with the sister ship "Sakura" equipped with a conventional rudder, they presented the superior performance of the Gate Rudder in terms of fuel efficiency, course keeping performance, speed deduction in turning manoeuvres and steerability in harbour operation. Carchen et al. (2021) presented a numerical model, based on an extension of the MMG model to cope with the specific angle definitions of the gate rudder. The wake was studied with RANS under different drifting conditions. The merits of the paper are the innovative design of the rudder being studied with an appropriate combination of the present engineering tools, but further discussion is expected to validate the Gate Rudder performance.

3.1.2 Numerical Methods

Potential flow methods. Dashtimanesh et al. (2019) proposed a mathematical model based on 2D+T theory to simulate the steady turning manoeuvres and PMM tests. They calculated the hydrodynamic derivatives of a planing hull at different speeds as well as different yaw and sway amplitude. The hydrodynamic derivatives seemed hardly influenced by the amplitude of pure sway and yaw motion and the motions in the vertical plane (heave, roll and pitch) seemed to affect the horizontal motion derivatives. Carstensen (2019) coupled a lifting line approach with a panel method to quickly predict the rudder-propeller interaction.

Commercial RANS methods. Most of the studies on RANS simulations are performed using commercial CFD software, among which STAR-CCM+ is most frequently cited. Liu Y. et al. (2018) investigated the effect of a ship's attitude on its manoeuvrability index by using the CFD package STAR-CCM+. They concluded that considering the dynamic sinkage and trim could improve the hydrodynamic force predictions, especially in the pure sway tests. They also analysed the attitude impact on the hydrodynamic derivatives and found that the predicted inherent dynamic stability of the ship could also be improved when the dynamic sinkage and trim were considered. Xia L. et al. (2018) analysed the hull-spacing effects on the manoeuvrability of a SWATH by using STAR-CCM+. Their results showed a larger demi-hull spacing leaded to a better inherent dynamic stability. However, the effect of demi-hull spacing upon the initial turning ability and the course-changing ability is not pronounced. Jin et al. (2019) simulated the self-propelled turning circle and zigzag manoeuvres for the benchmark combatant DTMB 5415M by using the URANS solver STAR-CCM+. Two different propulsion techniques were applied to drive the free running vessel: the body force propeller model (BFM) and the discretised propeller model (DPM). In general, the comparison between experimental and numerical results agreed mostly within about 10% for the turning circle and zigzag manoeuvres. The BFM propulsion method seemed to under-predict the magnitude of the propeller induced wake passing the rudders compared to the DPM approach. Rameesha and Krishnankutty (2018) used STAR-CCM+ to investigate the influence of the Froude number on the manoeuvring characteristics of a container ship The turning parameters were found to increase as the Froude number changed from 0.14 to 0.29. Steady turning radius and tactical diameter increased by 22.69%, 21.93% respectively, and transfer and advance by 18.79%, 13.73%, respectively.

Other commercial CFD packages are also being used. Gatin et al. (2018) simulated the ship's full-scale turning circle manoeuvre by using a Finite Volume (FV) based CFD software called Naval Hydro Pack. Two different approaches for modelling the free surface are investigated: a single-phase flow model with a simplified linearized free-surface method, and a two-phase numerical model with Volume of Fluid (VOF) method for interface capturing. The two-phase simulation showed a good agreement with the full-scale trial, which were performed in the Adriatic Sea by Brodardski Institut Zagreb, with errors mainly below 7%, while the linearized free surface model showed a reasonable agreement for a smaller rotation rate. At a higher rotation rate, the linearized free surface simulation exhibited larger differences up to 20%. However, it also exhibited more stable evolution of the circular trajectory and less computational efforts. Duman and Bal (2019) used a commercial unsteady RANS solver software based on FVM (Finite Volume Method) to predict the manoeuvring coefficients of a catamaran. It was concluded that the impact of the leeward-sided hull on Y_v and N_v was more dominant than the windward-sided hull. The commercial CFD software suite FINE/Marine was used by Van Hoydonck et al. (2018) to determine the open-water rudder characteristics. It was shown that for the CFD computations tested at full-scale, reliable coefficient graphs were obtained: the maximum lift coefficient in the astern flow condition was significantly lower than in the ahead condition and the lift curve slope in the ahead condition was steeper than that in the astern condition. The modelled full-scale drag values are also significantly lower than those obtained in the towing tank experiments. The same software was used by Visonneau et al. (2020) to analyse the flow around a surface combatant at various static drift and dynamic sway conditions. It was concluded that the Hybrid RANS/LES turbulence models based on Delayed Detached Eddy Simulation showed a better performance against the RANS model on capturing the flow around a ship under drift conditions. Similar conclusions are also supported by the results of Shevchuk and Sahab (2020) and Wang and Wan (2020).

Open source RANS methods. Apart from commercial software, open source RANS solvers provide good alternatives. The open source solver OpenFOAM has been used by Islam and Guedes Soares (2018) to predict the hydrodynamic derivatives. Wang J. et al. (2017) used their in-house CFD solver naoe-FOAM-SJTU to simulate the zigzag manoeuvre of a fully appended ONRT model in calm water and waves. A dynamic overset grid method was applied to handle the complex ship motions with consideration of the propeller and rudder. The same solver and overset grid technique are also used by Wang and Wan (2020) to simulate different types of stopping manoeuvres of a KVLCC1 model, including reversing propeller with/without turning rudder, inertia stopping, and the original turning circle manoeuvre. The reversing propeller case with port rudder could reduce the stopping distance, while the starboard rudder increased the stopping distance and the lateral deviation was smaller, as shown in Figure 6. They also investigated the shallow water effects on stopping manoeuvres.

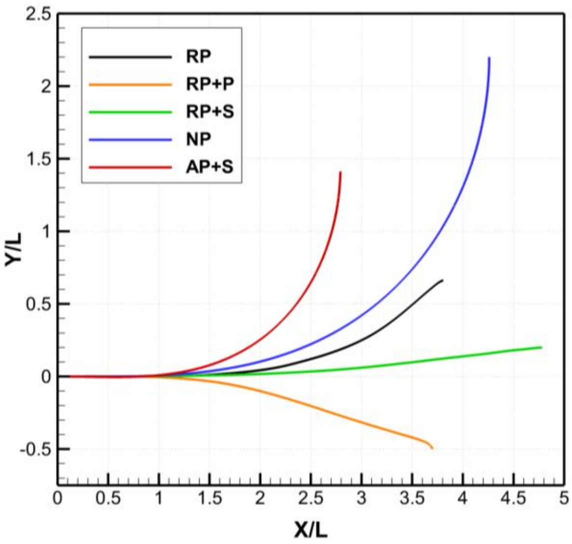


Figure 6: Comparisons of trajectories of different manoeuvres (Wang and Wan (2020)). RP: reversing propeller; RP+P: reversing propeller with port rudder; RP+S: reversing propeller with starboard rudder; NP: no rudder; AP+S: turning circle with actual rotating propeller and starboard rudder.

Ferrari et al. (2019) used the RANS solver ReFRESCO to investigate the effects of the center skeg installed with twin screw ships not only on the basic manoeuvrability such as turning circle and zigzag manoeuvres but also on the performance at low speed, i.e., in harbour operation such as turning on the spot and crabbing manoeuvres. Based on their CFD analysis, which also included propeller streams in combination of forward & reverse rotation, they mentioned the (dis)advantages on the manoeuvrability caused by the presence of the skeg and its size. Vink et al. (2017) conducted a verification and validation study of CFD simulations of the flow around a tugboat. The CFD code used in their study is ReFRESCO. Both EFD and CFD had high computed uncertainties for the prediction of the hydrodynamic forces of the tug. The selection of turbulence models did not improve the comparison error.

Very few studies are based on in-house developed CFD code. Silva and Aram (2018) used an in-house CFD solver, NavyFOAM, to perform captive model simulations of an Office of Naval Research Tumblehome (ONRT) under various conditions.

Hybrid methods. Calcagni et al. (2017) proposed a generalised hybrid viscous/inviscid flow computational model to simulate the propeller-rudder interaction. The methodology combines a Boundary Element Method (BEM) to predict propeller perturbation under inviscid-flow assumptions and a Detached Eddy Simulation (DES) Navier-Stokes solver to describe the viscous, turbulent flow around the rudder with propeller effects recast as volume-force terms from the BEM solution. The authors compared the results of the hybrid method against those of the full DES, and a very good agreement was achieved. This hybrid method could be applied to various hydrodynamic problems, including propeller-rudder interaction and propeller action during manoeuvres. A similar approach was also used by Su and Kinnas (2018), Dubbioso et al. (2017a) and Muscari et al. (2017) and the flow chart of a typical hybrid method is shown in Figure 7.

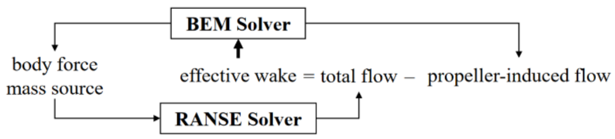


Figure 7: Flow chart of a typical hybrid BEM/RANS method (Su and Kinnas, 2018).

Dubbioso et al. (2017) and Muscari et al. (2017) used the hybrid approach to analyse the propeller bearing loads when a ship was in straight-ahead, steady turning (Dubbioso et al., 2017a) and transient manoeuvres (Muscari et al., 2017). Su and Kinnas (2018) applied the BEM/RANS scheme to analyse the hull-propeller-rudder interactions. The computational cost analysis showed the hybrid BEM/RANS scheme was around 6 times faster than a fully RANS simulation.

Mofidi et al. (2018) used a hybrid CFD/potential flow approach (CFD code REX and the propeller code PUF-1) to simulate the manoeuvring of a ship with consideration of propeller-rudder interaction. They analysed a 5/1 zigzag manoeuvre for the KCS container ship. It is shown that the hybrid approach provides an effective and economical way to perform direct manoeuvring simulation of surface ships at low to moderate propeller loading. However, it cannot resolve tip vortices and other flow structures generated by the propeller, which could potentially affect separation at the rudder for manoeuvres involving large angles of attack. A similar hybrid approach is also used by Ohashi et al. (2018). They developed a new structured URANS solver to estimate the free-running conditions of a conventional type of ship. The propeller effects were accounted for according to the body forces derived from the propeller model, which was based on potential flow theory. This hybrid approach was applied to predict the turning circle and zigzag motions.

Sukas et al. (2019) used a system-based approach to predict the manoeuvring performance of a twin-propeller/twin-rudder ship. An URANS method was used to obtain the hydrodynamic derivatives, which were then implemented in a MMG model to simulate turning circle and zigzag manoeuvres. Sakamoto et al. (2019) used a similar CFD-MMG method.

3.2 Shallow, Restricted or Confined Water

In the 28th MC shallow, restricted and confined water have been defined. The same definition is confirmed here.

New facilities. New facilities have been reported by Delefortrie et al. (2019). In May 2019 a brand new laboratory has been opened in Ostend, Belgium. The official name of the new lab is Flanders Maritime Laboratory (FML), which hosts two state of the art model scale facilities for the maritime industry, namely a Coastal & Ocean Basin (COB) and a Towing Tank for Manoeuvres in Shallow Water (see

Figure 8). Especially the latter is of importance for the MC. The design and build of the towing carriage for the new towing tank (useful dimensions: 140 m × 20 m × 1 m and design ship model length of 8 m) is planned for 2021-2022. The facility is expected to be operational by 2022 (free running model tests) and 2023 (captive model tests). More details are expected in the report of the 30th MC.

Figure 8. Top: view from the dock section of the new towing tank at FML (Delefortrie et al., 2019). Bottom: status January 2021. Due to COVID-19, the basin is being used as a training centre for the Belgian Olympic kayak team. (©Sporza.be).

Shallow water. Liu Y. et al. (2019b) used a RANS solver (STAR-CCM+) to simulate pure sway tests of a DTC in shallow water. A moving no-slip condition was used on the bottom as the boundary layer developed on the bottom may influence the flow in the gap. The predicted non-dimensional hydrodynamic forces and dynamic sinkage and trim were compared with benchmark test results and other numerical results with promising correspondence.

Lee and Hong (2017) did a RANS (STAR-CCM+) study to investigate the manoeuvring derivatives of a vessel in shallow water in order to analyse the course stability of different large vessel types cruising at low speeds.

RoyChoudhury et al. (2017) used a RANS solver (SHIPFLOW) to investigate the steady drift and yaw motions of the KVLCC2 in deep and shallow water. An Explicit Algebraic Stress Model (EASM) turbulence model was applied for all the calculations. The results compared well with the experimental model test data.

A scaled inland container ship with twin propellers and quadruple rudders was selected by Kaidi et al. (2018) to investigate the interaction between hull, rudder and propeller in deep, shallow and very shallow water. The flow around the ship was modelled by a steady RANS (ANSYS Fluent) with a free surface. The frame motion technique was selected to simulate the rotation of the propellers. The CFD model validation concerned only the hull and the propeller because of the unavailability of experimental rudder data. The impact of the water depth was found to have the largest effect on the hull-rudder-propeller interaction. It was also shown that the advance coefficient of the operating propellers amplified the hydrodynamic forces exerted on the hull and rudders.

Delefortrie et al. (2018) executed captive model tests with an estuary vessel, equipped with two Z-drives. The program focussed on the effects of the interaction between the Z-drives, each one being independently steerable over a 360° azimuth range, on the manoeuvring forces and lead to the development of a 6-DOF manoeuvring model, which accounts for these interaction effects.

Gornicz et al. (2019) estimated the push-pull manoeuvre of a twin shaft ship under three different environmental conditions: unrestricted deep, shallow and close to quay. The RANS viscous flow solver ReFRESCO was used and the free surface effects were neglected. The propellers were modelled with a Smart Actuator Disc (SAD) able to customize the distributions of the body forces based on the propeller mode. The accuracy of the SAD decreased for large rudder angles and in very shallow water due to the increased complexity of the flow (Figure 9).

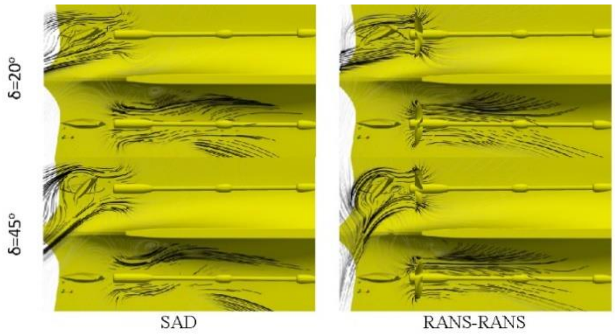


Figure 9. Streamlines in the horizontal plane through the shaft line for two different propeller modelling approaches. (Gornicz et al., 2019).

Squat. Hu et al. (2017) presented squat calculations in shallow water based in RANS (STAR-CCM+) simulations. To avoid negative under keel clearance and unphysical grounding in the start-up phase, an under-relaxation factor was included to slowly release the model in the vertical direction.

Terziev et al. (2018) investigated the sinkage, trim and resistance of a DTC model advancing in shallow water for varying channel cross-sections and ship speeds by using Star-CCM+. They confirmed the sinkage is important at low-speed range, whereas the trim is the leading factor at high-speed range.

In the investigation by Bechthold and Karstens (2020) RANS (STAR-CCM+) simulations were used to predict sinkage and trim of a ship in extreme shallow water with a water depth to draft ratio less than 1.2. The results were validated against the benchmark data of the DTC from the 5th MASHCON. A fair agreement was seen between experiments and numerical results for the towed setup without propeller.

Different authors, such as Ha & Gourlay (2018), Harkin et al. (2018) and Verwilligen et al. (2018) use full-scale measurements to validate or supplement model test tank measurements, especially to investigate the squat phenomenon. The presented methodology could be included in an extended version of the full-scale manoeuvring trials to extract information from any full-scale manoeuvre and to account for the environmental effects.

Ship-bank interaction. Studies have been conducted to investigate the importance of free surface modelling in shallow and confined water. Razgallah et al. (2019) used RANS (ANSYS Fluent) with and without free surface for the computations of an inland vessel at various water depths and drift angles in the middle of a waterway with sloped sides applying VOF method or symmetry condition in the waterplane respectively (Figure 10).

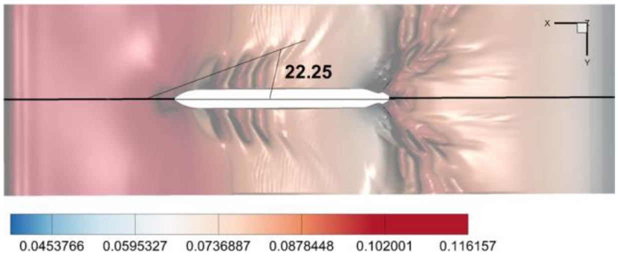


Figure 10. Model ship wave profile in confined water (h/T=1.2) at high speed. (Razgallah et al., 2019).

Van Hoydonck et al. (2019) used the RANS viscous flow solvers ISIS-CFD (Fine/Marine) and ReFRESCO with and without free surface deformation and with and without propellers for various computations at different water depth and distances to a vertical bank. The results were compared to potential flow predictions using RoPES (a 3D double-body potential flow solver) and model test data.

For both the above studies, it was found that the consideration of free surface deformation does not significantly influence the predicted forces and moments, except for very small under keel clearance values and/or distances to the bank. Furthermore, it was seen that for sailing close to a vertical bank in shallow water, the potential flow solver RoPES is not able to accurately predict the bank effects and viscous-flow methods should be adopted to obtain the correct trends of bank suction or repulsion.

Ship-lock interaction. A 3D boundary element method based on the Rankine Green function with free surface conditions was used by Yuan (2019) to predict ship hydrodynamics in different confined waterways. Predictions of the ship-ship, ship-bank and ship-bottom interactions showed reasonable correlation with the benchmark data sets of the MASHCON conferences except for the sign of the yaw moment for the ship-bottom and ship-bank interaction, indicating a so called Kutta condition should be imposed on the trailing edge of the wake region. For the ship-lock problem the method was able to predict the resistance and lateral forces but fails to predict the yaw moment due to flow separation at the lock entrance and the ship stern.

