Maritime Technology and Research

https://so04.tci-thaijo.org/index.php/MTR

Research Article

Experimental study on KCS container ship initial turning at low speed in regular waves

Evgeni Milanov*, **Dobrin Efremov and Anton Anastasov**

Bulgarian Ship Hydrodynamics Centre, Varna, Bulgaria

Article information
Received: September 24, 2020
Revised: November 20, 2020
Accepted: November 28, 2020

Keywords
Ship maneuvering,
Regular waves,
Maneuvering criteria,
International Maritime Organization,
Energy Efficiency Design Index

Abstract

Since the Energy Efficiency Design Index (EEDI) was introduced by the International Maritime Organization (IMO), increasing attention has been paid to ship controllability in waves, particularly at low speed. One of the main reasons for this is the fact that, in order to satisfy the EEDI requirements, there is a tendency to reduce power consumption and propeller RPM while maintaining existing control means, which results in reduced ship steerability, mainly at low speed. This study considers the effect of regular sea waves on ship initial turning parameters at a set of service conditions. By means of free running model tests, the influence of low advance speed on course and maneuvering trajectory changes in transient turning motion were investigated. The effects of the wave encounter angle variations were examined during the tests, including the application of different wave lengths. Using the experimental results, an attempt was made to normalize ship handling in adverse sea conditions by applying a simple criterion based on the initial time to reach a given course. The results of the present study can be used for the benchmarking of numerical simulations of low speed maneuvers in regular waves.

1. Introduction

Over the years, ship maneuvering qualities have been traditionally analyzed, predicted, and normalized for calm and deep water assuming a negligible influence of external sea conditions. However, because of the fact that the assumption of negligible external effects, such as wave, wind, current, or shallow water, is not strict, some studies have focused on research into ship maneuverability in waves using model tests or numerical methods. Motivation for research in this area was created by the introduction of the EEDI requirements by MEPC.203(62) (2011a), regarding sufficiency of propulsion and steering abilities of ships to maintain maneuverability in adverse weather conditions, and were followed by development of interim guidelines for 3-level assessment of ship installed power- MEPC 62/INF.21 (2011b), and approved by MSC-MEPC.2/Circ.11 (2012) and MEPC.232(65) (2013). Simply, reduction of engine power to keep a navigational speed of 4 knots in waves raised fears of losing vessel controllability in these conditions. The further development of the IMO requirements taking into account the proposals of the organizations involved in the problem, in particular with the implementation of the SHOPERA

*Corresponding author: Bulgarian Ship Hydrodynamics Centre, Varna, Bulgaria
E-mail address: e.milanov@bshc.bg

(Energy Efficient Safe SHip OPERAtion) Project (2016), led to the refinement of the interim guidelines on the assessment of ship maneuverability. Thus, the finally-revised interim guidelines MEPC 75/6/3 (2019) propose to study a speed range of 4 - 9 knots, which is used in principle in the present study.

In connection with the above requirements for the design of new ships, as well as for the modernization of vessels in operation, research in the field of maneuverability of ships in waves has intensified, and the results of studies on maneuvering in waves has been the subject of a number of publications. A characteristic feature of early studies is the use of linear analysis of ship course stability in regular waves. By this, the influence of environmental parameters on ship maneuvering in severe conditions was mainly studied experimentally and numerically. The analysis of the kinematics of the turning characteristics of ships in regular waves with the trajectory distortion presented by the drifting distance and by the angle of the path evolvement was originally proposed by some Japanese authors, like Ueno (2003). The results from the application of this approach were reported by Lee et al. (2009), Milanov et al. (2014), Sprenger et al. (2017), and Kim et al. (2019a, 2009b). Maneuvering behavior of vessels in irregular waves has been experimentally studied by Kim et al. (2019c). Free-running and captive model tests in waves delivering benchmark databases were carried out in the frame of SHOPERA EU Project (Sprenger et al., 2016).

Consequently, the problem arises with the formulation of criteria for vessel maneuverability in real sea conditions. Following the gradual introduction of the EEDI requirements in recent years, several authors have applied similar or modified rationing methods for the assessment of ship maneuverability in waves (Lee et al., 2009c; Milanov et al., 2014; Shigunov & Papanikolaou, 2014; Shigunov, 2018; Kim et al., 2019a).

In this study, the effect of regular waves on initial turning maneuver parameters, as well as the influence on a ship's ability to change course by means of free-running model tests, were investigated. Based on these data, an attempt was made to apply a simple preliminary criterion for the assessment of sufficient maneuverability under adverse sea conditions.

