TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 17
Number 1
March 2023

DOI: 10.12716/1001.17.01.06

Development and Validation of an Operational Fast Time Ship Manoeuvring Solver to Increase Navigation Efficiency in Horizontally Restricted Waterways

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ABSTRACT: Growth of demand for containerized cargo shipping has put more ports into pressure to accommodate larger vessels. Considering the limitations on dimensions of navigation channels, this is not feasible unless aiming for significant capital dredging or alternatively creating high precision predictions of vessel motions subjected to environmental forcing and interaction with shallow and restricted waterway. NCOS ONLINE (Nonlinear Channel Optimisation Simulator) is a state of the art navigation support tool which combines DHI's high level forecast of environmental conditions with mathematical model of ship motions to add an extra level of accuracy in predicting the under-keel clearance and vessel swept path to boost the efficiency of navigation and pilotage within restricted channels. NCOS Manoeuvring Module utilizes an autopilot scheme based on PID (Proportional / Integral / Derivative) controller and Line of Sight Algorithm to FORCE Technology's SimFlex4 manoeuvring solver for prediction of manoeuvring ship swept path and response, which will effectively bring the accuracy of real time full bridge simulator to fast time operation support tool. In this paper, the result of mathematical model is validated against fullscale measurements of containership transits through Port of Auckland Navigation channel by comparing pilot commands, leeway drift and swept path through output of portable pilotage unit. According to the results the model is found promising to predict the behaviour of human pilots with precision required in operational use. Finally, the swept path and manoeuvring performance of a sample transit is assessed on different environmental conditions and tide stages to evaluate the safe transit windows in operation.

1 INTRODUCTION

As more ports are targeting to accommodate larger ships at deeper drafts, there has been lots of pressure on port planners to increase the port access channel capacity through capital dredging. The main focus of such capital dredging attempts is typically deepening the channels as changing the horizontal profile of navigation channel is considered to be the expensive element. Consequently, ships are entering the port waters with larger drafts, length and breadth while the channel profile remains largely unchanged. Resulting in higher risk in handling and manoeuvering, especially when combined with extreme weather events. Although in channel development plans, minor modifications are made on bend configuration, still there are lots of risk in navigating big vessels through port waters. NCOS ONLINE Manoeuvring Module [8] is a cloud based online operational decision support tool that brings the capabilities of real time manoeuvring simulation of FORCE Technology's SimFlex4 [10] to fast time simulation, assisting the port operators to identify risks in pilotage of big vessels under the environmental forcing within shallow and confined waterway.

Both real time and fast time manoeuvring solvers are generally based on the determined hydrodynamic coefficients that come from captive model tests in a towing tank or planar motion mechanisms [1]. Most recently CFD application has been of interest as an alternative for towing tank model tests [2]. However, as it is difficult to take into the account the interaction of propulsion and steering with vessel main hull, these mathematical models should be validated before using in manoeuvring solvers. Towing tank experiments usually suffer from model scale effects, and as the viscous effects in manoeuvring are not fully understood, there would be a high level of uncertainty when extending these results to fullscale [3], There have been several attempts for validating the manoeuvring mathematical models. Free-running model tests can provide a higher level of accuracy as the size of the model is not restricted by carriage equipment in the tank and models are typically made in larger scales [4]. Although the scale effects for hull, rudder and propeller are still important in free running model tests, the interaction of hull, propeller and rudder are fully considered in free running model tests. Validation of manoeuvring mathematical models through this method shows more course-stability than measurements [5,11].

Standard ship manoeuvering tests in fullscale are considered as part of ship delivery sea trials [6], and the results are made available through pilot cards or wheelhouse posters. These results are often used for validation of ship manoeuvering simulation models [7]. Although sea trial results are good for developing manoeuvering models, there are still several reasons that they cannot be considered as a good measure for validating fast or real time manoeuvring solvers. The sea trial is typically handled in deep water as executing the tests in shallow waters is risky, and in most cases the vessels are in ballast or half-laden condition, where the manoeuvering characteristics can't be easily scaled to deeper drafts.