Veldman et al. (2018) presented a simple but accurate calculation method based on a calibrated Schijf's method to estimate vessel speed in a minimum capacity lock. The method is calibrated and verified against full-scale measurements with a prototype ship from five locks and one lift.

Ship-ship interaction. A number of studies using inviscid flow solutions have been reported. Yuan et al. (2018) proposed a superposition method to handle the unsteady free-surface boundary condition containing two or more speed terms and validated its feasibility in predicting the hydrodynamic behaviour in ship encountering. The methodology used in their study was a three-dimensional boundary-element method (BEM) based on a Rankine-type (infinite-space) source function. The results showed the free-surface effects need to be taken into account for Fr > 0.2. Ren et al. (2020) used a double body 3D potential flow code to compute hydrodynamic interaction forces. The code included a mesh cutting scheme to include the varying sinkage and trim during interaction.

RANS simulations have also been used to investigate ship-ship interactions. Wnęk et al. (2018) used a RANS solver (STAR-CCM+) to study the flow between a tug and a tanker at various relative distances in shallow water. The simulations were carried out with and without free surface and validated against model test data to study the influence of viscosity and wave making. The model accounting for viscosity and free surface effects resulted the most accurate.

Sano and Yasukawa (2019) performed captive model tests with 1/110 scale models of both KVLCC2 and Aframax tanker to assess the ship to ship interaction forces during steady lightering. A comprehensive captive manoeuvring test program was carried out with both ships rigidly connected to each other. The results lead to a dedicated MMG model for this two ship test system, which was validated by free running tests: course keeping with PD control and small +/-10° turns.

Moored ships. Van Zwijnsvoorde et al. (2018) also applied the RoPES package to simulate the behaviour of a moored vessel in a passing ship event. The passing ship force calculated by RoPES served as input to an in-house time domain package. The results of the simulations were validated against full-scale measurements recorded using AIS information logged in the port of Antwerp. The simulations showed good agreement with the full-scale measurements except for a single case, where the linear model for elasticity of the mooring line was seen insufficient to predict the motions accurately due to highly elastic lines and low pretension force.

Li, L. et al. (2018) used a hybrid method founded on the combination of 3-D Rankine source method and impulse response theory to estimate the transient response of a moored ship exposed to sea waves and wash waves produced by nearby passing ships. Nam and Park (2018) developed a time-domain numerical method based on a finite element method to investigate the passing ship problem with a moored barge alongside a quay. Separation & gap distance and water depth were identified as critical parameters for the passing ship forces. To handle the moving boundary problem, both Li, L. et al. (2018) and Nam and Park (2018) implemented a re-meshing algorithm using a local body-fixed mesh to overlap the global background mesh, thereby replacing the re-mesh process by simple connection operations.

Tug operations. Aydın et al. (2018) used RANS (ANSYS Fluent) to estimate the towline forces of tractor type escort tugs in a bare hull configuration. The simulations were carried out with and without free surface effects and heel angles. Up to the stall angle, the inclusion of the effects only slightly affected the results. However, after the stall, the inclusion of the free surface effect increased the obtained lift significantly compared to the lift in the simulations without the effect.

Barrera and Tannuri (2018) developed an offline interpolation method to obtain the actuation model of a vector tug during pull operations in real time. The formulation significantly increases the realism of manoeuvres when vector tugs are used including the actual position of actuation by exploiting the output of an advanced algorithm not able to run in real time.

Figure 11: Free escort model test (Figari et al., 2020)

Figari et al. (2020) conducted a comprehensive model tests campaign using a model scale tugboat. They also showed CFD results compared against the tank test results with practical precision. Their results imply a substantial possibility of the CFD application as a method of predicting hydrodynamic forces and moment in low speed manoeuvres. Related to the model test campaign summarized in Figari et al. (2020), Piaggio et al. (2020) gives an overview of the full CFD study carried out in parallel to the EFD campaign including a detailed study on the skeg effects and with references to their studies on identifying hydrodynamic forces acting on the tug and their examination and validation of EFD and CFD-arising manoeuvring models used for a real-time simulator (Figure 11).

Simulation studies. Lataire et al. (2018) presented methodologies used to evaluate manoeuvres in shallow or confined water based upon five different simulation techniques. The first four are fast time simulations, each with a different level of detail and control and the last is real time simulations, where the human factor is included as well.

Iribarren et al. (2018) described a methodology to analyze the effects of passing ships in a new terminal. Based on fast-time simulation of the ship speed and distance to the moored vessels, the program RoPES was used to obtain the interaction forces in shallow water considering bathymetry and lateral restrictions.

Ruggeri et al. (2018) presented an automatic draft computation system called ReDRAFT, which integrates the environmental conditions collected in real time (or a forecast) to the hydrodynamic model of the port and the customized dynamic ship model in order to define the safe under keel clearance for the manoeuvre.

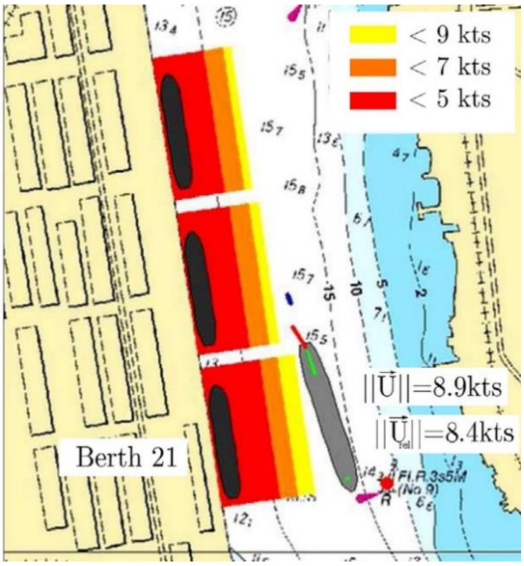


Figure 12. Operational limits for three passing distances printed in nautical chart of Port of Santos. (Watai et al. (2018)).

An analysis methodology for the passing ship problem in port combining a 3D time domain Rankine panel method with a dynamic simulator for moored ships and a real time simulator is presented by Watai et al. (2018) Emphasis is given to the proposed approach of including important contributions from the real time manoeuvring simulations in the analysis process. In many circumstances it is not possible to follow the desired path or speed as it depends on the pilot's ability to handle the ship rudder and engine (Figure 12).

3.3 Unmanned Surface Vehicles (USVs)

Preliminary remark. A vast amount of literature has been published on this topic and the closely related topic of Autopilot (see 3.4), however, articles have a fluctuating quality and mostly lack experimental validation. Here only the most significant contributions are covered. The topic of unmanned navigation should be a main point of attention for the next MC. Observe that the control of AUV is discussed in the dedicated section 6.2 and that this remark applies there as well.

Path Planning and Path Optimization are a fundamental research topic in USV navigation. Kim H. et al. (2017) proposed a path optimization method using a genetic algorithm and a new fitness function considering environmental loads, obstacle avoidance, and minimization of travel time. An optimized path is determined using evolutionary processes and repeating fitness evaluations of each chromosome over all generations using the fitness function. The simulation results show that the proposed path optimization method is effective to determine the optimal path for several conditions of environmental loads and obstacles (Figure 13).

Chen C. et al. (2019) proposed a path planning and manipulating approach based on Q-learning, which can drive a cargo ship by itself without requiring any input from human experiences. Q-learning is introduced to learn the action–reward model and the learning outcome is used to manipulate the ship's motion. By comparing the proposed approach with the existing methods, it is shown that this approach is more effective and closer to human manoeuvring. Wang Y. et al. (2018) proposed a path searching-based algorithm called the local normal distribution-based trajectory (LNDT) based on the COLREGs (Convention on the international regulations for preventing collisions at sea). The simulation results show that the proposed algorithm can plan paths to avoid static and dynamic obstacles safely. Wang N. et al. (2019b) also proposed a multilayer path planner (MPP) with global path-planning layer, collision avoidance layer and routine correction layer for an USV under complex marine environments including both coastal and surface constraints.

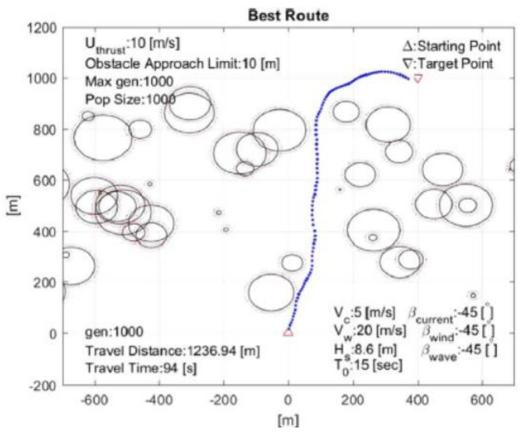


Figure 13. Optimized path by genetic algorithm (adapted from Kim H. et al. (2017)).

Xie L. et al. (2019) developed a trajectory planning based on a global multi-direction A* algorithm for working ships within offshore wind farms. The artificial potential field (APF) approach is modified to create a penalty function for perceiving a potential risk ahead in the trajectory. The simulation results indicate that the developed approach is a useful for ships navigating within wind farms. Niu et al. (2020) proposed a spatially-temporally energy efficient path planning algorithm by integrating the Voronoi diagram, Visibility graph, Dijkstra's algorithm and GA algorithm. To evaluate the performance, the Voronoi-GA energy efficient algorithm and Voronoi- Visibility energy efficient path re-planning algorithm are also implemented. The numerical simulation results indicate that the proposed algorithm has shown clear advantages in generating the most energy efficient path. Singh et al. (2018) proposed a constrained A* approach for optimal path planning of USVs in a confined maritime environment containing dynamic obstacles and ocean currents. Xu J. et al. (2019) studied an autonomous route planning algorithm based on the modified RRT (rapidly-exploring random tree) approach for ship through a canal estuary area with the strong currents.

Path Following and Trajectory Tracking are essential performance criteria for USV manoeuvring and navigation. Liu Y. et al. (2017) developed a novel guidance and control (NGC) system for a USV with environmental influences such as surface current and winds. The system is developed by integrating multiple functional modules, a robust autopilot module and an intelligent path planning. Hinostroza et al. (2018) investigated a motion planning, guidance and control system for an autonomous surface vessel in a practical maritime environment. The motion planning algorithm is developed by using the angle-guidance fast marching square method and the guidance system is developed by using the line-of-sight trajectory tracking algorithm. Huang H. et al. (2019) proposed a trajectory tracking controller for an USV with multiple uncertainties and input constraints. A trajectory tracking guidance law based on yaw angle and surge is proposed, and inner and outer disturbances is observed by reduced order extended state observers in the controller. Zhao et al. (2020) proposed a broken lines path following algorithm which USV can follow a series of broken lines by path following controller in an uncertain environment. The numerical simulations and water experiments verify the effectiveness of the proposed path following algorithm.

Peng et al. (2017) reviewed the design and implementation of the USV, including its hull design and structure of the control system. A trajectory tracking test and autonomous collision avoidance test were carried out to validate the controller of USV. Eriksen and Breivik (2018) proposed a Model-based speed and course controller for high-speed ASVs operating in the displacement, semi-displacement and planing regions. Through full-scale experiments, the proposed controller has been shown the improvement of the control performance for time-varying references. Liao et al. (2019) discussed berthing-oriented trajectory planning and trajectory tracking control, considering the dynamic changes of USV in berthing tasks and also divided the planning and control modes into two phases: the remote phase and the terminal phase. An improved artificial potential field method is proposed to complete autonomous berthing trajectory planning and an improved adaptive fuzzy PID control method is used to track the expected trajectory of USV. The simulation and field experiments show that the proposed method is more effective to plan the trajectory and has a better tracking performance than the traditional PID method (Figure 14).

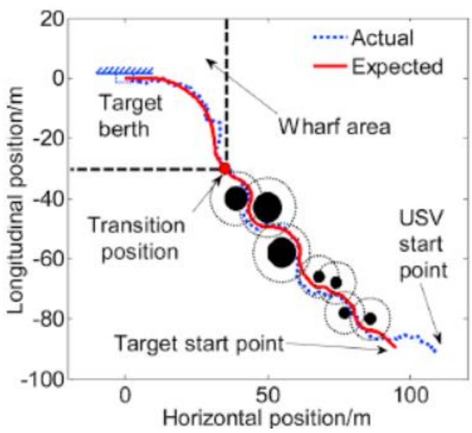


Figure 14. Berthing-oriented tracking control (adapted from Liao et al. (2019)).

Wen et al. (2020) proposed an adaptive path following controller for the USV. The path following controller uses the intelligent adaptive control method and vector field (VF) guidance law and the characteristic model-based heading angle. The comparisons with experimental results indicate the developed path following controller can simultaneously ensure accuracy in the expected range and defend negative effects induced by environmental disturbances.

Collision Avoidance is the most important ability required for USV to realize safe navigation. Song et al. (2018) proposed a two-level dynamic obstacle avoidance algorithm. In the first level (non-emergency situation), the primary task of the USV is to move to the next path target point while avoiding any obstacles by using the velocity obstacle algorithm. In the second level (emergency situation), the primary task of the USV is to move away from the obstacle immediately by using an improved artificial potential method. Li S. et al. (2019) also proposed a distributed coordination strategy which is composed of two phases for assisting ships in making decisions on the most efficient anti-collision operations when multiple ships encounter. Zhou et al. (2020) proposed an USV motion-planning method based on topological position relationships (TPR) to find the shortest search time and the shortest path for collision avoidance. Through numerical simulations and field tests, the effectiveness of the proposed method is verified.

Shen et al. (2019) proposed a novel approach based on deep reinforcement learning (DRL) for automatic collision avoidance of multiple ships particularly in restricted waters. A training method and algorithms for collision avoidance of ships, incorporating ship manoeuvrability, human experience and navigation rules, are studied in detail. Xie S. et al. (2019) proposed a model predictive control (MPC) based on an improved Q-learning beetle swarm antenna search (I-Q-BSAS) algorithm and neural networks for real-time collision avoidance with full consideration of ship manoeuvrability, collision risks and COLREGs. Zhao & Roh (2019) proposed an efficient method to overcome multi-ship collision avoidance problems based on the Deep Reinforcement Learning (DRL) algorithm. The proposed method directly maps the states of encountered ships to an own ship's steering commands in terms of rudder angle using the Deep Neural Network (DNN) which is trained over multiple ships in rich encountering situations using the policy-gradient based DRL algorithm and COLREGs. The simulation results indicate that multiple ships can avoid collisions with each other while following their own predefined paths simultaneously (Figure 15).

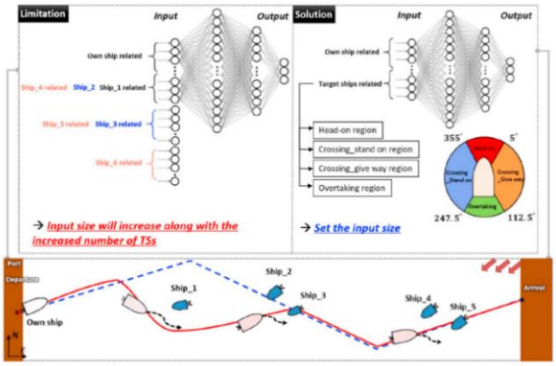


Figure 15. DNN learning-based collision avoidance method (adapted from Zhao & Roh (2019)).

Woo and Kim (2020) proposed a deep reinforcement learning (DRL)-based collision avoidance method for an USV. For the composition of the DRL network for collision avoidance, a neural network architecture and semi-Markov decision process model are used. The resulting DRL network is trained based on repeated collision avoidance simulations in various encounter circumstances. Simulations and experiments are conducted to validate the proposed method's effectiveness.

Huang Y. et al. (2019) proposed a collision avoidance system using a generalized velocity obstacle (GVO) algorithm. The system is composed of three main modules: Global planner, Local planner (searches a collision-free velocity to avoid collision) and Controller (calculates the required control force to follow the desired velocity). The simulation results show that the proposed collision avoidance system can work properly in various maritime environments. Wang X. et al. (2017) proposed a ship collision avoidance dynamic support system in close-quarters situation, which combines a mathematical manoeuvring model, a ship manoeuvring control mechanism and a ship collision avoidance parameter calculation model. The simulation results show that the proposed dynamic support system is an effective and practicable system for collision avoidance, particularly in close-quarters situation.

Zhang G. et al. (2018a) developed a novel DVS (Dynamic Virtual Ship)-based obstacles avoidance guidance with a priority selecting strategy and a robust adaptive path-following control for underactuated ships. The simulation results showed that the developed scheme is effective to improve the path following and the obstacle avoidance without information on the system model or external disturbances. Shi et al. (2019) proposed an intelligent collision avoidance and a recovery path planning system which combine an initial path generation module, a path optimization module and an autonomous recovery module for a waterjet-propelled USV. The simulation results proved that the proposed system is effective to avoid collision accidents for multiple obstacles and to plan a safe recovery path in the cluttered marine environment. An automatic collision avoidance system to calculate the risks and economic preferences of all vessels within a certain range and to select the optimal manoeuvring way is developed by Nakamura & Okada (2019). The comparison between the manoeuvring results by the developed system and by pilots, using a full mission type simulator, showed that the system was effective for realizing strategic collision avoidance and for preventing human errors. Wang T. et al. (2020) proposed an autonomous decision-making support algorithm for multi-ship collision avoidance based on the inference of objective's intention. Every ship makes decisions from its own perspective and only considers keeping itself safe during the decision-making process. In order to verify the flexibility of the algorithm, different scenarios are considered in simulations, including the non-compliance of ships with COLREGs. Lee M. et al. (2020) developed a collision avoidance and route-finding algorithm for multi-ship encounter situations based on artificial potential fields, complying with the COLREGs and local navigation regulations. The method was tested in a simulated environment with various traffic scenarios. The potential field model is consonant with the concept of ship handling and appears to be well suited for the automatic collision avoidance algorithm for multi-ship encounter situations.