2. Model and experimental setup

The free-running model tests were carried out with the benchmark model of the KRISO Container Ship (KCS) accepted by the International Towing Tank Conference (ITTC) and the SIMMAN Workshop on Verification and Validation of Ship Maneuvering Simulation Methods (2019). The model was manufactured on a scale of 1:52.667. The main particulars of the Glass-Fiber Reinforced Polyester scaled model and the full-scale ship are given in **Table 1**, including appendages.

Table 1 Main particulars of the hull and appendages.

Characteristics	Symbol		Ship	Model
Hull				
Length between perpendiculars	L_{PP}	[m]	230	4.367
Breadth	B	[m]	32.2	0.611
Draft at midship	T	[m]	10.8	0.205
Displacement volume	∇	[m^3]	52030	0.356
Longitudinal C.B., fwd "+"	LCB	[%]	-1.48	-1.48
Wetted surface area	S	[m^2]	9530	3.436
Rudder				
Type			semi-balanced skeg	semi-balanced skeg
Lateral area	AR	[m^2]	54.45	0.0163
Rudder rate	dr	[°/s]	2.32	16.837
Propeller				
Diameter	D	[m]	7.9	0.150
Pitch ratio at 0.7R	$P/D(0.7R)$	[-]	0.997	1.000
Expanded blade area ratio	A_E/A_0	[-]	0.800	0.700
Number of blades	z	[-]	5	5

The maneuvering tests with the KCS containership model were carried out in free-running mode in a BSHC Maneuvering & Seakeeping Basin. The tank has main dimensions L×B×T = 62×40×2.5 m^3, a general sketch of which is given by **Figure 1**. The basin is equipped with a flap-type wave maker capable of generating regular and irregular waves. **Figure 2** shows a side view of the model ready for testing.

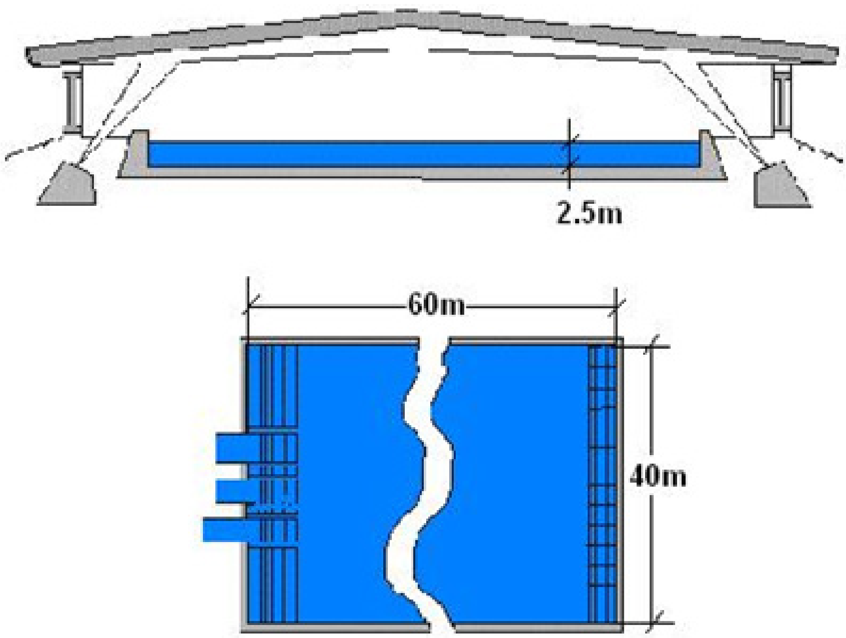

Figure 1 BSHC maneuvering & seakeeping basin.

Figure 2 KCS ship model.

3. Test program

The test program included a set of model initial turning runs in regular waves for a set of forwarding speed and ordered rudder angles at different encounter angles with 3 waves- Table 2. All motion parameter time histories were recorded, but for this study, the rudder angle δ, course ψ, the approach speed V, and CG coordinates xg & yg of the model trajectory were considered. Having in mind proposed by IMO Resolution MEPC 75/6/3 (2019) low-speed values which have to be used for ship maneuvering in waves assessment, as well as the following of 3 scenarios for maneuvering in severe weather conditions, proposed in the SHOPERA project- Shigunov and Papanikolaou (2014) and by IMO (2019), the adequate speed range was accepted, namely: 4, 6, 8, and 10 knots.

Table 2 Test matrix.