NCOS ONLINE Manoeuvring Module is DHI's advanced manoeuvring simulation tool which combines high level weather forecast systems with FORCE Technology's SimFlex4 manoeuvring solver to identify risks in pilotage and handling of deep drafted vessels in shallow and laterally restricted navigation channels. NCOS ONLINE uses an autopilot algorithm based on PID controller combined with line-of-sight algorithm to navigate the ship through the channel in fast time simulation [8]. The mathematical model implemented in NCOS ONLINE is a fully coupled six degrees of freedom dynamic model in which the hydrodynamic effects are tabulated based on the results of towing tank model tests, numerical calculations, and experiences with similar fullscale vessels [9]. NCOS ONLINE uses a detailed representation of forcing on vessel dynamic through databases coming from wind tunnel model tests. Ideally, the forecast system, the mathematical model of the ship hydrodynamics, confined waterway interactions models and the autopilot algorithm itself are considered as the sources of uncertainty in NCOS ONLINE simulation. Making the test bed for validating these various components individually through model scale tests not only time and cost consuming, but also fail to capture the interactions between various elements. In previous attempts, the performance of NCOS ONLINE autopilot has been validated against human pilot performance through real time full bridge simulation, by using the same mathematical models and forcing condition, which seemed promising in terms of autopilot following the human pilot decisions with acceptable accuracy [8]. However, in order to provide a basis for full validation of the model, in this paper the fullscale measurement on a real transit is identified as the most efficient way in terms of precision, time and cost. Fullscale measurements on actual vessel transits will enable the full validation of forecast models, vessel dynamic mathematical model, and autopilot algorithm performance all at a same time.

2 FULLSCALE MEASUREMENT

2.1 *Vessel particulars and metocean condition*

The measurements have been done on a Panamax class containership approaching to Port of Auckland. The outline of navigation channel is given in Figure 1.

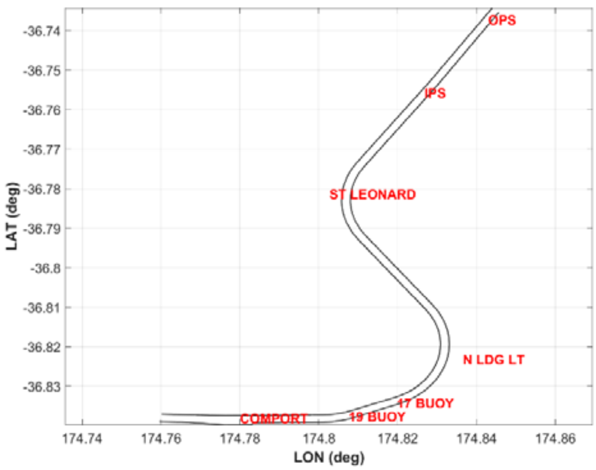

Figure 1. Port of Auckland navigation channel and significant waypoints

The main particulars of the vessel and loading conditions are given in Table 1.

Table 1. Vessel particulars and loading condition

Ship Type	Panamax Containership
LOA (m)	294.05
Beam (m)	32.2
Draft Mid (m)	11.9
Trim by Aft (m)	0.2
GM (m)	1.64 Free surface corrected
Lateral Windage Area (sq.m)	6761
Frontal Windage Area (sq.m)	1125
Engine MCR	41130 KW x 104.0 RPM
Rudder Type	X-Twisted Leading Edge
Rudder Aspect Ratio	1.533%
Wetted Rudder Area (sq.m)	60.23

The swell height during the approach was insignificant and is not expected to affect the results. The wind and current varied along the channel at time of the transit as given in Figure 2. Wind speed was moderate, between 14 to 20kn easterly, and the transit started on a moderate flooding current slightly exceeding 1kn, giving adequate under keel clearance during the passage.