Formation control of multi-USVs is getting more important due to the expansion of the application area of USVs. Gu et al. (2019) studied a distributed containment manoeuvring controller for a fleet of under-actuated USVs. The vehicle fleet was converged to a convex combination of multiple virtual leaders regardless of the model uncertainties and ocean disturbances. The simulation results show that the multiple virtual leaders could move along multiple parameterized paths with a formation. Hinostroza et al. (2019) proposed a full navigation system for cooperative operation of a USVs fleet in a complex marine environment including static (environment) and dynamic obstacles. In the proposed system, a formation shape is determined using strategy of team formation and a cooperative algorithm is deployed using a fast-marching method depending on the desired mission of the USVs. Tan et al. (2020) also proposed a path planning algorithm based on the fast-marching square (FMS) method for an USV swarm. In the proposed algorithm, the FMS method-based path planning algorithm is used to generate a path and the COLREGs rule is considered to avoid collision.

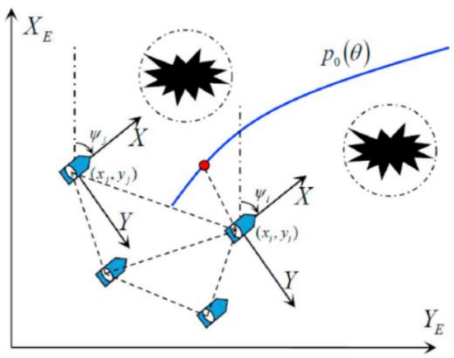


Figure 16. Path-guided time-varying formation control with collision avoidance (Peng et al. (2019)).

Peng et al. (2019) proposed a path-guided time-varying formation controller for a swarm of under-actuated autonomous surface vehicles. The proposed controller is based on a consensus approach, a path-following design, artificial potential functions, and an auxiliary variable approach. The advantage of the proposed controller is to have robustness against model uncertainties, ocean disturbances and unknown input gains, and the capability of collision avoidance and connectivity preservation. Simulation results show that the proposed controller has a good formation control performance and capability of obstacle avoidance for under-actuated USVs (Figure 16).

Liang et al. (2020) studied a coordinated tracking strategy with swarm center identification, self-organized aggregation, collision avoidance and distributed controller design for multiple USVs in complex marine environments including both unknown dynamics and external disturbances. Simulation studies are also performed to demonstrate the validity of the proposed coordinated tracking strategy.

Estimation and Simulator. Liu L. et al. (2019) studied a nonlinear extended state observer to estimate the state and disturbance of unmanned surface vehicles. Simulation results of state recovery and uncertainty estimation are provided to validate the effectiveness of the proposed state observer. Gu et al. (2020) studied a state estimation problem of a robotic unmanned surface vehicle with the measurements of GPS and IMU. Two nonlinear observers are used to estimate the position and velocity information. Kim S.Y. et al. (2018) developed an USV base station simulator for the purpose of training USV operators and to improve the user interface. The applicability of the USV base station simulator was confirmed by pilot tests.

3.4 Autopilot applications

Restricted Waters and Berthing. Autopilots are normally applied in non-restricted navigation areas, with the propeller at a constant rotation/pitch and the vessel subjected to slowly varying disturbances. However, the application of autopilots in restricted areas are being considered nowadays. Wang J. et al. (2019a) proposed a path following controller based on robust H_∞ theory to keep the vessel close to the centre line of the restricted channel, subjected to wind disturbance. Liu H. et al. (2018a) did a more comprehensive work, with a combination of Model Predictive Controller (MPC) and a Linear Quadratic Regulator (LQR) to design a course following autopilot considering bank and shallow water effects. They also demonstrated the advantages of adopting the speed variation as a second control input.

Automatic/autonomous berthing is an active research topic, with the popularization of machine learning techniques. A comprehensive review of automatic ship berthing is presented by Ahmed et al. (2020). Zhang Q. et al. (2017) proposed a PID-based nonlinear feedback algorithm for course keeping even when the propeller is stopping or reversing, in order to regulate the speed for berthing. The tests with a MMG ship model demonstrated that the controller could provide acceptable results during berthing (reduced speed). Maki et al. (2020) solved the off-line automatic berthing problem using an optimal control minimum-time technique. The collision risk with the berth was taken into account. The covariance matrix is adapted using an evolution strategy (CMA-ES). Simulation results demonstrated the performance of the proposed berthing control.

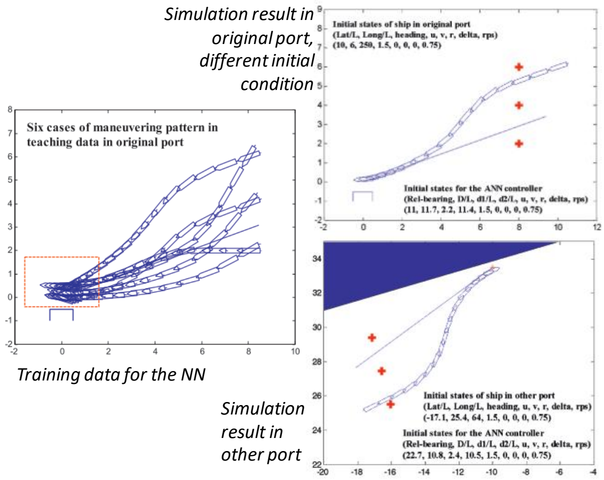


Figure 17. Automatic Berthing tests (adapted from Im and Nguyen, 2018).

Im and Nguyen (2018) noticed that the existing NN have limited capacity of generalization. The controllers can only berth a ship in the same port of the teaching data. By using the headup coordinate system, which includes the relative bearing and distance from the ship to the berth, a novel NN controller is proposed to automatically control the ship into the berth in different ports without retraining the NN structure. The results are satisfactory as illustrated in the Figure 17, but still did not take into account the environmental conditions.

Offshore Operations and Special Vessels. Modified versions of a conventional autopilot were applied to offshore cargo/fuel transfer operations. Liu Y. et al. (2019a) developed a MPC based target-follow autopilot to the underway replenishment operation. The numerical simulation considered the ship-to-ship interaction forces and the results proved the efficiency of the proposed controller. Moreno et al. (2019) proposed a sliding-mode based autopilot, with the objective of controlling the distance from a tanker underway and to transfer the oil cargo. It is an alternative to the ship-to-ship underway operation, in which both tankers navigate at low speed and are connected side-by-side, with high risks associated to the relative motion between the vessels and failure of the mooring lines. The operation was tested in fast-time and real-time simulations, including evasive manoeuvres in case of propeller drive-off. The hose system for this operation still needs to be developed and offers engineering challenges due to the large distance between the manifolds.

The application of autopilots has been extended to special vessels, such as hovercraft and sailboats. Wang Y. et al. (2019) presented a nonlinear adaptive path following controller for an amphibious hovercraft, that typically has a shallow draft and a lack of lateral force characteristics, resulting in a large sideslip angle. Therefore, the controller has to accurately estimate and compensate such sideslip angle. The authors proposed a bounded gain forgetting estimator, with an adaptive update law. The good performance of the controller was demonstrated by numerical simulations. Concerning sailboat autopilots, the surge motion is mainly controlled by the sail while the yaw motion by the rudder. Based on this strategy, Deng et al. (2019) proposed a controller with 2 objectives: to obtain the sail angle to maximize ship speed and to control rudder angle to keep the vessel in the desired course. The novelty of the paper is to apply such controller to a retrofitted bulk carrier.

Machine Learning Autopilots. Non-Supervised Machine Learning based controllers are getting more popular due to the increase on computational capacity, with the advantages of a self-learning process, non-necessity of training data and previous knowledge of the mathematical model. Martinsen (2018a) and Amendola et al. (2019) proposed a framework, based on deep reinforcement learning, to solve the straight-path following problem for under-actuated marine vessels under the influence of unknown disturbances. The policy search algorithm has no prior knowledge of the system it is assigned to control. A deep neural network is used as function approximator. Different reward functions are proposed, trying to minimize the distance of the vessel to the required path. The first paper also proposed a reward function to prevent noisy rudder behaviour. The simulation results demonstrated good performance. Martinsen (2018b) extended the previous results and implemented a framework based on deep reinforcement learning for curved path following of marine vessels in the presence of ocean currents. The algorithm was tasked to find suitable steering policies without having any prior info about either the vessel or its environment. The author tested the controller with three different vessels to demonstrate the practicality of the approach and its ability to generalize, using transfer learning technique, with success. Similar results were obtained by Amendola et al. (2020) in a real port access channel. Woo et al. (2019) went a step further. They developed a path controller based on deep reinforcement learning using deep deterministic policy gradient (DDPG) algorithm. The control policy is obtained from a self-training stage using a numerical simulator, and was then tested in a model scale experiment, but still without external disturbances. The results are quite satisfactory, as shown in Figure 18. Four control policies (A, B, C, D) are extracted from different stages of the training, being the policy D (with the best track performance) the one with most adequate number of episodes.

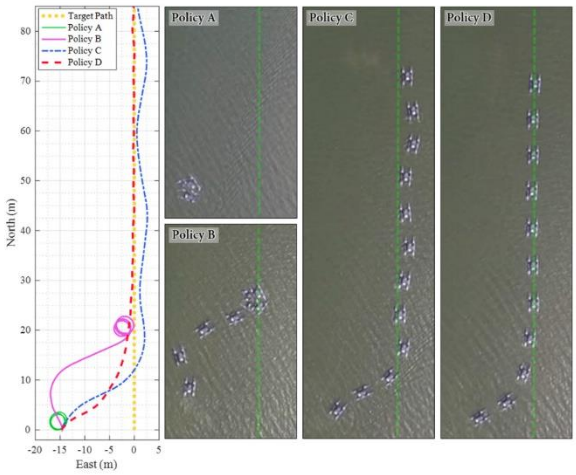


Figure 18. Trajectory data from path-following experiment (Woo et al., 2019).

Nonlinear Controllers. Zhang X. et al. (2019) proposed a concise robust integrator back-stepping control in which the user can define a steering restriction, to avoid rapid variation of rudder control. The controller design procedure is simple with only two tuning parameters. Adaptive control theory (combined with other techniques) has been applied to improve the performance of autopilots and path controllers. For example, Wang N. et al. (2019b) combined a fuzzy observer with robust adaptive control. Esfahani et al. (2019) developed a trajectory control based on higher order sliding mode theory (Super-Twisting), improved by a method for the optimal tuning of gains.

General Topics / Improvements in existing Autopilots. Zhang J. et al. (2017) proposed a MPC based path following controller that takes into account the roll motion in the optimization process. They improved the work of previous researchers, by integrating a Kalman Filter to estimate the full state of the vessel and the disturbances. This makes the proposed MPC feasible to be implemented in real applications. Gupta et al. (2018) improved the trajectory control algorithm named Target Path Iteration (that is similar to a Model Predictive Control - MPC), integrating to a genetic optimization to define the best parameters in real time. The proposed control algorithm was implemented on straight line and curved trajectories and the results show that the method used is accurate and robust. Chen C. et al. (2020) executed towing tank tests in shallow water with 4 different autopilot controllers (PID, adaptive PID, IMC and fuzzy). They concluded that the adaptive PID is the one that performed better, followed by the fuzzy. The advantage of the fuzzy controller is the simplicity, since it is a model-free control strategy. Only the controller coefficients need to be tuned. It does not depend on the identification of ship model parameters.

In order to improve the position control accuracy, Wang L. et al. (2018) applied a Beetle Antennae Search (BAS) self-optimizing PID control algorithm, that automatically optimizes the ship motion control parameters using a biomimetic algorithm. They demonstrated by means of numerical simulations that the BAS self-optimizing PID algorithm can optimize the system control parameters, with higher efficiency and accuracy than manual adjustment of control parameters.

Lee and Chang (2018) tested an improved version of the traditional LOS guidance method, with different approaches to determine the reference heading angle based on the cross-track and the heading errors (Figure 19). The numerical simulations revealed that the alternative methods have, smaller deviation, better rudder response and heading error under environmental disturbances. Wang Y. et al. (2020) designed an intelligent autopilot based on Extended Kalman Filter (EKF) trained Radial Basis Function Neural Network (RBFNN) control algorithm. Model scale tests indicated that the proposed autopilot is robust and can deal with random environmental disturbances and complex reference trajectory. The controller is compared to a conventional PD controller showing better performance regarding course keeping and trajectory tracking.

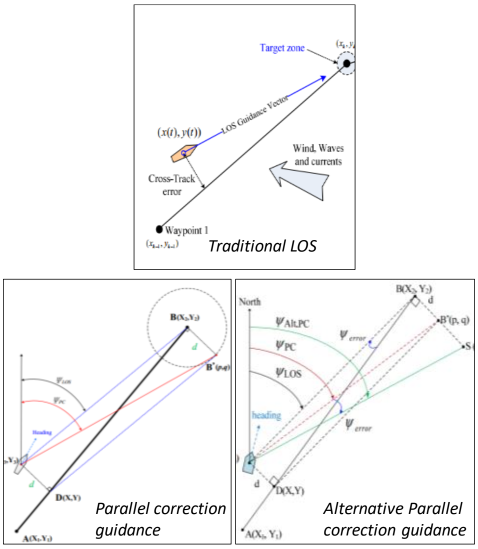


Figure 19. New Guidance Concepts (Lee and Chang, 2018).

4. PROCEDURES

4.1 Overview

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

The MC updated the following four procedures:

- 7.5-02-04-02 Manoeuvring Tests in Ice. (see section 4.2)
- 7.5-02-06-03 Validation of Manoeuvring Simulation Models. (see section 4.3)
- 7.5-02-06-04 Uncertainty Analysis for Manoeuvring Predictions Based on Captive Manoeuvring Tests. (see section 4.4.)
- 7.5-02-06-02 Captive Model Test Procedure. (see section 4.4)

The MC made minor updates to the following procedures:

- 7.5-02-06-01 Free Running Model Tests. Minor updates were carried out to make sure that the procedure keeps track with the captive model test procedure.
- 7.5-04-02-01 Full Scale Manoeuvring Trials. Missing references were included, and minor English corrections were carried out.
- 7.5-03-04-02 Validation and Verification of RANS Solutions in the Prediction of Manoeuvring Capabilities. Missing references were included, and minor English corrections were carried out.
- 7.5-03-04-01 Guideline on Use of RANS Tools for Manoeuvring Prediction. A correction of a few references was carried out.
- 7.5-02-06-05 Uncertainty Analysis for Free Running Model Tests. Minor English corrections were carried out.
- 7.5-02-01-06 Determination of Type A Uncertainty Estimate of a Mean Value from a Single Time Series Measurement. Different corrections were proposed to the QSG to solve the differences with the original paper.

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

- 7.5-04-02-02 UV Full Scale Manoeuvring Trials (see Section 4.6)
- 7.5-02-06-06 Benchmark Data for Validation of Manoeuvring Predictions (see Section 4.5)
- 7.5-02-06-07 Captive Model Test for Underwater Vehicle (see Section 4.4)

In November 2020 a review was performed of two guidelines proposed by the Specialist Committee Manoeuvring in Waves. The suggestion was made to include the wave relevant information next term in the procedures 7.5-02-06-01 and 7.5-02-06-02, rather than creating new guidelines.

4.2 Manoeuvring in Ice

Manoeuvring Tests in Ice (7.5-02-04-02.3). During the 2nd meeting in Tokyo, the MC members discussed the possible updating of 7.5-02-04-02.3. These recommendations have been sent to the Specialist Committee on Ice to review. The MC recommended the following updating:

- include the captive manoeuvring tests in ice;
- include the zigzag test in the free-running manoeuvring tests in ice;
- include an example from a “breaking out of channel test”;

- include captains turn/modified captains turn in the free-running manoeuvring tests in ice;
- consider the other important manoeuvres in the free-running manoeuvring tests in ice;
- update the parameters from all tests;
- identify uncertain parameters and consider repeatability of the tests;
- include all references.

The Specialist Committee on Ice reviewed the recommended procedure for manoeuvring tests in ice and finalized the revision, which was sent to the MC committee to review after the 5th MC meeting (online, January 2021). More information can be found in the report of the Specialist Committee on Ice.

4.3 Validation of Manoeuvring Simulation Models

This procedure mainly addresses the necessary steps and documentation for the development of a simulation model. The updated procedure distinguishes the purpose of the manoeuvring simulation model. The step-by-step validation of manoeuvring simulation models using benchmark data, model test data, full-scale data and pilot expertise was recommended.

In section 3, the purpose of the model was distinguished into 5 levels, based on the required complexity of the model:

- ship manoeuvrability in deep water;
- ship manoeuvrability in shallow water;
- ship manoeuvrability in restricted water;
- ship manoeuvrability using a 4-DOF or a 6-DOF model;
- application of simulator design for training of crews.

In particular, the purpose of application of simulator design for training of crews was added to emphasize the assessment of new ports and crew training. The necessity of measuring and documenting the environmental conditions was added in the use of full-scale trials for the purpose of identifying forces.

In section 4, the step-by-step validation procedure of manoeuvring simulation models was proposed:

- Step 1: direct evaluation of the mathematical model and comparison with benchmark and/or model scale data;
- Step 2: fast-time simulations and comparison with benchmark, model and/or full-scale data;
- Step 3: real-time simulations commanded by local pilots and qualitative evaluation based on his/her expertise.

In particular, the effectiveness of the assessment of free running trajectories using benchmark data such as SIMMAN 2008 and SIMMAN 2014 was described. The questionnaire results of the validation procedure of simulation models (see section 7.3) was also described briefly to emphasize that each institute chooses more than one validation method.

4.4 Captive Model Tests

Captive model test procedure (7.5-02-06-02). The 2017 version of this procedure was marked as a concern by the AC because of too many options that were presented to carry out captive model tests. It is indeed a fact that many options or reasons exist to carry out such tests, however, the main goal is believed to be to check IMO standard manoeuvres. For that reason, the procedure was corrected to focus on such manoeuvres. This also meant that some sections, such as executions of simulations, which present the goal of the procedure were moved forward. From the results of the 2015 questionnaire, only the main points were maintained, and reference is made to the Appendix of the 28th MC for more background information. Effects of water depth and blockage on the results are now highlighted by giving these a dedicated chapter in the procedure.