					Regular wave parameters			
V* [kn]	***V*** [m/s]	***n*** [rps]	***δ*** [°]	***μ*** [°]	***λ/L*** [-]	***T**** [s]	***s*** [-]	***H**** [m]
4	0.28	3.30	35	30; 45 60	1.0	12.13		4.6
4	0.28	3.30	25; 30; 35	30	1.0	12.13		4.6
6	0.43	4.30	35	30; 45 60	1.0	12.13		4.6
6	0.43	4.30	15	30	0.8; 1.0; 1.2	10.85; 12.13; 13.28		3.5; 4.6; 5.2
6	0.43	4.30	15	45	0.8; 1.0; 1.2	10.85; 12.13; 13.28		3.5; 4.6; 5.2
6	0.43	4.30	15	45	0.8; 1.0; 1.2	10.85; 12.13; 13.28	0.02	3.5; 4.6; 5.2
6	0.43	4.30	15	60	0.8; 1.0; 1.2	10.85; 12.13; 13.28		3.5; 4.6; 5.2
8	0.57	5.45	35	30; 45 60	1.0	12.13		4.6
10	0.71	6.80	35	30; 45 60	1.0	12.13		4.6

*Wave height ***H**** for the ship in [m]

In **Table 2**, the characteristics of the generated waves, as perceived in seakeeping, are denoted:

V - initial speed
n - propeller rps
δ - rudder angle
μ - wave encounter angle
λ/L - non-dimensional wavelength
μ - wave encounter angle
T - wave period
s - wave steepness
H - wave height

The coordinate system used in the present investigation consists of earth fixed (X_0,Y_0) and body fixed (X,Y). Above, it is assumed that, during course change maneuvers, the wave encounter angle μ lies in the range of 30° - 60°. It should be noted that, in contrast to ship seakeeping, in maneuverability studies, encounter angle is equal to zero in the head sea. At this point, it is necessary to clarify why the port maneuver was chosen. The ship was a single-screw single-rudder and the BSHC calm water turning maneuver test showed lower rudder efficiency on that board, so this case is considered to be more severe; thus, it was been used in the present study.

The model maneuvering tests were performed in accordance with the requirements of the relevant procedures of the International Towing Tank Conference ITTC. The similarity between the ship and the model was ensured by modelling the physical dimensions and the phenomena according to Froude's law. Based on the above law and the dependencies derived, the results of the model tests are recalculated for real ships. In this report, this was done, and the data were for the ship.

4. Result of experimental investigations

As stated, the purpose of the model tests was to investigate the dependence of the ship's initial turning characteristics on the parameters of regular wave excitation under the prescribed initial conditions of the experiments. The results of the different impact categories are discussed in detail below.

4.1 Effect of advance speed

One of the important circumstances in maneuvering a vessel in adverse conditions is the requirement of the IMO (2019) to provide "sufficient" ship controllability at low speeds in the range of 4 - 10 knots. For this reason, tests were performed at 3 initial speeds, and other conditions were maintained. In **Figures 3 - 5**, trajectories of such turning motions with rudder 35° on port at initially fixed wave encounter angles of 30°, 45°, and 60° are given.

For this, a regular wave with a characteristic relative length of λ/L = 1.0 was used. In the graphs, the trajectories are shown from the moment of command to the rudder.

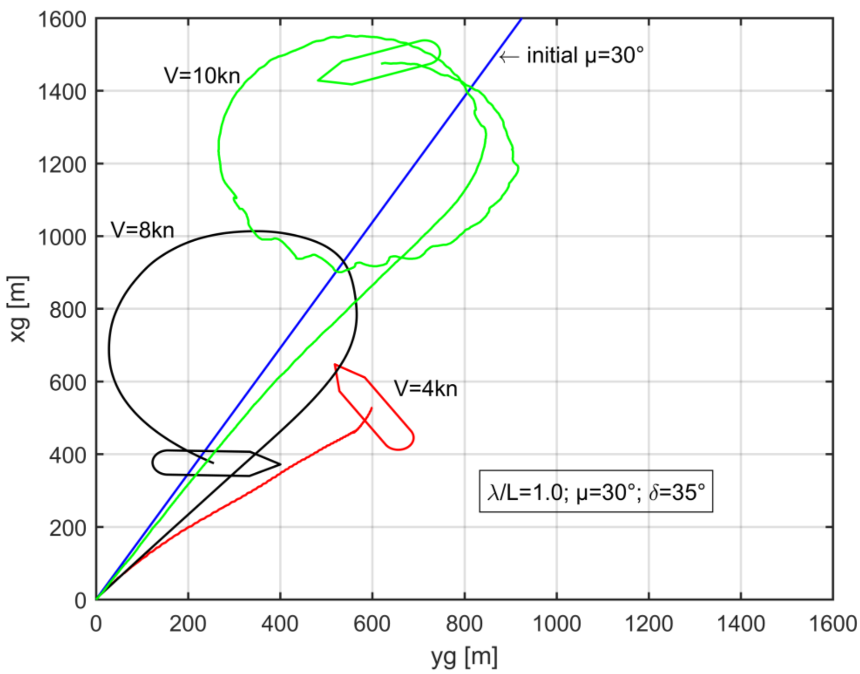

Figure 3 Trajectories at V = 4, 8, and 10 kn, μ = 30°.