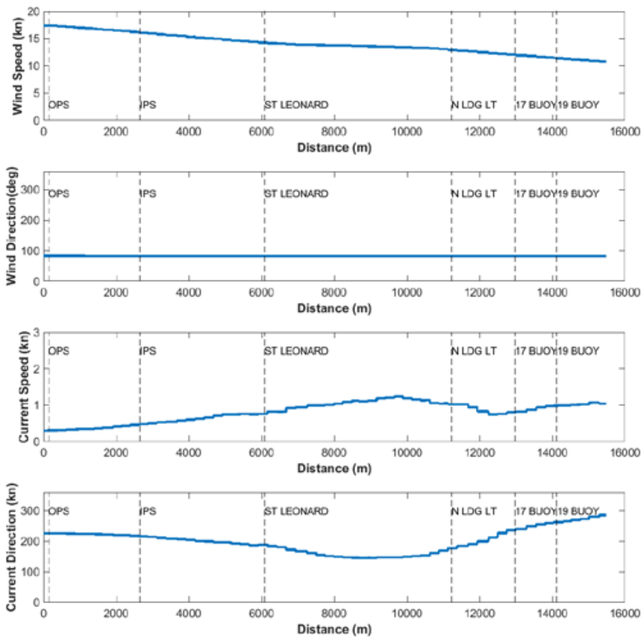

Figure 2. Environmental forcing during the transit

2.2 *Measurement methodology*

The position of the vessel, heading and rate of turn was extracted from high precision pilot portable units. Three Leica DGPS units were also installed, with one on each bridge wing and the third on the bow along the vessel centreline. These were used to measure vessel roll, pitch and heave during the transit and in turn calculate the under-keel clearance.

The vertical error for each corrected DGPS signal was typically below 25mm. Some satellite signal reflection off the forward container stack was expected and usually meant the bow DGPS performed slightly worse than the unobstructed receivers on the bridge wings.

A bridge voice recording was used to reconstruct the pilot rudder, course and engine commands during transit.

Figure 3. DGPS unit and PPU (Portable Pilot Unit) receiver on bridge wing

2.3 *Field measurement results*

The vertical profile of the channel and vessel keel position is plotted in Figure 4. At each location, as the ship hull has curvatures, the lowest point of hull is assumed here. According to the results simulation output is in general conservative when compared to measurements, especially on the bends, which will result in lower rate of turns and turning ability when compared to the measurements.

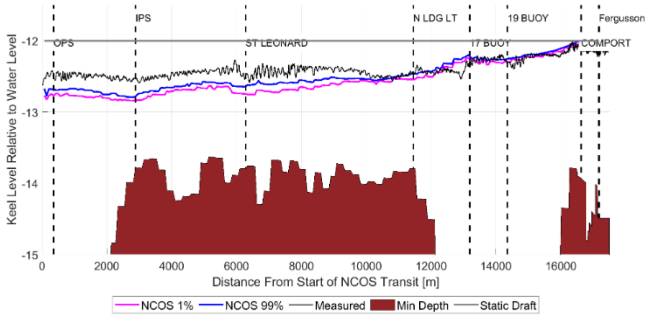

Figure 4. Measured maximum keel excursion compared to NCOS safety 1% and high probability 99 % lowest keel excursions. All depths to chart datum

The vessel forward speed, rate of turn and executed rudder angle is given in Figure 5. According to the results, the autopilot and simulation model was successful in matching the transit speed with only some differences in the last stage of the approach. Measured rate of turns are slightly higher than simulation, specifically on the bends, which confirms that the mathematical model is conservative as it was more difficult to initiate the turns on the bends considering the reduced under keel clearance. Rudder executions are in general higher than the measurements. The human pilot sets the rudder commands as step-wised function, however, in simulation, the PID controller and line-of-sight algorithm sets the input rudder angles smoothly according to heading deviation at each simulation time step.

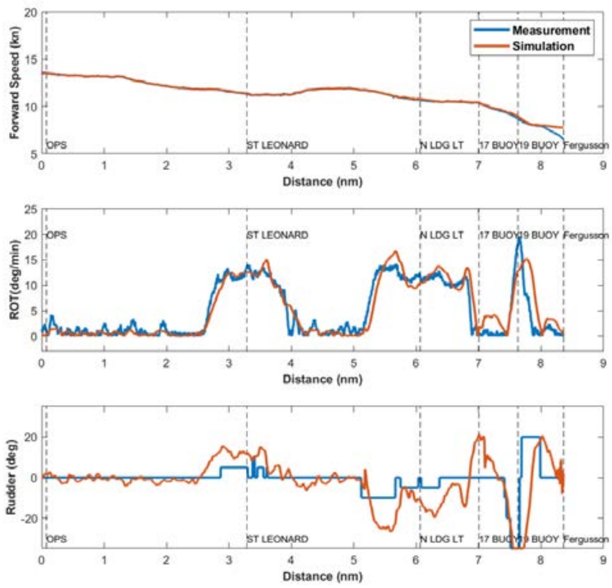

Figure 5. Speed, rate of turn and rudder execution comparison

To evaluate the vessel position relative to channel boundaries, two new parameters are introduced as channel occupancy which is the ratio of vessel swept path width to channel width at each time step, and minimum distance to toelines as the least clearance of vessel extremities to channel boundaries as illustrated in Figure 6. From the Figure 6, when the vessel is running with higher leeway angle, the channel occupancy would be higher.