Uncertainty Analysis for manoeuvring predictions based on captive manoeuvring tests. (7.5-02-06-04). The procedure has been extended with the effect of the uncertainty of the carriage kinematics, for which a new example has been added to an Appendix G. No newer material was found with respect to carriage kinematics than the publications of Vantorre (1988, 1989, 1992). The contents of these publications were added to the procedure expressed with the ISO GUM guidelines and applied to the KCS.

The effect of the uncertainties induced by noise and data reduction, or signal processing in general, are now also included (see section 7.1). The procedure is now built up with different examples in different appendices written by different MC's. It is recommended to have a single integrated example, based on a well-known ship such as the KCS, which was the subject ship in the latest Appendices.

4.5 Guideline on Benchmark Data

The aim of the guideline "Benchmark Data for Validation of Manoeuvring Predictions" is to highlight the processes relevant for benchmarking within the field of manoeuvring, to provide a list of the present benchmark database available and to serve as an aid in selection of benchmark cases for validation.

The first part of the guideline describes the procedure of benchmarking; summarizes the steps of data collection, uncertainty assessment, analysis and sharing; and highlights additional requirements to be considered and possible pitfalls. In the second part of the guideline the present manoeuvring benchmark database is presented. An overview of the available benchmark hull forms covering tankers, container vessels, surface combatant hull forms, bulk carriers and underwater vehicles (UV) is given along with a summary of available restricted water cases and a complete table listing all available data, including references to these.

The database is intended to be updated continuously (following the cycle of ITTC), based on recommendations from the steering committees of the manoeuvring workshops, who will also be responsible for QA and availability of the data.

4.6 Guidelines for Underwater Vehicles

Investigations into the manoeuvring hydrodynamics of Underwater Vehicles are becoming more common and more complex. To date, there are not yet standardised test guidelines for such vehicles. The MC has developed two new guidelines that are specific to Underwater Vehicles, with the following topics:

<u>Captive Model Test for Underwater Vehicle (7.5-02-06-07).</u> The guideline is specifically intended for underwater vehicles, such as Autonomous Underwater Vehicle (AUV), Remotely Operated Vehicles (ROV) or submarine models, which all share similar hydrodynamic characteristics. The aim of this guideline is to provide an outline of captive model tests for underwater vehicles to determine the values of the manoeuvring coefficients for a simulation model of the underwater vehicle. The guideline is based on literature and especially the book of Submarine Hydrodynamics by Renilson (2018). It includes an overview of test facilities, test manoeuvres and the respective coefficients obtained for underwater vehicles and recommendations concerning model tolerance and blockage effects. Recommendations on benchmark data and uncertainty analysis are provided at the end.

<u>UV Full Scale Manoeuvring Trials (7.5-04-02-02)</u>. The guideline provides an outline of full-scale trials to determine the manoeuvring characteristics of an Underwater Vehicle. The present version focuses on the behaviour of an AUV as a reaction to rudder, elevator, and other control device actions. The guideline includes a total of 12 manoeuvring tests with descriptions of the manoeuvres, measured variables, and AUV handling characteristics checked for each test. It also includes an overview of the instrumentation and AUV system components that are commonly involved. Recommendations on uncertainty analysis are provided at the end.

<u>Acknowledgements.</u> The following scientists kindly reviewed the Guidelines for Underwater Vehicles in 2019:

- Professor Ettore A. Barros, University of São Paulo (7.5-04-02-02)
- Dr. Toshifumi Fujiwara, National Maritime Research Institute, Offshore Advanced Technology Dept. (7.5-04-02-02 and 7.5-02-06-07)
- Dr. Hisashi Koyama, Mitsui E&S Shipbuilding CO., Ltd. Naval ship & Defence system design Dept. (7.5-04-02-02 and 7.5-02-06-07)
- Professor Ye Li, Harbin Engineering University (7.5-02-06-07)
- Professor Zuyuan Liu, Wuhan University of Technology (7.5-02-06-07)
- Professor Hua Zhang, China Ship Scientific Research Center (7.5-02-06-07)

5. BENCHMARK DATA

5.1 SIMMAN 2021

In continuation of the Workshop on Verification and Validation of Ship Manoeuvring Simulation Methods in 2008 (SIMMAN 2008) and SIMMAN 2014 (Quadvlieg et al., 2014), the new workshop SIMMAN 2021 was scheduled for April 2020, but has been postponed to the end of 2021. The objective of the workshop is the assessment of current simulation methods for ship manoeuvring to aid code development, establish best practices and guide industry.

For the new workshop, some of the deep and shallow water cases have been replaced with new measurements, in particular the free running model tests in shallow water, to enable better comparisons.

Further, a few changes have been made to the test cases of SIMMAN 2021 compared to 2008 and 2014:

- The 5415M has been replaced with the ONR Tumblehome (ONRT) model 5613. Like the 5415M, the ONRT is an established surface combatant hull form test case used in workshops with twin screw arrangement with struts and rudders.
- The captive and free running test cases are reduced to maximize the number of submissions for more robust statistical analysis.
- KCS and ONRT turning circles in a regular wave are included a new tests cases, extending the test matrix to include manoeuvres in waves, since this is also of importance in assessment of manoeuvring prediction capability.

5.2 Datasets

To be able to predict manoeuvring behaviour, reliable predictions or simulation methods are required. Therefore, it is important to make a dedicated verification and validation effort related to the simulation methods and hereby asses the accuracy of the methods.

At present the benchmark database covers the following hull forms and test cases:

- Tankers (KVLCC2 in both deep and shallow water)
- Container Vessels (KCS in deep and shallow water and in waves, DTC in shallow water and in waves, HTC in deep water)
- Surface Combatants (5415M in deep water, ONRT in deep water and in waves)
- Bulk Carriers (JBC in deep water)
- Underwater Vehicles (DARPA Suboff in deep water)
- Manoeuvring in restricted water (Bank effects, Locks and ship-ship interaction)

The full list including references to all data is found in the new guideline 7.5-02-06-06. This lists shows that the focus is on the seagoing vessel types and none of them, except the HTC, a 153.7 m container ship built by Bremer Vulkan in 1986, exists in full-scale. It would be a reinforcement of the present benchmark data-base to include model scale vessels with a documented full-scale variant. This would open opportunities to investigate scale effects and increase the quality of manoeuvring predictions.

In general, benchmark studies are essential, also for inland vessels. According to Quadvlieg et al. (2019) inland waterway transport plays an important role in the transport of cargo in Western Europe and the manoeuvrability of the vessels dictates amongst others the capacity of the waterways. The knowledge on manoeuvring models for inland ships and pushed/towed convoys can be deepened, considering inland benchmark ships/datasets. This will stimulate the development and validation of manoeuvring simulations in waterways. Mucha et al. (2019) support the statement of Quadvlieg et al. (2019) of the need for inland vessels in the benchmark dataset. Both papers suggest typical inland vessels and are willing to share their data to give an impulse to the research.

Besides the need for inland vessels, benchmark datasets for (autonomous) under water vehicles are also on the wish list for new datasets. At present only data for the DARPA Suboff, a submarine hull form, is available.

6. UNDERWATER VEHICLES

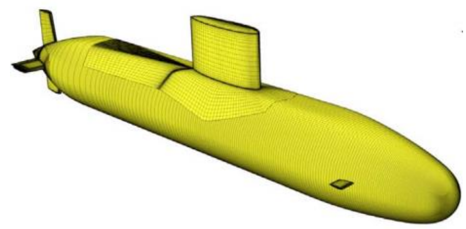
6.1 Manoeuvring Hydrodynamics

Overview. The focus is put on research that have been carried out on the hydrodynamics and manoeuvring of underwater vehicles. As expected, a lot of attention is devoted to the methods adopted within the research in the pursue of accurate evaluation or prediction of the vehicle hydrodynamic characteristics; be it experimental, numerical or empirical.

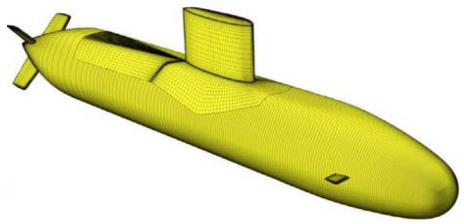
The purpose of the research on the manoeuvring hydrodynamics of underwater vehicles can be commonly categorised into the following:

- to identify and understand the hydrodynamic manoeuvring performance of an underwater vehicle and/or its components (Dubbioso et al. 2017b, Go and Ahn 2019, Kim H. et al. 2018, Maki et al., 2018, Pan et al. 2019);
- to identify and understand the effects of the interaction between an underwater vehicle and its environment (Crossland 2017, Amiri et al. 2020);
- to identify and understand the underlying flow phenomena that affects the performance attributes of the underwater vehicle and/or its components (Ellis et al. 2018, Patterson et al. 2018), or
- a combination of the above (Harwood et al. 2018).

Numerical Methods. A review of the methods adopted in the research above shows a clear transition from experimental methods to numerical methods in recent years with CFD RANS being the dominant approach. The aim of such studies tends to focus on evaluating the manoeuvring hydrodynamics of underwater vehicles in conditions that are beyond the spatial and instrumentation limits of conventional experimental testing facilities, or when there are multiple design or operation options.



(a) Cruciform configuration



(b) X rudder configuration

Figure 20. CFD models of the CNR-INSEAN 2475 (Dubbioso et al. 2017b)

Dubbioso et al. (2017b) analysed the turning ability of the CNR-INSEAN 2475 free running submarine model with different rudder configurations, i.e. cruciform (default) and X (see Figure 20). The study was carried out using a 3-DOF RANS model with active control planes and an actuator disc to represent the propeller. Partial validation was carried out for the cruciform configuration against published experimental data from QinetiQ. The study showed that the turning abilities of the X rudder configuration are superior to the cruciform configuration for the CNR-INSEAN 2475. The findings were also supported by breakdown of the forces on the hull and individual rudders.

Amiri et al. (2020) investigated the free surface effect on the manoeuvrability of an axisymmetric underwater vehicle in the horizontal plane traveling close to the free surface using CFD (Figure 21). Captive tests involving straight-ahead resistance, drift and circular motion tests were performed to predict the coefficients over various submergence depths. The obtained coefficients were then used in a coefficient-based manoeuvring model to evaluate the free surface effect on the vehicle undergoing turning circle and zigzag manoeuvres at the respective submergence depths. Observations regarding the forces and moments on the vehicle and its stability at different submergence depths are also shown.

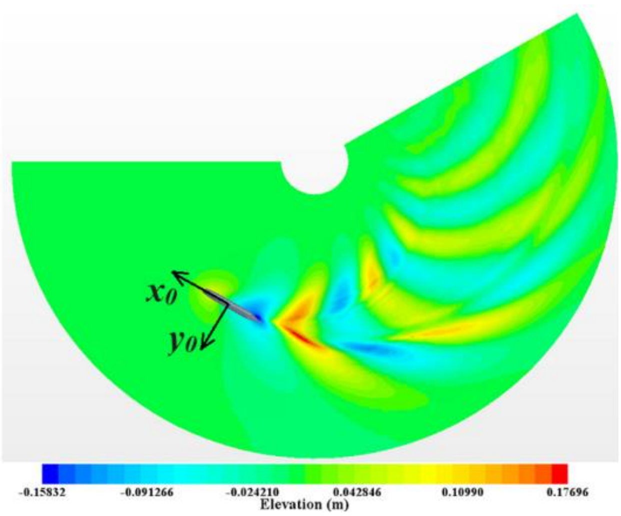


Figure 21. Free surface elevation of the rotating arm test on the axisymmetric underwater vehicle (Amiri et al. 2020)

Go and Ahn (2019) presented a new methodology to determine hydrodynamic derivatives of a tow-fish underwater vehicle using CFD. The linear and non-linear hydrodynamic derivatives of the vehicle were determined using RANS and the added mass coefficients were obtained analytically using strip theory. The effectiveness and applicability of the methodology were demonstrated via coefficient-based 6-DOF manoeuvring simulations using the CFD-determined derivatives for three different scenarios (*L*-, *U*-, and *S*-turn manoeuvres) at various towing speeds (see Figure 22). Verification was carried out by comparing the forces and moments produced by the 6-DOF manoeuvring model and the CFD results which was shown to be in good agreement. Go and Ahn noted that validation of the methodology via experimental tests is currently in progress and soon to be reported in a subsequent paper. The highlight of the paper is the demonstration of a comprehensive new methodology to determine and assess the applicability of the hydrodynamic derivatives of an underwater vehicle.

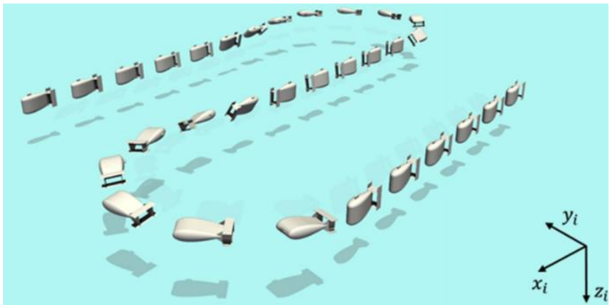


Figure 22. S-turn manouvres of the tow-fish vehicle (Go & Ahn 2019)

Kim H. et al. (2018) developed a 6-DOF free running CFD simulation model of the BB2 submarine model with active control planes and assessed its fidelity for straight line and turning manoeuvres. The depth keeping of the model was controlled via an autopilot. The propeller was explicitly modelled for the straight-line manoeuvre. For the turning manoeuvre, the propeller was replaced with an actuator disk to reduce computational requirements. The simulation results were found to be in good agreement with published free running test data from MARIN. The comparison included time histories of the vehicle trajectories and the deflections of the control planes (Figure 23).

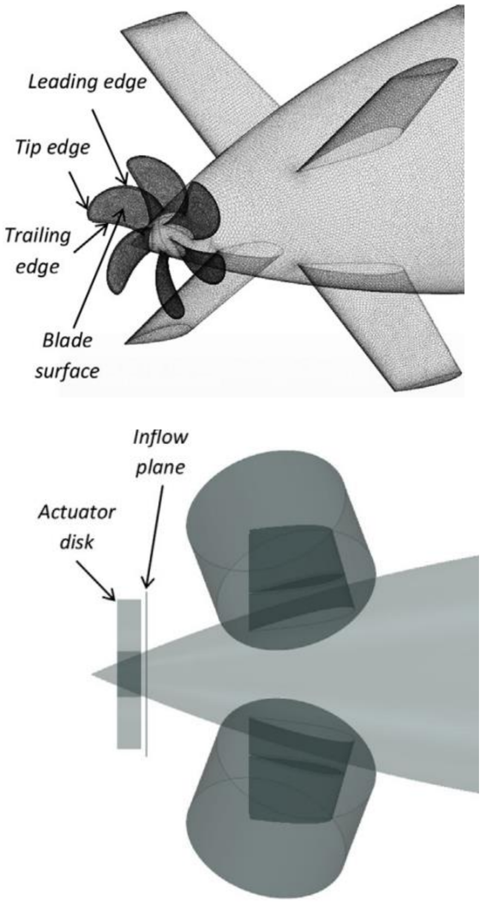


Figure 23. Overview of the propeller arrangement for the CFD free running model: with propeller (top), with actuator disk (bottom) (Kim H. et al., 2018).

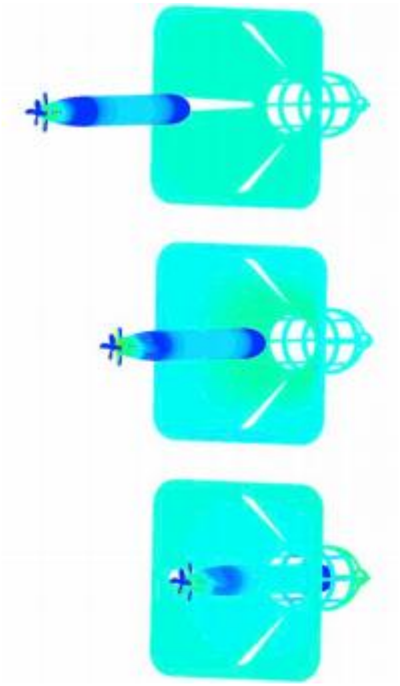


Figure 24. Overview of the SARV AUV approach the dock (Wu et al., 2019)

Wu et al. (2019) carried out a CFD-based study to analyse two straight line docking approaches (i.e. constant RPM docking and brake docking) with a dock for their SARV AUV. They used a coupled RANS and equations of motion model to simulate the straight-line manoeuvring dynamics of the AUV. The coupled model was validated against field tests data and then extended to simulate the two straight line docking approaches with the dock. The results were then analysed to identify the pros and cons of the approaches.

Pan et al. (2019) investigated the flow field around a modified SUBOFF submarine model with rudder flaps during straight ahead motion and steady diving conditions using RANS (Figure 25). The two conditions were simulated with and without its propeller. The CFD model was validated using the original SUBOFF submarine model (no rudder flaps) against published experimental data by the David Taylor Research Center (DTRC). The results showed the harmonic characteristic of the nominal wake at the propeller plane and the unsteady propeller force for the different flap deflections and manoeuvring conditions investigated. Visualisation of the wake profile was also provided to support the findings.