Maximum deviation from the initial course is observed for a wave encounter angle of 30° at the lowest speed of 4 knots (**Figure 3**). The same trend continues in reduced form in the case of 45° and 60° initial course values.

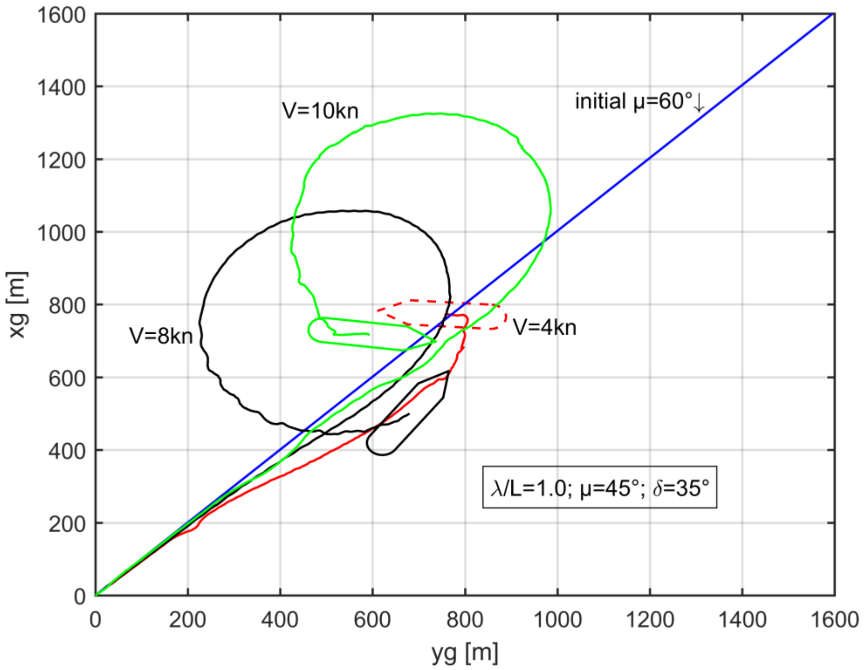

Figure 4 Trajectories at $V = 4$, 8, and 10 kn, $\mu = 45°$.

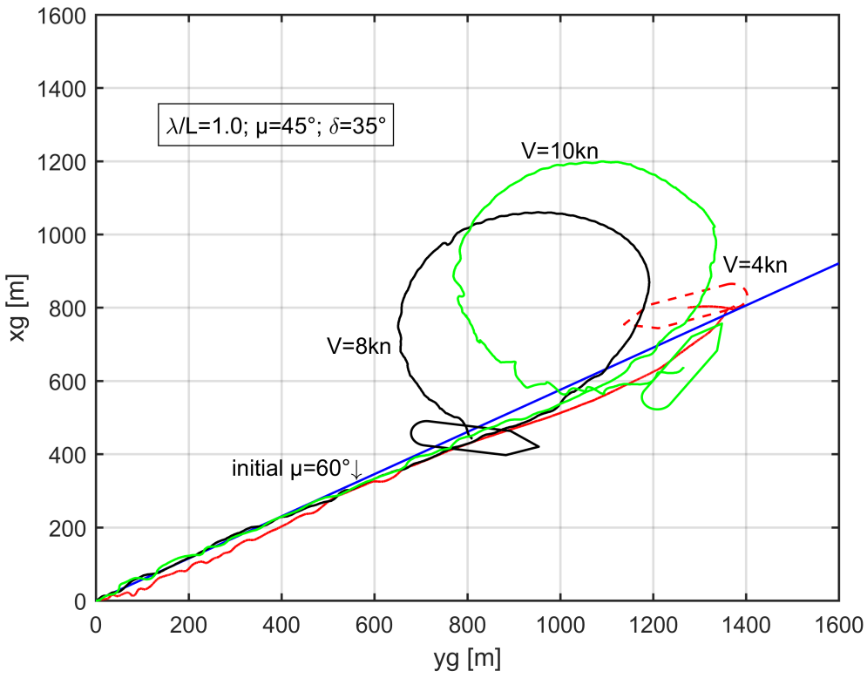

Figure 5 Trajectories at $V = 4$, 8, and 10 kn, $\mu = 60°$.