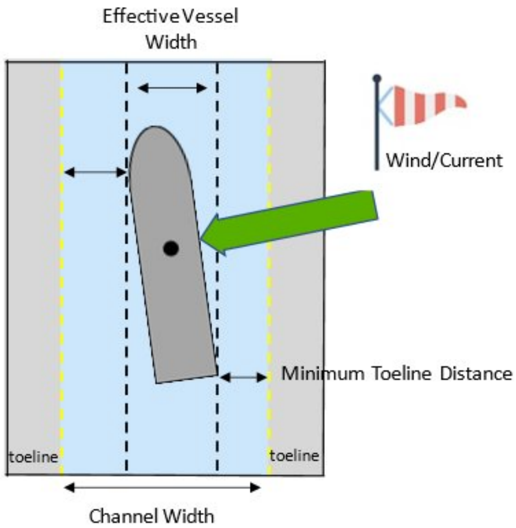

Figure 6. Channel occupancy and minimum distance to toelines concept

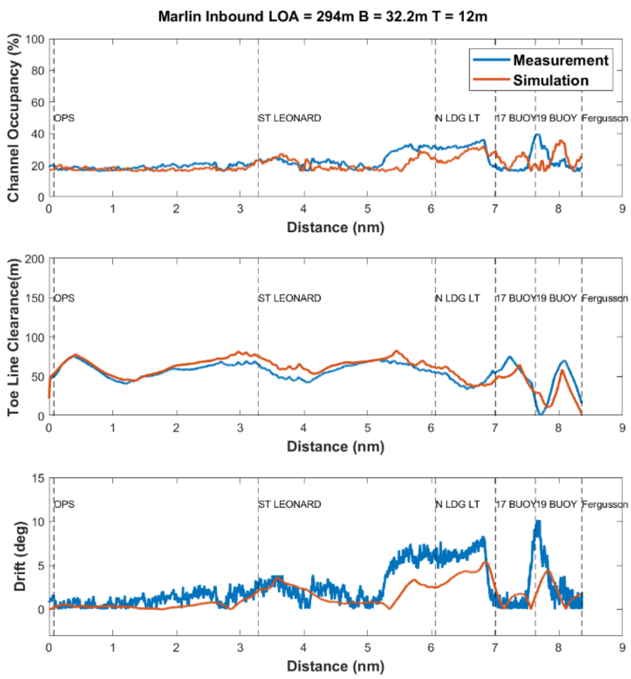

Figure 7. Comparing transit geometric parameters to measurements

The channel occupancy of actual transit is slightly higher than the simulation on the straight sections of the channel (Figure 7). This basically means that the drift angles are higher in actual transits and vessel has proceed with higher level of course-stability in simulation. Most ship manoeuvering mathematical models suffer from the same issue, which the reason could be sought through the source of hull hydrodynamic damping coefficients which basically comes from towing tank model tests in model scale, where the level of flow turbulence around ship hull is not as high as fullscale and viscous damping effects are exaggerated in model scale. Another reason for lower simulation drift angles is the lower under keel clearance and higher vertical motion in simulation. In general drift angle would be less in lower under keel clearance ratios. From the operational point of view, those small differences in drift angle in simulation will not impose any significant risks to transit simulation, while the conservatism in under keel clearance model is highly favoured with regard to grounding risks.

The vessel swept path on fullscale measurement and simulation are compared in Figure 8. On the curved sections of the channel the swept path is wider due to higher measured leeway angles. However, the autopilot was able to finish the manoeuvre close to areas swept by actual vessel.

3 OPERATIONAL APPLICATION

Combining the validated manoeuvring solver and autopilot scheme with high level accurate weather forecasts in NCOS ONLINE can provide port and pilots with the ability to plan transit arrival times with an anticipated level of risk, mitigated through safe transit windows. The risks in navigation could be in relation to vessel swept path geometry (channel occupancy and clearance to channel boundaries, leeway drift), under keel clearance and grounding risks and pilot workload as steering and propulsion variation during the manoeuvre or capacity to respond to unforeseen circumstances.