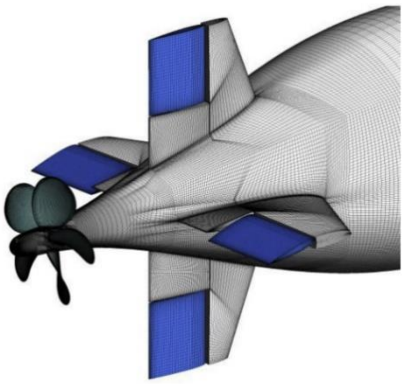


Figure 25. Surface mesh of the modified SUBOFF with rudder flaps (Pan et al., 2019)

Petterson et al. (2018) carried out a detailed LES-based study of the vorticity and wake flow structures generated by a full-scale, fully appended generic conventional submarine at 0°, +10° and -10° yaw with a speed of 4.6 knots and propeller turning at 23 rpm. Detailed visualisation of the flow structures were provided and discussed with additional insight into the influent of the propeller on the flow structures over the three yaw angles (Figure 26). The study also examined the time-history and frequency spectra of forces induced on the hull, fin and components of the propeller. The work was carried out using mesh models of up to 344 million elements and approximately 2 million CPU hours. The work highlights the intensive computational requirements, but also, the progress of CFD and the fidelity of result that is achievable for such studies.

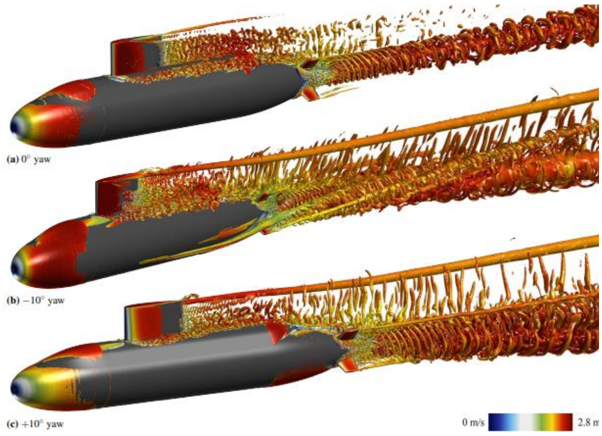


Figure 26. Visualisation of the vorticity and wake flow around the full-scale BB2 submarine at different yaw angles (Patterson et al., 2018)

With many of the CFD-dominant research, they still involve a degree of experimental work or data at model scale or limited conditions for the purpose of validating the numerical models. However, in cases where confidence in the measured physics is difficult to establish, both CFD and experimental methods are employed with equal emphasis to co-validate the two methods and co-supplement the findings. A good example of this approach is the study by Harwood et al. (2018) on the drag and wave-making of a blunt submersible over a range of forward speeds. The study was conducted in a towing tank and replicated numerically using CFD with reasonable agreement between the two methods. The comparison included hydrodynamic loads and the free surface elevation (Figure 27).

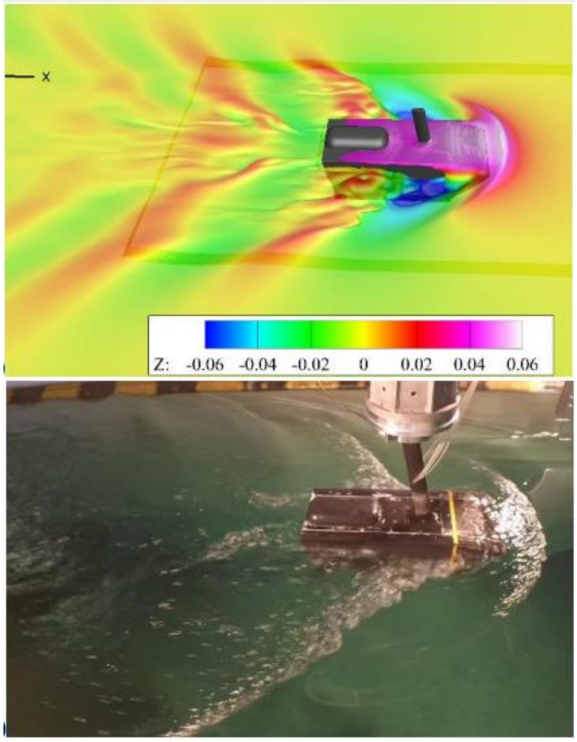


Figure 27. Free-surface deflection generated by the blunt submersible: CFD (top), experiments (bottom) (Harwood et al., 2018)

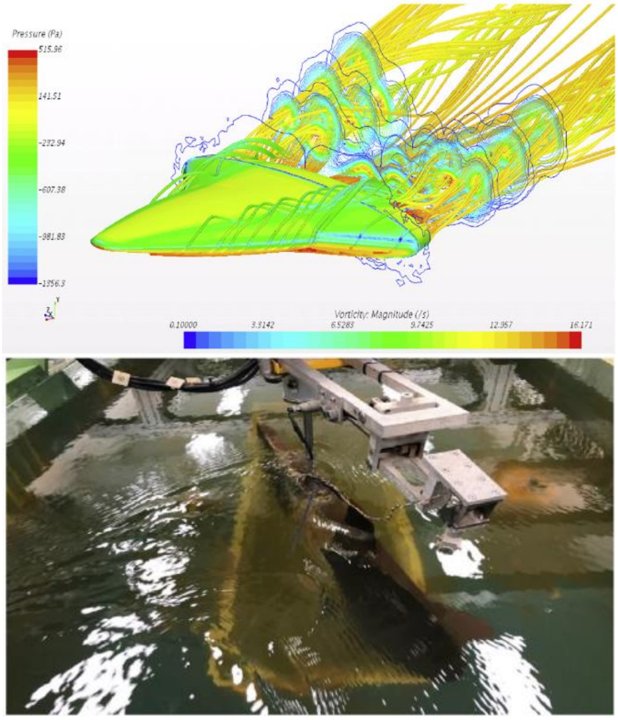


Figure 28. Pressure and vorticity contours 8n drift conditions(top), static drift model test at CWC (bottom) (Lee S. et al. 2020)

Lee S. et al. (2020) estimated the hydrodynamic manoeuvring derivatives for the heave-pitch coupling motion of a ray-type underwater glider (RUG) using RANS-based CFD method (Figure 28). Validation studies were performed using the resistance and the oblique motion of a manta-type UUV and compared to model test results. After validating the method, resistance, static drift, and dynamic PMM calculations for the RUG were performed to obtain the hydrodynamic manoeuvring derivatives. The CFD method can be utilized to obtain the hydrodynamic manoeuvring derivatives, which can be used in manoeuvring simulations of underwater gliders in the initial design stages. However, further studies on the optimization of the turbulence model and the grid refinement are required, and more model tests should be performed for underwater vehicles such as the RUG to confirm the CFD method.

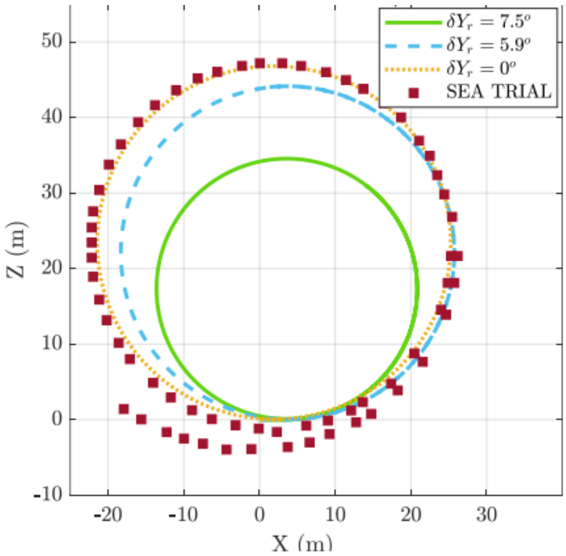


Figure 29. Simulated trajectories of a turning circle manoeuvre for the cycloidal propeller-augmented UUV (Desai et al. 2020)

Desai et al. (2020) studied the manoeuvring characteristics of a UUV driven by a screw propeller and control fins only, and compared it to that of the UUV augmented with retractable cycloidal propellers. The cases considered are a turning circle manoeuvre, a low-speed 180° turn and a low-speed heave manoeuvre. A 6-DOF motion prediction model that accounts for the non-linear and coupled loads on an underwater vehicle was developed and validated using MATLAB code. Simulation results showed that compared to conventional propulsion systems, cycloidal propellers could potentially enable more swift, compact and decoupled manoeuvres in unmanned marine vehicles (Figure 29).

Experimental Methods. It is important to note that critical bodies of research with experiments as the primary method still prevail, in particular, for the following purposes:

- tests involving strong transient physics dependency in the manoeuvre or environment;
- evaluation of physical and hydrodynamic changes at a microlevel that affect the performance of a body of a much larger spatial scale;
- benchmarking of experimental facility for UV tests, and
- evaluation of propriety technology

Figure 30. Submarine model in-situ for the under waves experiment (Crossland, 2017)

Crossland (2017) carried out captive model tests in the Qinetiq Towing Tank at Haslar, UK to investigate the hydrodynamics characteristics of a submarine manoeuvring under head seas (Figure 30). A mathematical model was developed to describe observed hydrodynamics in the tests which enabled the implementation of an appropriate depth controller in response to the wave loads, providing guidance on hydrodynamic and hydrostatic control mechanisms. The paper also highlighted that a fully captive experimental arrangement suppresses the second order forces on a submarine under waves and the improvements observed with arrangement that restrained the model in the horizontal plane and surge but allowed it to freely move in the vertical direction whilst being lightly restrained using a suitable spring system.

Ellis et al. (2018) investigated the influence of root gap and boundary layer thickness on the performance of a rudder that is representative of those used on submarines (Figure 31). The work was carried out at the Australian Maritime College Cavitation Research Laboratory. The results showed that increased roots gaps increased stall angle, increase drag and reduced lift at low angles of incidence. The thickened boundary layer was observed to increase stall angle and maximum lift and significantly reduce the stall hysteresis.

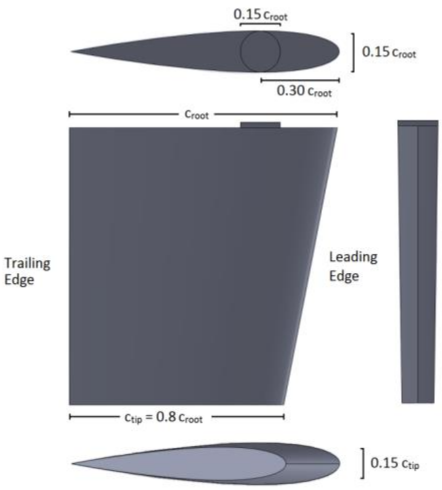


Figure 31. Overview of the submarine rudder (Ellis et al., 2018)

Lin Y.H. et al. (2018a) carried out PMM tests on the SUBOFF submarine model at the towing tank of the National Cheng-Kung University. The results were benchmarked the manoeuvring derivatives with good agreement against experimental data published by the DRTC with the observable discrepancies discussed. The adopted test arrangement was bespeaking with the model mounted to a single cylinder strut whereas a twin strut arrangement was used in the DTRC experiments (Figure 32).

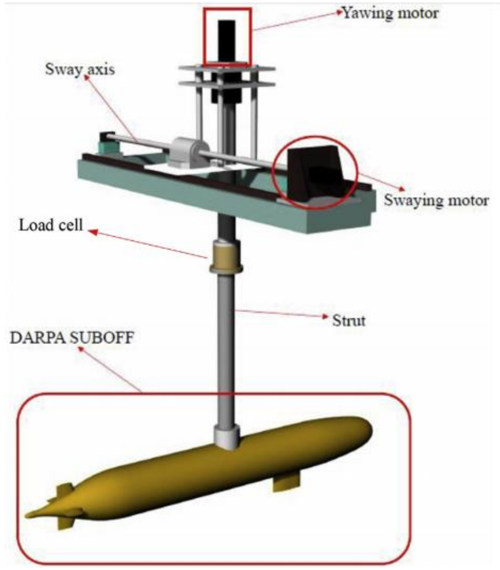


Figure 32. Arrangement of the PPM test for the single strut mounted SUBOFF (Lin Y.H. et al. 2018a)

Maki et al. (2018) carried out both captive model and free running model tests to evaluate a novel thrust vectoring system (TVS) for underwater vehicles in the towing tank of the Naval Systems Research System (NSRC) Cat Tokyo, Japan (Figure 33). The VTS was integrated into NSRS's free running model. The tests identified the hydrodynamics coefficients of the system which then used develop a mathematical model of the TVS dynamics. Optimal control theory was applied to the mathematical model, and manoeuvres were simulated to understand the performance of the TVS.

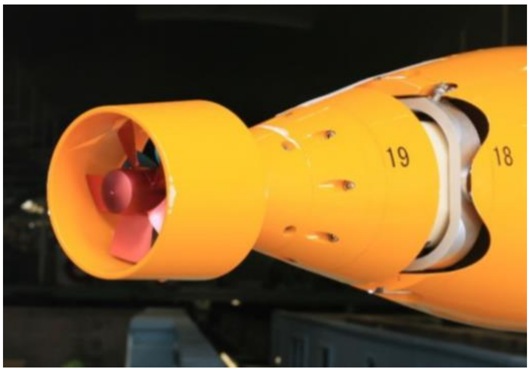


Figure 33. VTS integrated with the NSRC free running model (Maki et al., 2018)

Park et al. (2020) performed captive model tests with and without propulsors using the

VPMM equipment to investigate the propulsor effects on AUV manoeuvrability (Figure 34). A mathematical manoeuvring model using a polynomial model was established, and static drift, control fin deflection, pure heave and pure pitch tests using VPMM equipment were performed to obtain manoeuvring coefficients. In static drift tests, the yaw moment with respect to the drift angle was remarkably reduced by the propulsor operation under large drift angle conditions. In the control fin tests, the results were analysed by focusing on the flow acceleration induced by the propulsor and increased lift on the control fins. The dynamic tests, i.e., the pure heave and pitch tests, showed that the propulsor affected the added mass and second moment of inertia.

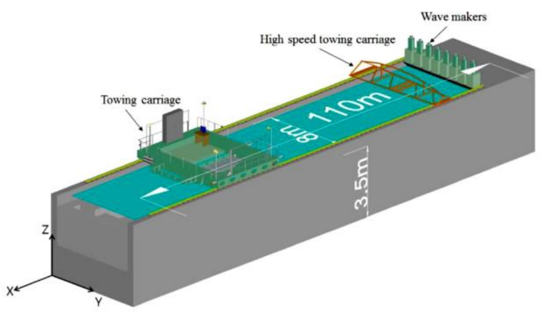


Figure 34. A drawing of the Seoul National University towing tank (Park et al., 2020)

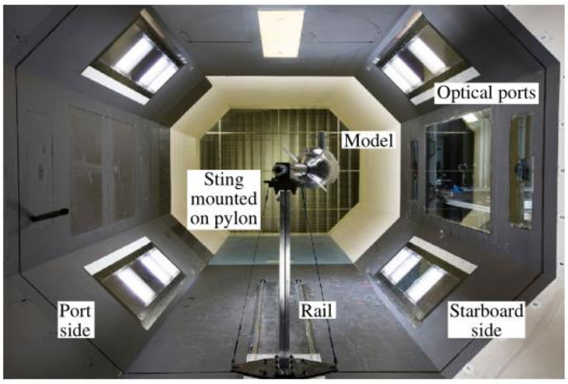


Figure 35. Test section of wind tunnel (Lee S.-K. et al., 2020)

Lee S.-K. et al. (2020) carried out the generic submarine BB2 model tests at 10° yaw in the DST wind tunnel (Figure 35). The most significant flow feature is on the model upper hull. Surface-streakline patterns obtained from China-clay allowed the visualisation of flow separation on the model BB2 cruciform appendage. Ensemble-averaged measurements of the wake, by high-resolution (planar 3-component) stereoscopic particle image velocimetry (SPIV), allowed the tracking of vortices downstream of the cruciform. The tests provided a benchmark to allow future comparisons with numerical simulations and other experiments on the BB2 (or a variant of this model geometry).

6.2 Control

In the case of Underwater Vehicles (UV), a control system for controlling the UV’s motion is indispensable in order to achieve the operation purpose of an UV. The control system is the key technology and the main indicator for measuring the advanced level of an UV.

Path Following. Path following control aims at regulating a vehicle to converge to and follow a desired path, without any temporal specifications. Yu C. et al. (2017) proposed a simplified and nonlinear single-input fuzzy controller to follow the guidance speeds and angles for an autonomous underwater vehicle with unknown environmental disturbances. An improved 3D line-of-sight guidance law is derived to transform 3D path following position errors into controlled guidance speeds (Figure 36).

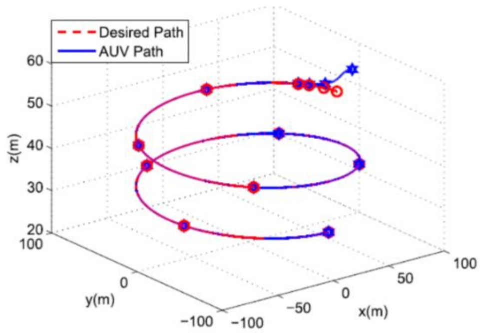


Figure 36. 3D helix path following (adapted from Yu C. et al., 2017).

Sans-Muntadas et al. (2019) proposed a path planning and guidance control law for under-actuated autonomous underwater vehicles with limited field-of-view, in particular vehicles that cannot control their sway motion and can only move forward. In this research, a path planning method which calculates a series of waypoints that generate a path that ensures the visibility is proposed. A guidance and control system that enables an underactuated vehicle to follow the proposed path preserving the vision of the landmark is also proposed. Abdurahman et al. (2019) studied an application and stability result of a modified line-of-sight guidance law for 3-D path-following of an unmanned underactuated underwater vehicle subject to environmental disturbances. The PF problem is solved using a revised relative system model with an improved FLOW frame and a complete model of ocean disturbances. The vertical course control and speed allocation are also used. Zhang G. et al. (2018b) proposed an adaptive second order sliding mode controller to eliminate the chattering motion through a sliding surface during the path following control considering nonlinearities and external disturbances. An adaptive tuning law was applied to estimate the upper bound of external disturbances.

Qi et al. (2020) investigated the coordination control of multiple Underactuated Underwater Vehicles (UUVs) moving in 3D space. The coordinated path following control task was decomposed into two sub tasks, path following control and coordination control. In the path following subsystem, the control law was designed based on Lyapunov theory and back-stepping techniques. In the coordinated control subsystem, by adjusting the speed of the UUV, the coordination error tended to zero. The effectiveness of the controller was visualized by simulation experiments.