During maneuvers, the speed drop is significant, as illustrated by **Figures 6 - 8**. In the 4 knot tests, the speed decreases below 1 knot, and the ship is purely drifting in the final maneuvers stage.

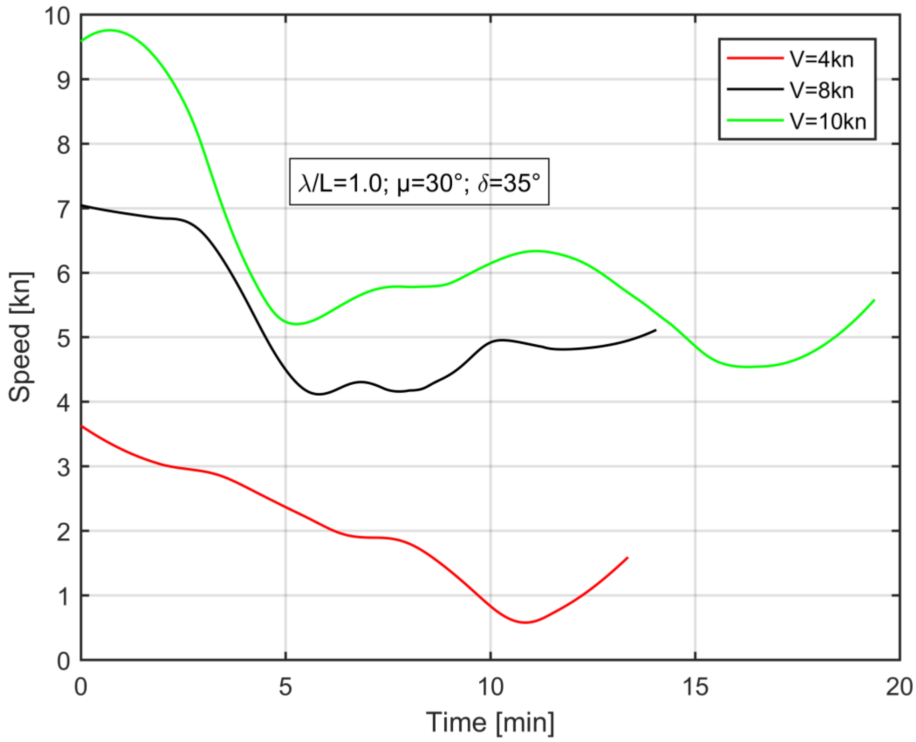

Figure 6 Speed reduction μ = 30°.

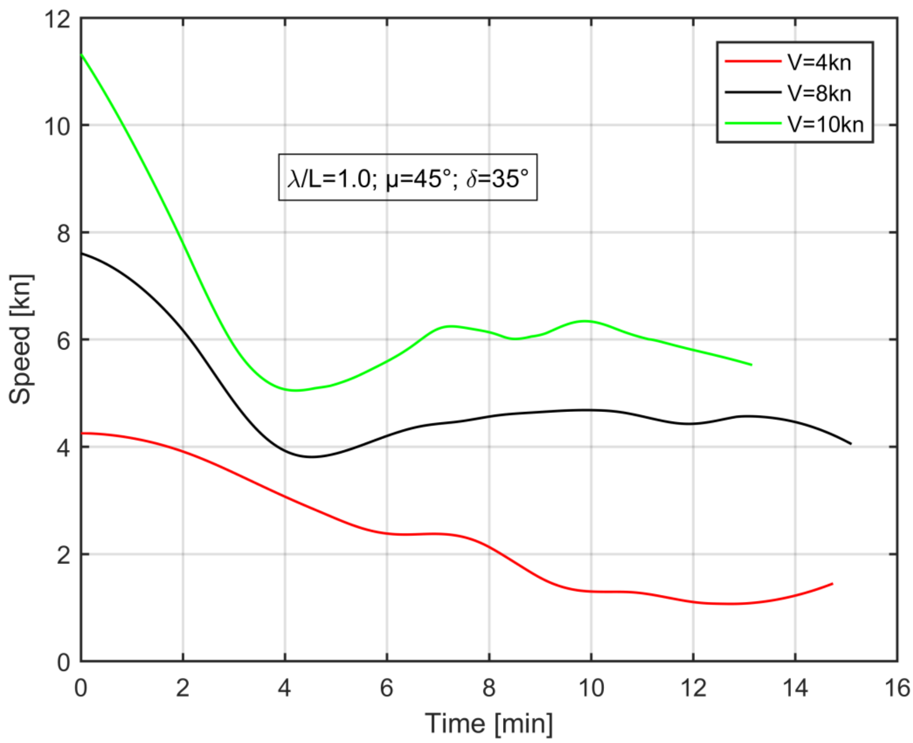

Figure 7 Speed reduction μ = 45°.