In this section, the risks of excessive rudder usage on transits of same containerships are evaluated for different arrival times during a full 24-hour tide cycle. On the straight sections of the channel the transit is rated as low risk if average rudder usage is below 10 degrees, high risk if average rudder usage above 15 degrees and medium risk in between. Similarly, on the parts that ship is turning through the curved sections, thresholds of average rudder attempt are increased to 15 and 20 degrees respectively. The results of the fast time simulation are given in Figure 9. According to the results, at the flood stage, there are some arrival times where the pilot rudder usage could be relatively high. Considering the reduced speed through water and flow velocity fed into the rudder, it is expected that vessel steering would be less effective at flood stage. However, the arrival on slack water on peak of tide seems to be the best option for accommodating this vessel, as it will provide higher under keel clearance and with least adverse influence on ship steering performance.

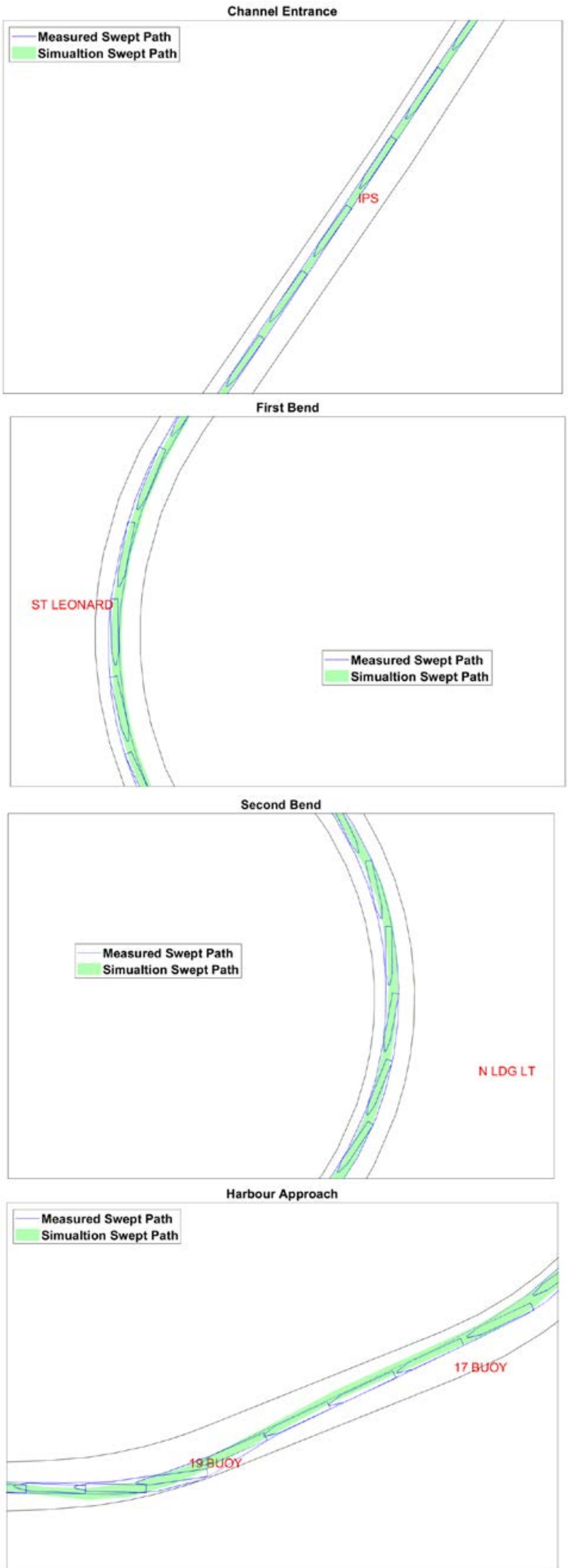

Figure 8. Measured maximum keel excursion compared to NCOS safety 1% and high probability 99 % lowest keel excursions. All depths to chart datum