Sun et al. (2020) proposed a DDPG algorithm based on optimized sample pools and average motion critic network (OSAM-DDPG) to realize the path following control of an AUV. The random interference force model was added in the training process to simulate the dynamic underwater environment to train a DDPG-based control system with anti-interference ability. The conventional DDPG algorithm was improved by optimizing the sampling mode and the motion evaluation. Compared with other control algorithms, using the improved reinforcement learning algorithm as the controller of the AUV does not require an accurate mathematical model for the AUV, and has the advantages of anti-interference, good stability and high robustness (Figure 37).

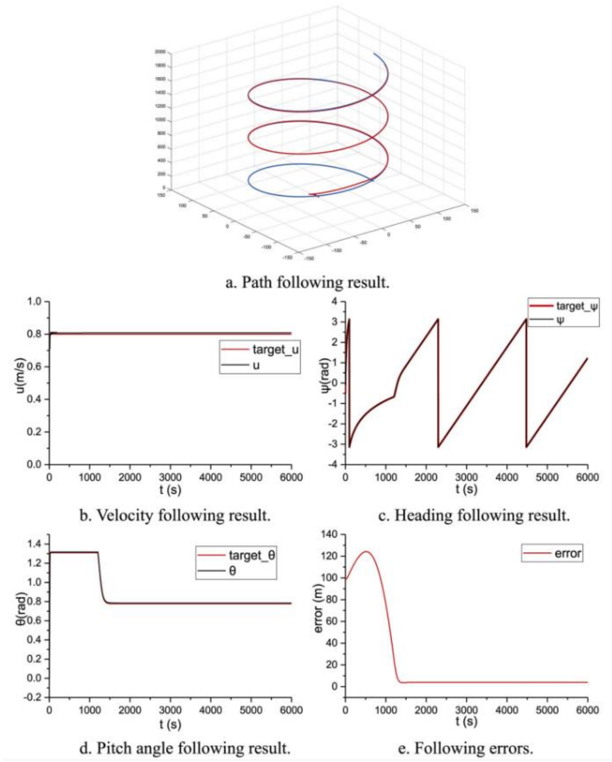


Figure 37. Simulation results of the AUV's 3D curve path following (adapted from Sun et al., 2020).

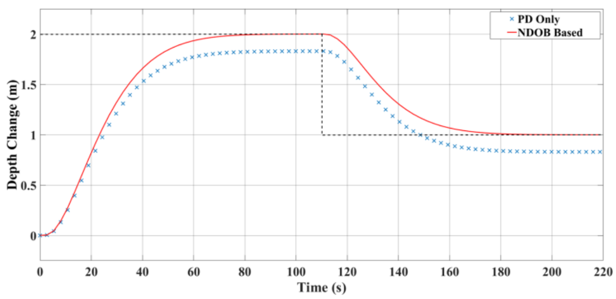


Figure 38. Depth responses of different control schemes (adapted from Bi and Feng, 2019).

Bi and Feng (2019) proposed a composite hovering control scheme to improve the disturbance rejection performance of under-water vehicles via variable ballast systems (VBSs). Simulation results showed that the

NDOB based composite hovering control system exhibits more desirable performance in disturbance rejection than a conventional PD control system.

Trajectory Tracking is the most studied subject in UV control. Trajectory tracking requires a vehicle to track a time-parameterized reference trajectory, which means the vehicle needs to reach the specified position at the specified time. Al Makdah et al. (2019) developed trajectory tracking controller based on a 6-DOF nonlinear kinematic and dynamic model for a Hybrid Autonomous Underwater Vehicle. In the developed controller, a time-varying linear quadratic regulator is designed and applied to the nonlinear model of AUV to track the trajectory ensuring minimal tracking error and energy consumption in the thrust mode and gliding mode. Yan J. et al. (2019) studied a tracking control problem for a remotely operated vehicle (ROV) in the presence of time delay and actuator saturation constraints. A model-free PD controller is designed to enforce the position tracking and the domain of attraction (DOA) is estimated and optimized by using linear matrix inequalities (LMIs) to guarantee the tracking stability.

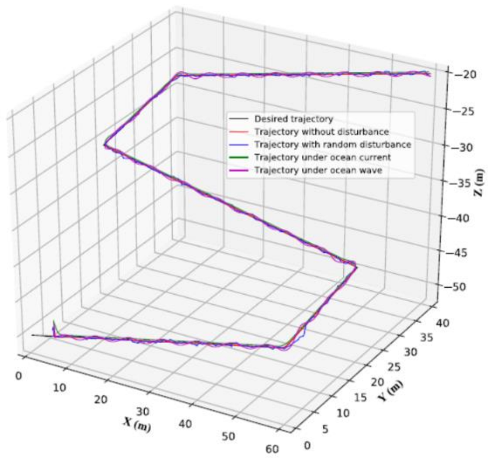


Figure 39. 3-D trajectory tracking for raster scan task under different disturbances. (adapted from Zhang et al. (2019)).

Zhang Y. et al. (2019) studied a novel three-dimension (3-D) underwater trajectory tracking method for an autonomous underwater vehicle using model predictive control (MPC). In the research, the trajectory tracking control is proposed as an optimization problem and then transformed into a standard convex quadratic programming (QP) problem. The optimal control inputs be recalculated at each sampling instant, which can improve the robustness of the tracking control under model uncertainties and time-varying disturbances. The simulation results are given to show the feasibility and robustness of the MPC-based underwater trajectory tracking algorithm (Figure 39).

Kumar & Rani (2020) proposed an efficient hybrid trajectory tracking control scheme for an AUV in the presence of structured and unstructured uncertainties. In the proposed scheme, the model-dependent control scheme is combined with the model-free control scheme to cope with the uncertainties. An adaptive compensator is also added to the part of the controller to compensate for the unknown external disturbances and the reconstruction error of the neural network.

Shojaei & Dolatshahi (2017) studied a line-of-sight target tracking control of AUVs with model uncertainties and environmental disturbances. Dynamic surface control, neural networks and adaptive control techniques are utilized to develop a target tracking controller and to compensate model uncertainties and environmental disturbances. Dai & Yu (2018) proposed an indirect adaptive control scheme to solve the trajectory tracking problem of the underwater vehicle and manipulator system (UVMS) in the presence of dynamic uncertainties and time-varying external disturbances. They proposed an indirect adaptive control scheme which consists of three parts: an extended Kalman filter (EKF) estimation compensative system, a model-based computed torque controller (CTC), a H_∞ robust compensative tracking controller. Simulation results show that the proposed control scheme can provide a better tracking performance than traditional methods. Wadi et al. (2019) proposed a novel adaptive Nussbaum-function-based controller to solve the trajectory tracking problem for an underactuated AUV. In the proposed controller, high- and low-level controllers are synthesized to guide the vehicle to its set trajectory, and a novel adaptation law tunes the gains of kinematic and dynamic controllers so that the AUV can safely track the desired trajectory. Xu R. et al. (2019) studied the trajectory tracking problem of an underwater vehicle based on control moment gyros (CMGs) in the three-dimensional (3D) space. In the proposed controller, the tracking errors are converged to zero and the error dynamics are stabilized by introducing virtual control laws. Anti-windup compensators are taken in order to deal with the problem of input saturation and then back-stepping methods are exploited to construct the dynamic controller. Finally, the constrained steering law is utilized to achieve the actual control input for the CMG system. Zhou et al. (2018) proposed a method of integrating bio-inspired models and the back-stepping technique to carry out 3D trajectory tracking control for an underactuated AUV with constant external disturbances. A bio-inspired model which is based on the biological neuron system is adopted to express surge velocity error and angular velocity error and is used to design dynamic velocity regulation controller for a three-dimensional trajectory tracking. Wang J. et al. (2019b) presented a nonlinear robust control scheme based on the command filtered backstepping method for the three-dimensional trajectory tracking control problem of an AUV. The effectiveness and good robustness of the proposed tracking controller were illustrated by comparative simulations.

Elmokadem et al. (2017) developed a terminal sliding mode control scheme to solve the trajectory tracking problem of AUVs in the horizontal plane. The obtained simulation results indicated that the proposed control schemes work well for the trajectory tracking of AUVs moving in the horizontal plane and has a robustness against bounded disturbances. Yan Z. et al. (2019a) studied an adaptive sliding mode controller for the trajectory tracking control of underactuated AUVs in 5-DOF (exclusion of roll), where the vehicle dynamics are unknown and also subject to environmental disturbances. In the research, the dual closed-loop control is designed to achieve the trajectory tracking and a novel direct adaptive neural network controller, combined with a conditional integrator, is designed to provide the robustness and adaptation for underactuated AUVs. Yu H. et al. (2019) studied a spatial trajectory-tracking control for underactuated unmanned underwater vehicles (UUVs) in the presence of model parameter perturbation and unknown ocean currents. In the research, the spatial trajectory-tracking guidance, based on the dynamic virtual vehicle method, is proposed to compute the desired motion states of an UUV for trajectory tracking. The globally finite-time control strategy based on the PID sliding mode control is also proposed to globally stabilize all tracking errors in the finite time. Karkoub et al. (2017) designed a hierarchical robust nonlinear (HRN) controller for the trajectory tracking of an AUV with disturbances and system uncertainties. In the proposed controller, the virtual reference input is designed based on a kinematic model using the backstepping control technique and then a sliding-mode controller is designed to achieve control of the planned virtual reference input. Gao et al. (2017) proposed a hybrid visual servo (HVS) controller for the tracking control of underwater vehicles with various motion sensors. A dynamic inversion-based sliding mode adaptive neural network control (DI-SMANNC) method is developed to track the HVS reference trajectory and a single hidden-layer (SHL) feedforward neural network is used to compensate for dynamic uncertainties.

Ferreira et al. (2018) presented multivariable control strategies, based on a backstepping methodology and a Control Lyapunov Function (CLF) for the trajectory tracking problem of a Hybrid ROV. The proposed control responded appropriately to the trajectories selected as reference and presents robustness for unmodelled external disturbances. Chen J.W. et al. (2018) proposed a path tracking method based on a line-of-sight method and designed a fuzzy controller based on the fuzzy control algorithm for underwater robots. Results show that the path control method, based on the fuzzy controller optimized by the genetic algorithm, ensures that the vehicle sails along the expected path. Guerrero et al. (2019) presented an adaptive high order sliding mode controller for trajectory tracking of underwater vehicles. The robustness of the controller in depth and yaw dynamics was demonstrated through real-time experiments. An et al. (2020) proposed a modified proximate time-optimal control (PTOC) based on a reduced order extended state observer (RESO) and a controller scaling method. First, a simple and practical modified ADRC is proposed for heading control with input nonlinearities. Then, a parameter self-tuning strategy is proposed for the feedback controller with the control gain changed by the controller scaling method. Finally, the modified PTOC, based on RESO and with an updating strategy for the limit of linear region, was proposed to improve the control performance.

Xia Y. et al. (2020) addressed the trajectory tracking problem of a X-rudder AUV in vertical plane subjects to velocity sensor failure and uncertainties. An optimal robust trajectory tracking controller was developed based on linear velocity observers, a LOS based back-stepping kinematics controller, a robust disturbance rejection dynamics controller, and a multi-objective optimal rudder allocator.

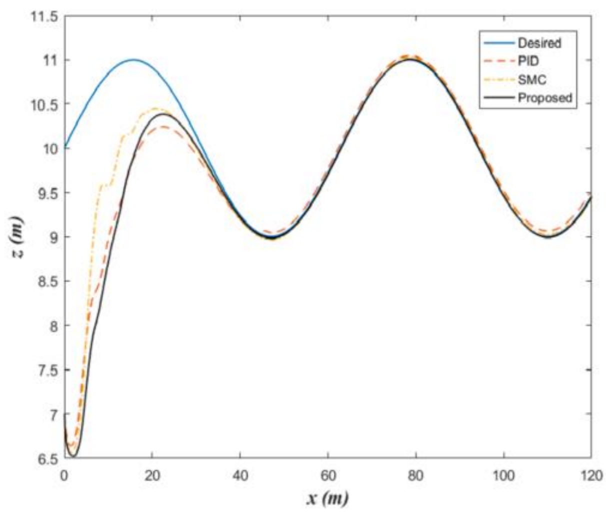


Figure 40. Trajectory tracking comparison (adapted from Xia Y. et al. 2020).

Collision avoidance is usually the research content of path planning, which is mainly to improve the safety of the UV and to reduce both energy consumption and navigation time. Lin Y.H. et al. (2018b) integrated a PSO (Particle Swarm Optimization) − based dynamic routing algorithm, a self-tuning fuzzy controller, a stereo-vision detection technique and a 6-DOF mathematical model into the inspection system of an AUV. The result verified that the MOPSO-based dynamic routing algorithm in the system of the AUV is not only able to estimate the feasible routes intelligently, but also to identify features of underwater structures for the purpose of positioning. Albarakati et al. (2019) developed a 3D trajectory planning framework that can account for multiple static obstacles and the ocean state, as provided by an Ocean General Circulation Model (OGCM) simulation or forecast. The efficiency of the model was demonstrated by the optimal time trajectory planning of an AUV operating in the Red Sea and Gulf of Aden. Zhuang et al. (2019) presented a two-stage cooperative path planner for multiple AUVs operating in a dynamic environment. A novel, Legendre pseudo spectral method based, cooperative path planner was proposed that works offline and online. The simulation results show that the proposed path planner is capable to react quickly to a dynamic ocean environment, and to avoid the collisions successfully and efficiently.

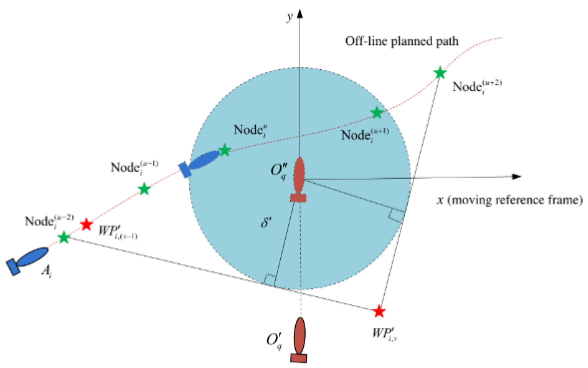


Figure 41. Template for the collision resolution. (adapted from Zhuang et al., 2019)

Li Y. et al. (2017) presented an AUV optimal path planning method for seabed terrain matching navigation, namely to avoid some of these areas and to solve the problem of existing methods of terrain matching having low precision in areas with small eigenvalues. This method builds a field map and value map that represent obstacle and matching performance, respectively, and a planning algorithm, which includes a dynamic matching algorithm, a cost function, a search length and a min length, a second-goal point and a dynamic path planning algorithm, based on a star algorithm. The simulation results show the proposed method is feasible.

Li J.H. et al. (2019) presented the autonomous swimming technology developed for an AUV operating in the environment of an underwater jacket structure. To prevent the position divergence of the inertial navigation system constructed for the primary navigation solution for the vehicle, a sonar image processing based underwater localization method was developed. According to an Occupancy Grid Map (OGM) based path planning algorithm, an obstacle collision-free reference path was derived. Wang D. et al. (2020) investigated an obstacle avoidance strategy for a wave glider in a marine environment. Aiming at dynamic obstacle avoidance for the wave glider, a collision prediction model (CPM) and an improved artificial potential field (IAPF) based fusion algorithm (CPM-IAPF) was developed. The simulation results show that the wave glider can accomplish the obstacle avoidance task with the proposed algorithm when facing different dynamic obstacles in marine environments.

Formation Control and Docking Control. The formation control is a fundamental problem of multiple-UV cooperation and is getting more important due to the expansion of the role of USV. Fabiani et al. (2018) proposed a general framework to manage a team of AUVs, while keeping the communication constraints, during mission execution. In the proposed framework, a virtual spring-damper coupling is utilized to define the distributed interaction forces between neighbouring vehicles. The passivity theory is applied to ensure stable convergence of the network vehicles to an equilibrium point and to provide robustness in presence of communication fading and delays. Moreover, the potential Bilateral Symmetric Interaction (BSI) game theory is adopted to maintain desired communication performance and fulfil each agent task.

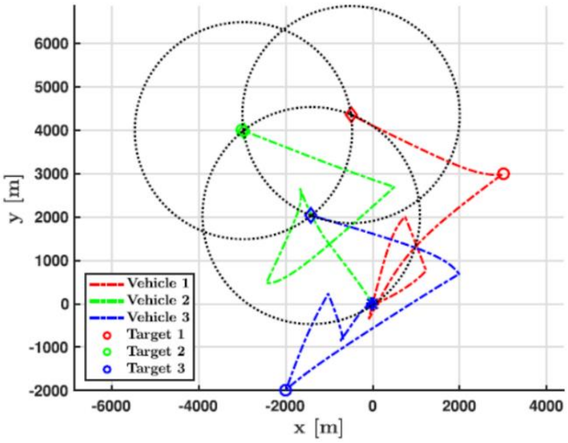


Figure 42. Cooperative exploration task of a AUVs team. (adapted from Fabiani et al., 2018)

Li J. et al. (2019) developed a robust control scheme for time-varying formation of multiple underactuated AUVs with disturbances under input saturation. In the developed control scheme, firstly, the reference trajectory of the follower is defined using a body-fixed coordinate transformation based on the leader position and predetermined time-varying formation. The robust time-varying formation control law is designed so that the trajectory of the follower can track the reference trajectory while securing the formation of AUVs. The disturbance observer is also constructed to estimate unknown time-varying disturbances in the control system. Jia et al. (2019) proposed a novel distributed cooperative search strategy based on the initial target information for multiple underwater robots to reduce the average time of searching target and improve the search target probability. Yan Z. et al. (2019b) proposed coordinated control protocols with or without time delay for the coordination control problem of multiple AUVs under switching communication topologies based on discrete information. The coordination control protocols are designed for the cases of no time delay and time delay, and sufficient conditions for the consensus algorithm are analysed and given based on the matrix theory. Wang J. et al. (2020) investigated a neural adaptive formation control of leader-following AUVs with model uncertainties and external disturbances in 3D space. A filter-backstepping technique has been effectively utilized to design a formation tracking controller. Simulation results for a group of AUVs are provided to demonstrate the tracking performance of the designed formation controller. Chen Y. et al. (2020) introduced a control strategy for multiple AUVs to improve the cooperative operation ability in formation control, to cluster search operations and to minimize the likelihood of collisions and interference with teammates and obstacles in complex working conditions. The simulation results show that the proposed formation control and path planning strategies are suitable for complex, unknown underwater environments.