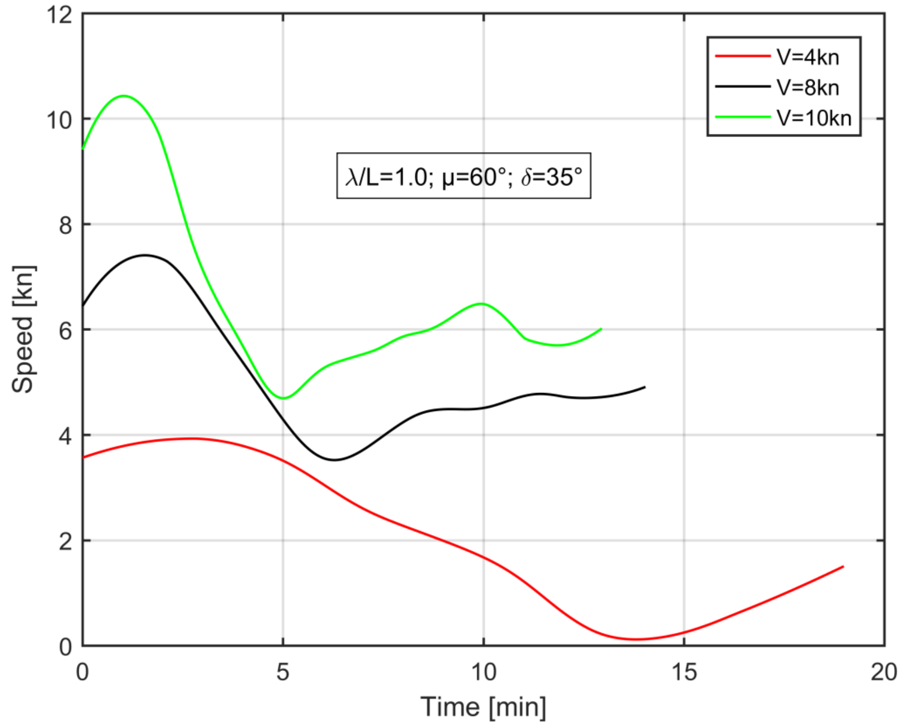

Figure 8 Speed reduction μ = 60°.

4.2 Effect of wavelength

To study the influence of wavelength on the parameters of the steered motion, the initial turning maneuvers were implemented, the trajectories of which are given in **Figures 9 - 11**. It seems that, in short waves, the rate increase is slower; that is, the angular velocity is lower.

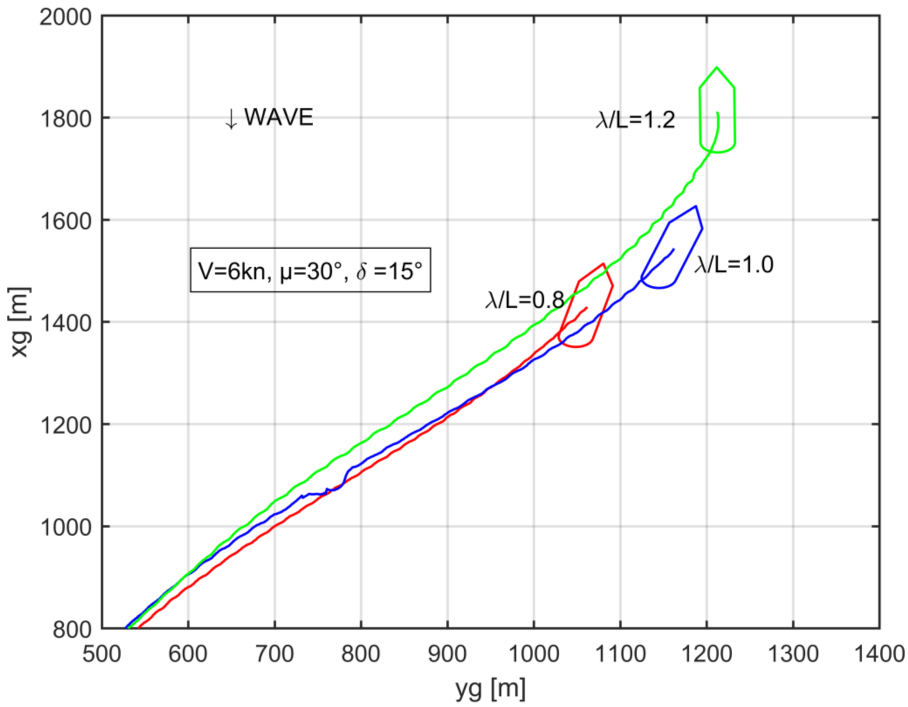

Figure 9 Initial path at λ/L = 0.8, 1.0, 1.2, μ = 30°.