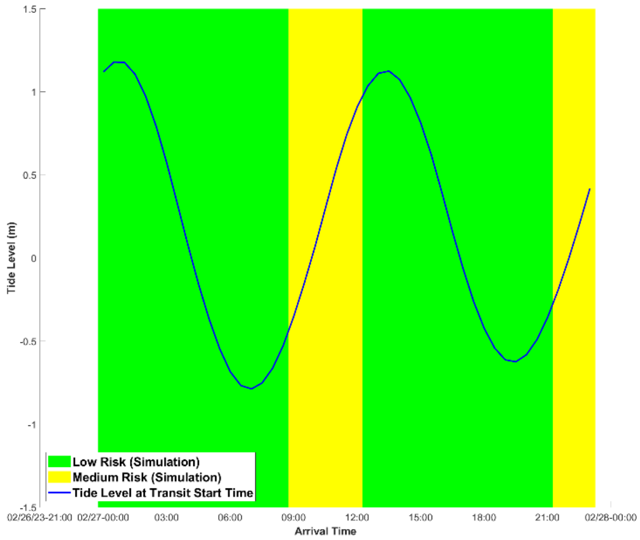

Figure 9. Manoeuvring risk on averaged rudder attempts with respect to tide level at arrival time

4 CONCLUSIONS

The fullscale measurement of vessel manoeuvring performance in actual transit conditions provided the basis for full validation of the manoeuvring mathematical model and autopilot performance. According to the simulation results the agreement between the measured vessel swept path, rate of turn and rudder executions during the transit is within acceptable range which provides a strong platform for fast time manoeuvring simulation for operational navigation support services. The simulation model is proven to be more course-stable than the actual vessel, finishing the manoeuvres with less swept path width and leeway angle, which is slightly less conservative on the curved sections of the channel, however the differences are minimal. This is basically due to lower under keel clearance predicted in the simulation and model scaled based hydrodynamic coefficients applied in manoeuvring mathematical model which suffers from viscous scale effects. The rudder use in simulation is generally higher than the measurement due to a higher level of course-stability in simulation method which is the result of using model test based hydrodynamic coefficients in simulation.

ACKNOWLEDGEMENTS

The authors would like to thank Ports of Auckland for facilitating the fullscale measurements and their continuing support in development of NCOS ONLINE.

REFERENCES

[1] Yoshimura T., Sakurai H., Mathematical model for the manoeuvring ship motion in shallow water (3rd Report), Journal of KSNAJ, Vol. 211, pp 115-126, 1988

[2] Du P., Cheng L., Tang Z., Ouhsine A., Hu H., Ship manoeuvering prediction based on virtual captive

model test and system dynamic approach, Journal of Hydrodynamics, Vol. 34, pp 259-276, 2022
[3] Jin Y., Chai S., Duffy J., Chin C., Scale effects on hydrodynamic manoeuvring force prediction, 25th International Ocean and Polar Engineering Conference, 2015, Hawaii, USA
[4] Im N., Sea J., Ship manoeuvring performance experiments using a free running model ship, International Journal on Marine Navigation and Safety of Sea Transportation, Vol.4, No.1, 2010
[5] Eloot K., Delefortrie G., Vantorre M., Quadvlieg F., Validation of ship manoeuvring in shallow water through free-running tests, OMAE 2015, Newfoundland, Canada
[6] American Bureau of Shipping (ABS), Guide for vessel manoeuverability, March 2006
[7] Gug S.G., Harshpriya H., Jeong H., Yun J., Kim D., Kim Y., Analysis of manoeuvring through sea trials and simulations, IOP conference Series, 2020
[8] Mortensen S., Kazerooni M., Harkin A., Womersley T., Jensen B., Dynamic assessment of safety in manoeuvring through constricted navigational channels using online operational system. Australasian Coasts & Ports 2021 Conference, Christchurch, New Zealand, 2021
[9] Kazerooni M., Womersley T., Harkin A., Jensen B., Turning induced heel of large containerships in shallow water through a fully coupled 6DOF manoeuvering solver, 6th MASHCON Proceedings, May 2022, Glasgow UK
[10] Chislett M., A generalized mathematical model for manoeuvring, marine simulation and manoeuvrability, Proceedings of International Conference MARSIM, May 1995, Denmark
[11] ISO 13643-1 Ships and Marine Technology, Manoeuvring of Ships, 2017, pp 2