The docking control for autonomous docking is a basic, required ability for an AUV to reduce the need for frequent launch and recovery operations at the surface. Sans-Muntadas et al. (2019) proposed the use of a convolutional neural network (CNN) to guide and control an autonomous underwater vehicle into the entrance of a docking station by using mapping camera input. The CNN is trained to estimate the error between the actual vehicle heading and the desired vehicle heading that guides the vehicle into the docking station. After the training period, the camera input and the CNN are used to control the vehicle towards the docking station, achieving autonomous docking. Experimental tests show that the approach allows the vehicle to reliably perform a docking manoeuvre using only a camera as sensor.

Lin et al. (2019) developed a non-contact docking system for AUVs. The system includes both acoustic and optical navigation, underwater wireless communication, non-contact power transfer, and monitoring and controlling of the docking system. The reliability of the developed docking system was verified by sea trials at depths 50 m and 105 m. Trslic et al. (2020) studied an autonomous docking system of a ROV to both static and dynamic docking stations using visual based pose estimation techniques. The full system including the ROV automated navigational control was tested using a static docking station in the North Atlantic Ocean and the results were within the tolerances to allow multiple successful dockings.

7. CHALLENGES WITH RESPECT TO EXPERIMENTAL RESEARCH

7.1 Signal processing

Deformation of the measured signals during model tests or during full-scale tests may be induced by signal processing techniques, due to characteristics of e.g. filters, AD-conversion (time step, resolution). The 29th MC has studied this issue with the aim of improving the test quality for manoeuvring purposes. This section gives more information on these uncertainties.

AD-conversion. During model testing the measurements are still dominantly performed in an analogue way. The conversion from such an analogue signal to a digital signal is governed by a resolution or least significant bit (LSB), which is given by (with range typically the measured voltage):

$$\mathrm{LSB} = \frac{\mathrm{Range}}{2^{\mathrm{bit}}}$$

For instance, the measurement range could be 20 volt. As the quantization is now mostly 16 bits or more, the AD-conversion only induces a negligible uncertainty. Care should be taken for converters which have a quantization below 16 bits.

The LSB uncertainty is mostly expressed as ± 0.5LSB.

Filtering. An analogue filter can be used to smooth a measured signal. There are a few reasons to do this:

- To have a better graphical representation of the signal, but at the same time this does not always improve the measurement accuracy;
- To remove high frequency noise (so-called blue noise, to be investigated in the frequency domain), which may deteriorate the signal to noise ratio of the low frequency manoeuvring components due to the "aliasing" effects;
- To condense oversampled signals, e.g. when applying a 1 kHz sampling rate.

Analogue low pass filters (or online filters) should be applied to smoothen the measured signal when unwanted harmful noise exists, but care is needed when applying this technique:

- The transfer function characteristics have to be known. In particular, the cut off frequency and the transition band are of importance, see Figure 43.
- Care should be taken that the governing manoeuvring (or PMM) frequency is on the low pass side of the transition band (no filtering of relevant frequency range).
- The filter is never perfectly real time and a time delay is therefore introduced.
- Even in the passing band, signal variations may occur due to gain differences which depend on the filter design, see Figure 43.
- Additional noise can be induced by the filter.
- Actual noise can be hidden by the filter and should be accounted for during the uncertainty propagation.

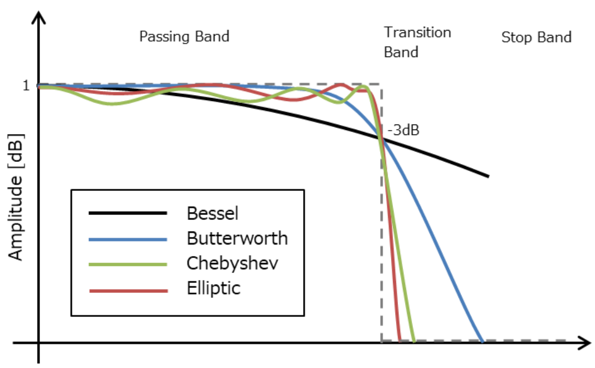


Figure 43. Amplitude response of an ideal filter and actual filters

For these reasons, applying a software filter (or offline filter) in post processing should be considered.

Mansuy et al. (2017) compared different filtering techniques applied to shallow water tests with the DTC. Although the aim was oriented towards the seakeeping tests, the outcome seems useful for harmonic PMM tests.

Time step. A sufficiently small time step (or a sufficiently large sampling rate) is required to capture all manoeuvring effects. In practice sampling rates between 10 Hz and 1000 Hz have been reported with 50 Hz and 100 Hz as most frequently used values. The sampling rate has to be at least twice the filter rate.

Propagation of noise uncertainty. Figure 44 shows a typical time trace of force measured by a dynamometer during captive model tests. During a PMM test, the force will also follow a harmonic trace, which is mostly analysed with Fourier harmonics up to the 3rd order (see the appendix of the 28th MC report). The question is then how this noise affects the different Fourier components. A dedicated study has been carried out by the 29th MC, which has been published by Delefortrie & Kishimoto (2019). In this report a summary is given.

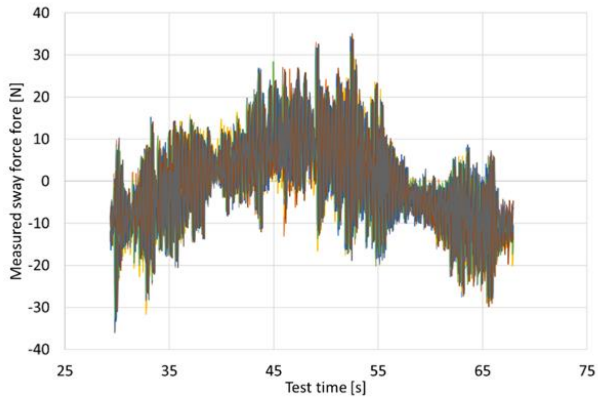


Figure 44. Measured sway force at the fore dynamometer during a captive harmonic yaw test with the KCS at 20% ukc, first cycle of 9 repetition tests (Delefortrie & Kishimoto, 2019).

This work extends the research carried out by Brouwer et al. (2019) for steady straight-line tests and is currently adopted by the ITTC as 7.5-02-01-06. Taking account of the assumption that the Fourier components represent the true signal, the difference between the time trace and true signal is attributable to noise.

Monte Carlo simulations have been performed based on a true signal supplemented with realistic Gaussian noise levels. Such synthetic signals were each subjected to a Fourier analysis and the resulting distribution of the harmonics was investigated, leading to the observation that the uncertainty in the higher harmonics is always $\sqrt{2}$ times the uncertainty of the mean value or 0^{th} harmonic.

The uncertainty of the latter is dependent on the noise level. The application of analogue filters, however, lowers the noise level, and thus affects the outcome of the uncertainty analysis, without changing the physics behind it. For captive model tests, it seems more useful to apply filtering in post processing, however, if this is not feasible, it is recommended to multiply the obtained uncertainty with the frequency cut off ratio.

System identification techniques heavily rely on signal processing and are thus affected by the previously described uncertainties. Revestido Herrero et al. (2018) investigated an estimation efficiency when determining experimental coefficients on a 6-DOF non-linear manoeuvring model for underwater vehicles, and proposed a procedure that solves problems such as reduction in autocorrelation, elimination of heteroscedasticity and reduction of multicollinearity. They also assessed the effectiveness of the procedure by Monte Carlo studies. The methodology is considered to be applicable to other type of test data. Furthermore, Xu H. & Soares (2019) proposed another method, optimal truncated LS-SVM (Least Squared - Support Vector Machine) which has a low computational cost by reducing the dimensionality of the kernel matrix. This method is a robust method for estimating coefficients, diminishing the uncertainty of the measured signal from captive model tests.

Another possible SI technique is the use of wavelets. An example of such approach is given by Todorova & Parvanova (2019), who apply the technique to a synthetic decaying signal to find the corresponding inertia and damping terms.

More complex applications can be found in the field of deep learning algorithms (Woo et al., 2018), which introduce artificial intelligence to increase the automation level of ships. In the present case the deep learning mechanism can couple e.g. yaw rates at times t and $\mathrm{t}-1$ (referred to as LSTM or Long Short-Term Memory) rather than perceiving them as independent data as in a common feed forward neural network. In the SI process, a Savitsky-Golay filter (polynomial fitting) is used to differentiate the positions towards velocity. A simplified linear manoeuvring model of USV was identified by using the free running test data and the proposed model identification method. Simulation results show that the proposed dynamic model identification significantly outperforms conventional simplified manoeuvring models and the effectiveness of the proposed method is validated by comparing simulation results and free running test data.

Another way to cope with nonlinearities is the use of the so-called LWL or locally weighted learning, which approximates the nonlinear function by segmented linear functions. An example of this application is given by Bai W. et al. (2018).

Wang Z.H. and Zou (2018) assessed the degree of collinearity in ship manoeuvring identification modelling. A variance Inflation Factor (VIF) was applied to quantify and analyse the collinearity with different model structures and training samples. The results showed the hybrid approach was capable to predict the trajectory of ships in typical manoeuvring tests. Their results showed that quantifying collinearity was meaningful before modelling by the identification algorithm. It can be applied to evaluate the rationality of selected model structure and training sample, and it can also be combined with model selection and optimization design algorithms, which is a good way to help deal with parameter drift issues and build accurate mathematical models. This approach has been enhanced by Wang Z. et al. (2020a). They proposed a nonparametric identification method based on ν ('nu')-support vector regression, which can establish robust models of ship manoeuvring motion without prior model structure. This method avoids high dimensionality when solving matrices and provides powerful modeling capabilities with high computation efficiency. In addition, the principle of structural risk minimization allows a balance between approximation accuracy and model complexity, which minimizes overfitting.

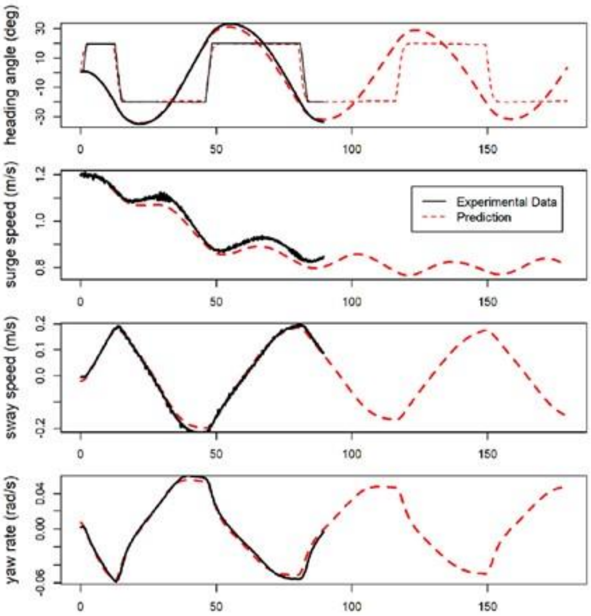


Figure 45. Comparison of predicted manoeuvre with experiment (Wang Z. et al., 2020a).

Wang Z. et al. (2020b) also proposed an optimal design scheme of excitation signal (i.e. steering) to determine the training data that can provide the maximum dynamic information which can improve the stability and accuracy of the identification of ship manoeuvring models. They demonstrated that the optimized training data had significant effects on improving the performance of the identified model.

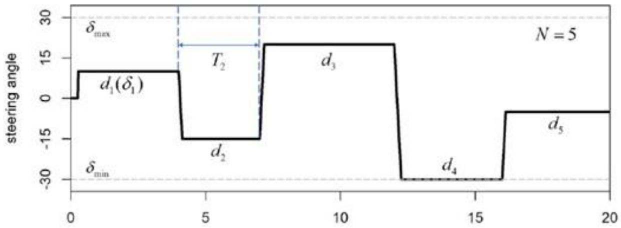


Figure 46. Excitation signal in time domain (Wang Z. et al., 2020b).

Sensitivity studies are a useful method to analyse the uncertainties not only induced by noise or filtering, but also due to other causes. Gavrilin and Steen (2018) performed a sensitivity analysis on the coefficients of the MMG model. They revealed that steering and interaction coefficients significantly affect the results of simulation. Through identification of those coefficients from full-scale trials, they found that different combinations of the coefficients results in similar time-series, and clarified the presence of correlation between the coefficients and showed its difficulties to solve the scale effect problem.

Giles et al. (2018) conducted a frequency domain based analysis of a submarine manoeuvring model, and investigated the effects on the sensitivity and the stability of the coefficients used in the model. They clarified that a more simplified manoeuvring model was obtained by reducing insensitive coefficients and excluding insignificant modes of motion.

Sensitivity studies are considered to be applicable not only for uncertainty analyses but also for initial conceptual design for various vehicles. Jeon et al. (2018) performed sensitivity analyses for a torpedo shape under-water vehicle taking into account the geometric parameters for the bare hull and the rudder. Through those analyses, they specified sensitive geometric parameters which significantly affect the dynamic characteristics and suggested a procedure to determine the configuration of the vehicle which satisfies required performance.

7.2 Shallow water testing

Recently, several towing tanks are equipped with a false bottom to enable model tests in shallow water conditions. For large size towing tanks, primarily aiming at model tests in deep water, the size of the false bottoms is generally limited and the towing tank is only partially covered: the length and the breadth of the false bottom are smaller than the length and the breadth of the towing tank. In this section, the uncertainties with respect to the false bottom are discussed based on recent published literature.

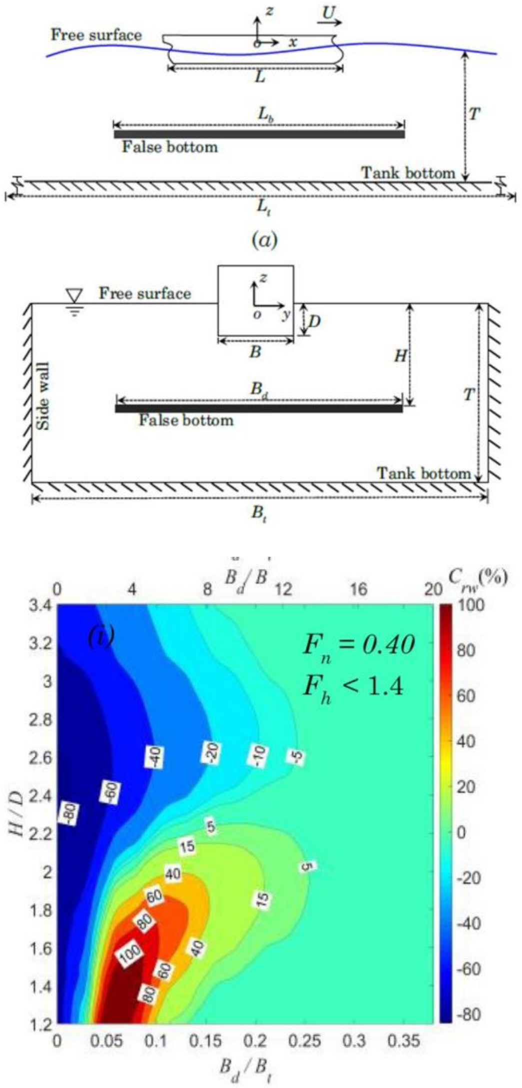


Figure 47: Sketch of tank equipped with false bottom and error coefficient Crw as function of H/D and Bd /Bt (Li M. et al., 2019)

Li M. et al. (2019) investigated the error caused by such imperfection of the false bottom on the realization of the shallow water conditions. They applied the boundary element method (BEM) based on the potential theory, and quantified the false bottom effect on the wave making coefficient C_W as function of the depth to draft ratio (H/D), the false bottom breadth to tank breadth ratio (Bd/Bt) and Froude number (Fr). The y_{infl} formula seems appropriate to determine the necessary width of the false bottom.

Liu H. et al. (2018b) used the false bottom facility of the circulating water channel of Shanghai Jiaotong University to perform ship-bank interaction tests with KVLCC2 at scale 1/128.8. No details are provided on the setup of this false bottom. The novel content is rather the application of uncertainty propagation methods to assess the uncertainty on the ship bank interaction forces based on the well-known Norrbin formulae. It seems that the uncertainty from the water depth has the major contribution in the total uncertainty, which confirms the importance of a well-designed false bottom.

7.3 Turbulence stimulation and scale effects

Questionnaire. In order to gain more insight in the issues concerning turbulence stimulation and scale effects, a new questionnaire has been sent out in March 2018 to the 32 institutes who participated in the 2015 questionnaire (see 28th MC) and who carry out manoeuvring tests. By the closure of the questionnaire in October 2018, 19 institutes responded or almost 60%.

The questionnaire had four main parts:

- measures taken to deal with scale effects prior or while executing tests;
- measures taken to deal with scale effects after executing tests;
- means of validating the test results;
- applications of turbulence stimulation.

Each part consisted of a number of statements with five possible agreements (not at all or 0% or -2, not really or 25% or -1, not applicable or 50% or 0, likely or 75% or +1 and certainly or 100% or +2). The average percentage of the answers gives then a resulting agreement percentage for a given statement. The integer values are used as short hand abscissa notations in the following histograms.