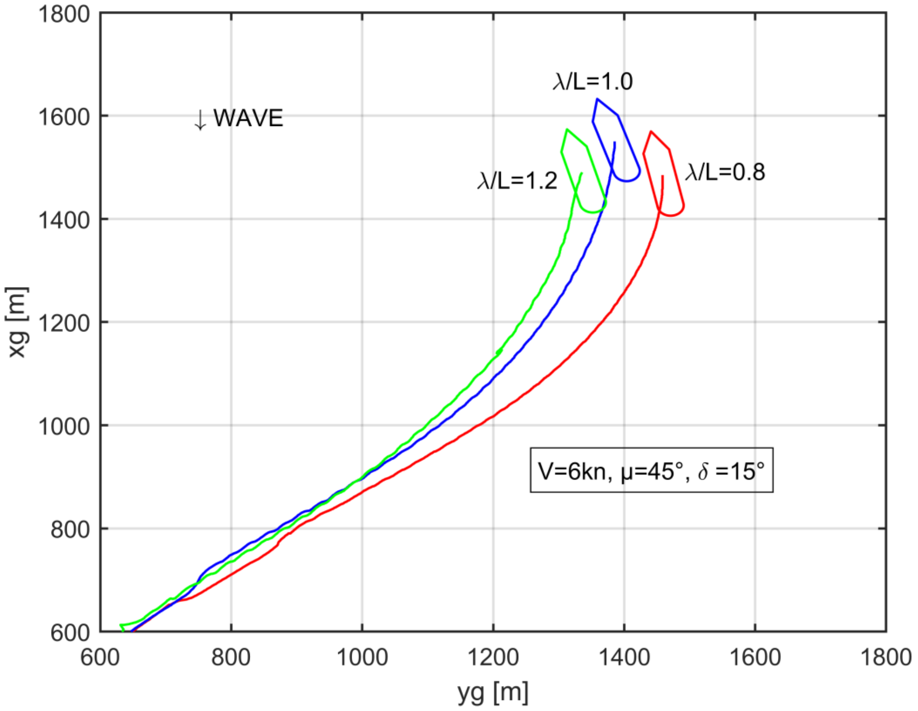

Figure 10 Initial path at λ/L = 0.8, 1.0, 1.2, μ = 45°.

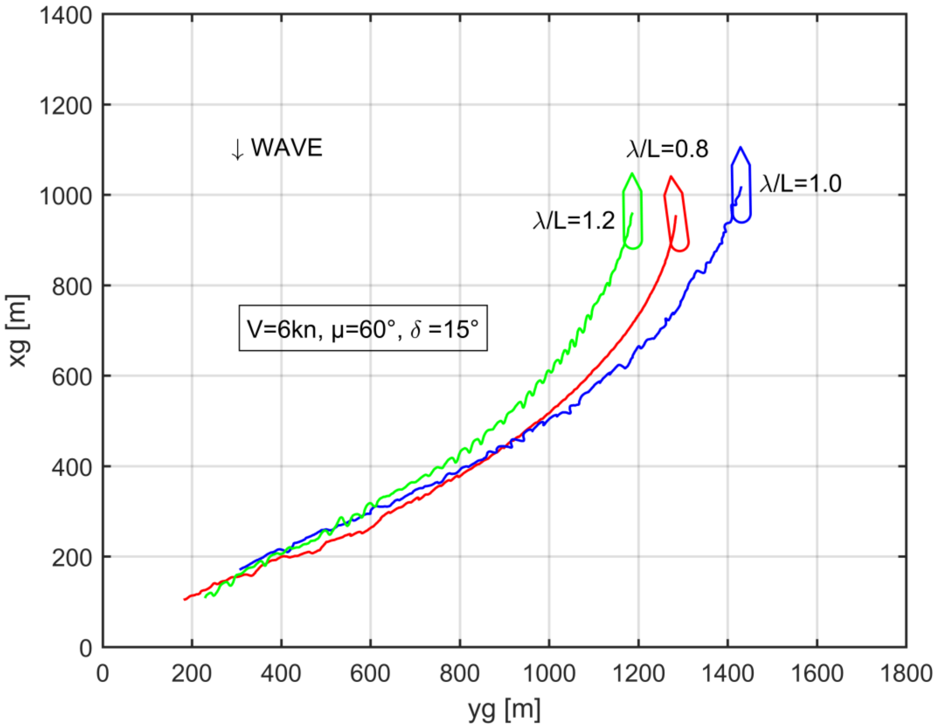

Figure 11 Initial path at λ/L = 0.8, 1.0, 1.2, μ = 45°.