Scale effects. 77% is concerned with scale effects in the results of captive model tests. The 27th ITTC MC proposed an estimation scheme to deal with scale effects, which is known by 69%, but only (partially) used by 52%. Observe, that the questions were mainly organized according to that estimation scheme. In general scale effects are counteracted by selecting the ship model as large as possible (82% agree), but as visualised on Figure 48 the tank size is a first order limiting factor, followed by the carriage possibilities and the available stock propeller's size.

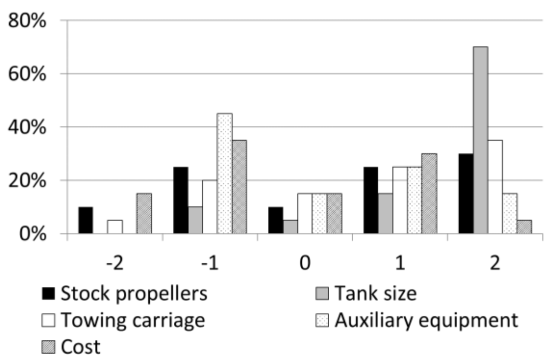


Figure 48. Factors limiting the maximal ship model size.

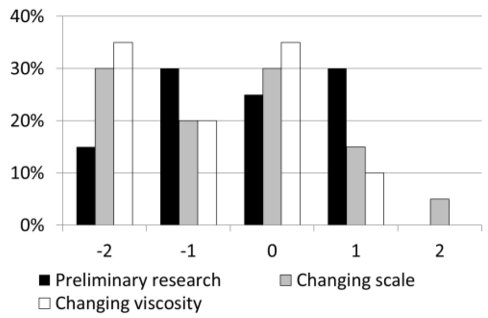


Figure 49. Preliminary numerical research.

Due to these limitations, turbulence stimulation is frequently applied (86%). A second mean to deal with scale effects is changing the propeller rate (58%). A limited number of institutes use auxiliary thrusters, but this seems more applicable for free running tests. A last alternative concerns preliminary numerical research (42%), which is not so common as the turbulence stimulation, see Figure 49. If preliminary numerical research is performed it is not necessarily aimed at scale effects. Only 4 institutes mentioned that they perform preliminary research at a different scale and 2 institutes investigate the effect of the Reynolds number.

The treatment of the test results for scale effects is mostly performed in longitudinal direction only, with the ITTC 1978 performance method being the first choice (74% agreement) and an equal share of more complex or simpler methods (Figure 50).

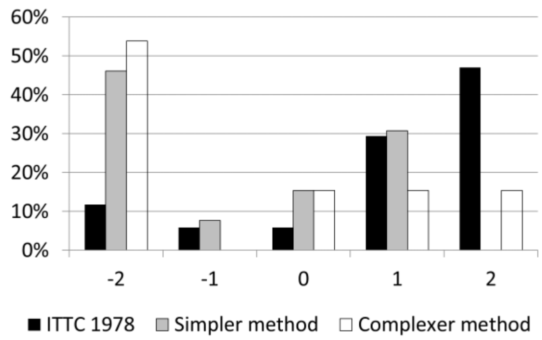


Figure 50. Means to correct for scale effects in longitudinal direction.

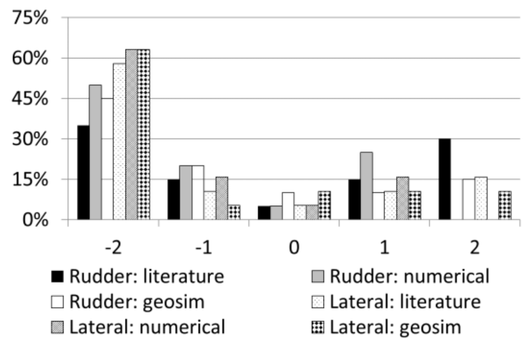


Figure 51. Means to correct for scale effects for manoeuvring forces.

In case of manoeuvring lateral forces and rudder forces play an important role, however, corrections for these components are less frequent (Figure 51). If corrections are used it is mostly for the rudder forces and the institutes rely on information available in literature.

The opinion of the MC is that scale effects will become more important with increasing drift angle (increasing viscous force) and with decreasing water depth. In the latter case, the return flow will play a dominant role and hence influence the frictional resistance. However, this opinion is not generally accepted based on the responses to the questionnaire.

Validation of test results. Given the uncertainty connected with captive model tests, the institutes were asked how they validated their results. These results can either be validated directly, for instance by comparing them with free CFD trajectories or with other ships, or indirectly by deriving a mathematical model based on the results and check the agreement of simulated manoeuvres with the information on wheelhouse posters or by expert judgement, comparison with free running trajectories or even real time simulation runs. Figure 52 gives an overview of the responses to each method. The comparison with other (benchmark) ships is by far the preferred validation method (78%), followed by free running tests (63%) or expert judgement (62%). As can be seen on the graph, CFD is mostly validated by EFD and not the other way round and real-time simulations are not a frequent choice for most institutes. Either they do not have a real-time simulator and if they had one, the process is too complex to be used as a validation tool.

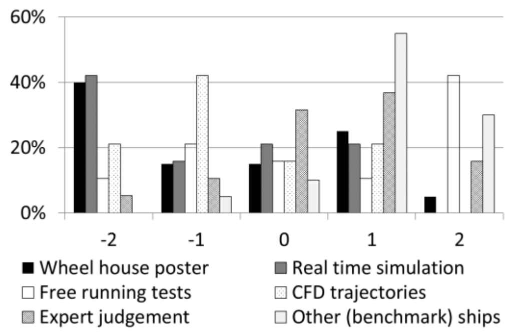


Figure 52. Ways to validate the results of captive manoeuvring tests.

Based on the validations, the results are tuned in 52% of the cases. This is mostly achieved by changing the rudder dependent coefficients as shown in Figure 53. As an alternative the rudder area itself of the simulated ship is changed in order to achieve the desired behaviour. As can be seen in Figure 54 tuning is mostly needed in shallow water conditions.

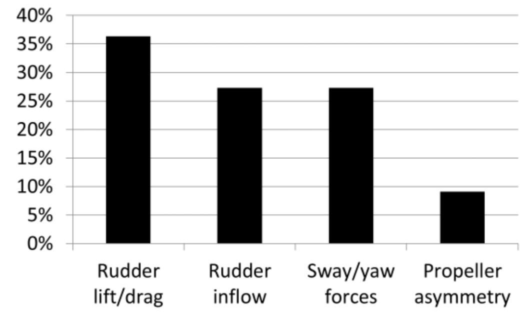


Figure 53. Components of the mathematical model that are tuned if necessary.

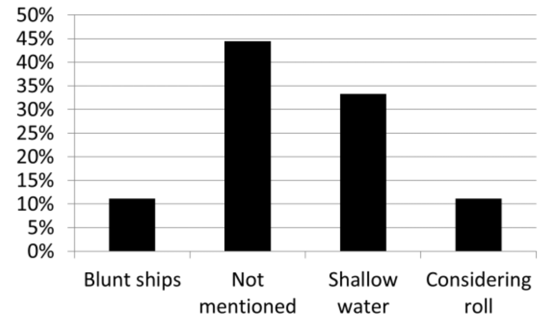


Figure 54. Conditions when tuning is mostly needed.

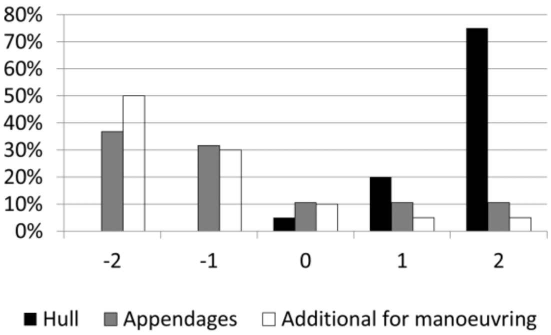


Figure 55. Use of turbulence stimulation.

Turbulence stimulation. Figure 55 shows that turbulence stimulation is almost only applied on the ship's hull and mainly based on the prescription for resistance tests. On the hull 79% uses studs and 21% uses sand strips and 92% does it according to the ITTC, while on the appendages the sand strips are the most popular choice (75%). The occasional additions for manoeuvring are mostly classified, although the bilge keels have been mentioned by some.

Literature review. No new references were found with respect to turbulence stimulation for manoeuvring purposes. A limited number of authors described scale effects in the field of manoeuvring. Araki (2018) performed research on scale effects for the manoeuvring behaviour of the KVLCC2. Geosim (scale 1/1 and 1/110) captive simulations with deflected rudder were carried out with the RANS solver of NMRI. The lift generation is less effective on model scale, unless the model scale self-propulsion point is used instead the ship self-propulsion point, which seems to confirm previous literature (see the report of the 27th MC).

In order to solve the scale effect problem, Suzuki et al. (2017), Ueno et al. (2017) and Suzuki et al. (2019) have been carrying ongoing investigations on free running model tests with auxiliary thrusters. They attempt predictions of full-scale ship performance in wind and wave disturbances taking into account the operational limit of main engine as well.

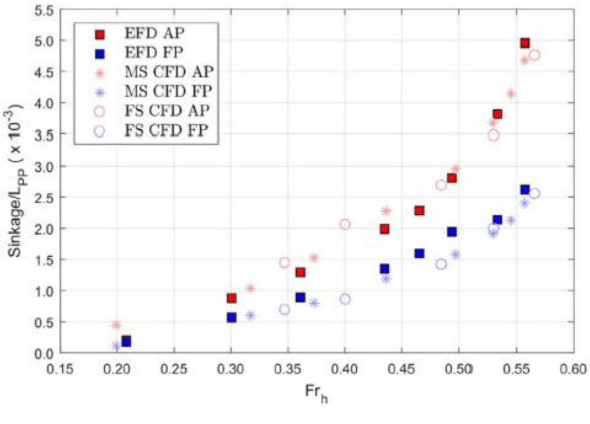


Figure 56 Comparison of model-scale and full-scale CFD AP and FP sinkage against that of the benchmark EFD at h/T = 1.23 (Kok et al., 2020)

Scale effects on squat in shallow water were investigated by Shevchuk et al. (2019). Squat computations were performed using an in house CFD package and focussing of geosim conditions of (post) Panamax container vessels. The scale effects become more dominant with decreasing water depth and lead to an under-prediction of up to 15% of the full-scale squat. This phenomenon can be counteracted by changing the hull's roughness; however, no general guideline could be derived. A similar research was conducted by Zhang H. et al. (2018) who studied scale effects with an in-house RANS code on a bare hull DTMB 5415. They only considered a deep water condition, but contrary to Shevchuk et al. (2019) the obtained heave and pitch motion were smaller on full-scale. The most recent research was performed by Kok et al. (2020), who studied scale effects of squat in confined environments with the DTC hull. Star-CCM+ RANS computations were used with a full-scale ship and a 1/40 model scale variant, including the propeller effect on squat. The latter was implemented with a body force model. The study revealed that the differences due to scale effects are smaller than 6%.

Based on the different conclusions the MC recommends that more extensive CFD research (covering various hull forms and a broad range of speeds and water depths) are needed to investigate this effect.

8. CONCLUSIONS

8.1 State of the Art

Deep Unrestricted Water. Recent research results focus on the topics of manoeuvring performance, unmanned surface vehicles and autopilot applications. Particularly for the latter too many articles have been published.

Manoeuvring performance studies are carried out using a variety of methods such as experimental methods, empirical methods, potential flow methods, RANS methods, and hybrid methods. Among these methods RANS simulation using commercial CFD software has become the most popular.

For unmanned surface vehicles (USV) or MASS (Maritime Autonomous Surface Ships), articles can be grouped according to a focus on path planning, trajectory tracking, collision avoidance, or formation control. In particular, many studies have been conducted on collision avoidance, which considers COLREGs and moving obstacles also artificial intelligent methods such as DRL (Deep Reinforcement Learning) or DNN (Deep Neural Network).

More advanced autopilot applications are being studied such as autopilots for berthing in restricted areas or for offshore operations. In particular, with the rapid development of machine learning techniques, studies on the application of machine learning based controllers and on the improvement of the existing autopilots by applying model predictive control, adaptive PID, neural network, etc., have been actively conducted.

Shallow, Restricted or Confined Water. As for deep water applications a raise in numerical research is noted. In most of these studies the free-surface effects, considering low-speed cases, are neglected. Another interesting trend is that there are more shallow water studies focusing on hull-rudder-propeller interaction, which benefit from flow visualization capabilities of CFD techniques.

For ship-bank interaction free surface effects are mostly considered. This should certainly be the case for very small under keel clearances and/or distances to the bank. RANS solvers outperform potential flow methods in the ship-bank problem.

Ship-lock and ship-ship interactions continue to be challenging problems in ship hydrodynamics. Although the RANS method has been successfully applied to predict the interaction forces, the potential flow method is still the most popular way to investigate the ship-ship interaction problem. The free surface effects in the ship-ship problem were quantified in some studies based on potential flow methods. There are still many research gaps in ship-lock interaction problem, e.g. the wave phenomenon in front of the ship. Further research is required to provide an accurate prediction of the hydrodynamics of a vessel when entering a lock.

Research trends. It is clear that USV is the research trend of the coming years. In general, the number of articles with respect to manoeuvring is booming, which has to be attributed to a vast number of papers dealing with numerical methods, which are cheaper to apply, compared to experimental research.

The downside of these numerical articles is that very few present experimental validation material to proof the applicability of the presented statements.

8.2 Procedures and Guidelines

The MC reviewed the procedures and guidelines under its responsibility. Major updates and improvements were made to:

- Validation of Manoeuvring Simulation Models (7.5-02-06-03)
- Uncertainty Analysis for Manoeuvring Predictions based on Captive Manoeuvring Tests (7.5-02-06-04)
- Captive Model Test Procedure (7.5-02-06-02).

The MC developed three new guidelines:

- UV Full Scale Manoeuvring Trials (7.5-04-02-02) provides an outline of underwater vehicle full-scale trials to determine their manoeuvring characteristics.
- Benchmark Data for Validation of Manoeuvring Predictions (7.5-02-06-06) highlights the processes relevant for benchmarking and provides a list of the present benchmark database available.
- Captive Model Test for Underwater Vehicles (7.5-02-06-07) outlines captive model tests for underwater vehicles to determine the hydrodynamic coefficients for a manoeuvring simulation model.

8.3 Benchmark Data

The third SIMMAN workshop has been postponed to late 2021. The workshop introduces new benchmark data, in particular in shallow water and in waves, to enable better comparisons and to extend the assessment of manoeuvring prediction capability.

All presently available benchmark datasets, including references, have been collected in the new guideline 7.5-02-06-06. The overview of the benchmark data shows that the main part of the available data concerns seagoing vessel types, which do not exist in full-scale. The database should be reinforced so that, in the future, datasets for full-scale variants of vessels, inland vessels and underwater vehicles are created/considered and added as well.

8.4 Underwater Vehicles

Manoeuvring hydrodynamics. A lot of attention has been devoted to methods adopted to evaluate or predict the UV characteristics. In recent years an increasing transition from experimental methods to numerical methods is observed, in particular for conditions that are beyond the spatial and instrumentation limits of conventional experimental testing facilities, or when there are multiple design or operation options. In certain research, such as strong transient or microlevel physics dependency and establishing benchmark data, experimental methods as the primary method prevail. Also noted is the combination of numerical and experimental methods to evaluate complex variables, having low measurement confidence in either methods when carried out individually.

Manoeuvring control. Increasing research in control systems, for the purpose of path following, trajectory tracking, collision avoidance, formation control and docking, is noted. Control systems are indispensable to achieving the operation purpose of underwater vehicles. The advancements in control system research provide a key indicator for measuring the state of UV manoeuvring and technologies.

8.5 Challenges with Experimental Research

Signal processing. The propagation of noise and the effect of filters has been investigated. Noise as such is mostly neglected, which is acceptable for sufficiently long measurements and a uniformly distributed noise in terms of frequency. The procedure 7.5-02-01-06 can also be used for manoeuvring tests, provided that the uncertainty of the mean propagates with a factor $\sqrt{2}$ in the higher order harmonics. A minimum necessary filtering is advised when performing measurements.

Shallow water testing. The MC conducted a literature search concerning the effects on the measurements induced by imperfections of a false bottom, including side-wall interaction. The uncertainty from the water depth has the major contribution in the total uncertainty, which confirms the importance of a well-designed false bottom.

Turbulence stimulation and scale effects. A questionnaire has been distributed to ITTC members. Almost 8/10 are concerned with scale effects for manoeuvring. These tend to be more important with increasing drift and decreasing water depth. The latter is also confirmed by literature, although not much was published lately in this field. Means to counteract scale effects include extra turbulence stimulation, but details on this seem classified. Tuning of manoeuvring coefficients is common, especially in shallow water conditions.

9. RECOMMENDATIONS

Study the potential impact of Unmanned Surface Vehicles (or Autonomous Navigation) to the Manoeuvring Committee:

- the state of the art of autopilots, with proven applicability in a tank environment or at full-scale;
- the state of the art of artificial intelligence.

Support SIMMAN with the post processing and analysis of the results of SIMMAN 2021.

Continue the work with (autonomous) underwater vehicles towards completion of the guidelines:

- draft a guideline on the validation of UV models for manoeuvring purposes;
- extend the AUV full-scale trials guideline to consider submarines and ROV as well.

Support the creation of benchmark data, specifically for:

- (autonomous) under water vehicles;
- inland navigation, including pushed or towed convoys;
- model scale vessels with a documented full-scale variant.

Expand the full-scale manoeuvring trials procedure to account for the measurement of any kind of full-scale manoeuvre as a supplement to (virtual) tank tests.

Maintain the attention on scale effects and the effect of tank blockage on the interpretation of results, by stimulating geosim research.

Continue the update of the captive model test procedure, with specific attention to the treatment of amplitudes, frequencies and inertial coefficients as recommended by SIMMAN.

Update the captive model uncertainty procedure, to have a single integrated example, based on the SIMMAN results (2021), instead of different appendices.

Investigate the effect of novel manoeuvring devices and clean fuel technologies on the manoeuvrability.

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

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