Estimation is supported by the corresponding time characteristics of the yaw rate (**Figures 12 - 14**). The yaw rate development is higher in the case of long waves.

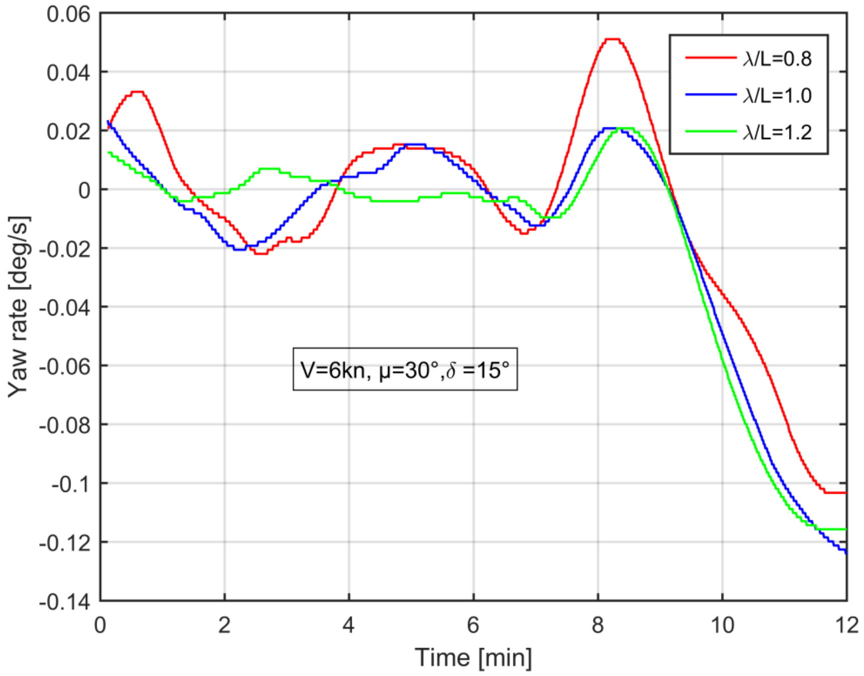

Figure 12 Yaw rate in turn at λ/L = 0.8, 1.0, 1.2, μ = 30°.

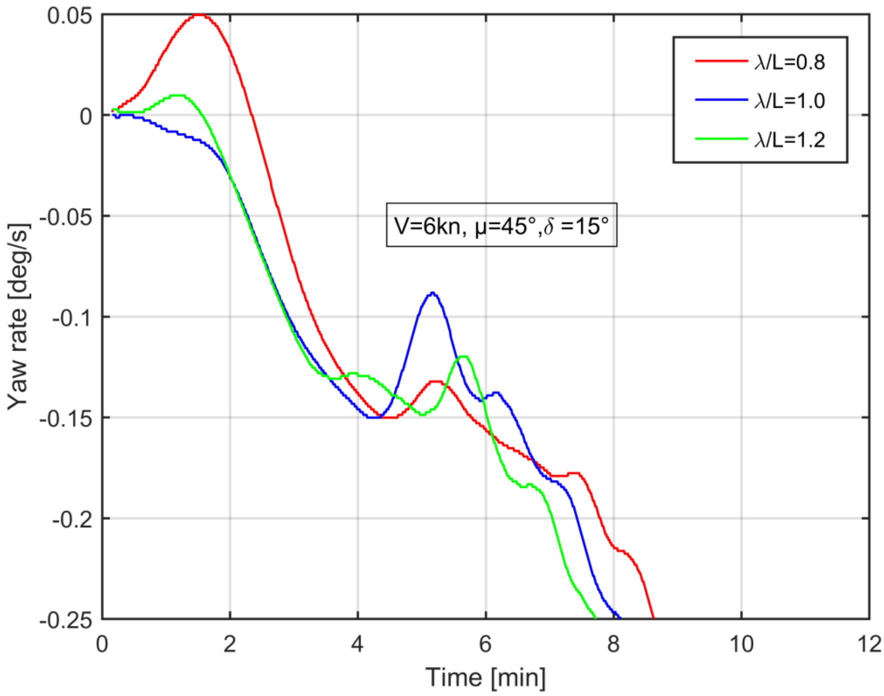

Figure 13 Yaw rate in turn at λ/L = 0.8, 1.0, 1.2, μ = 45°.

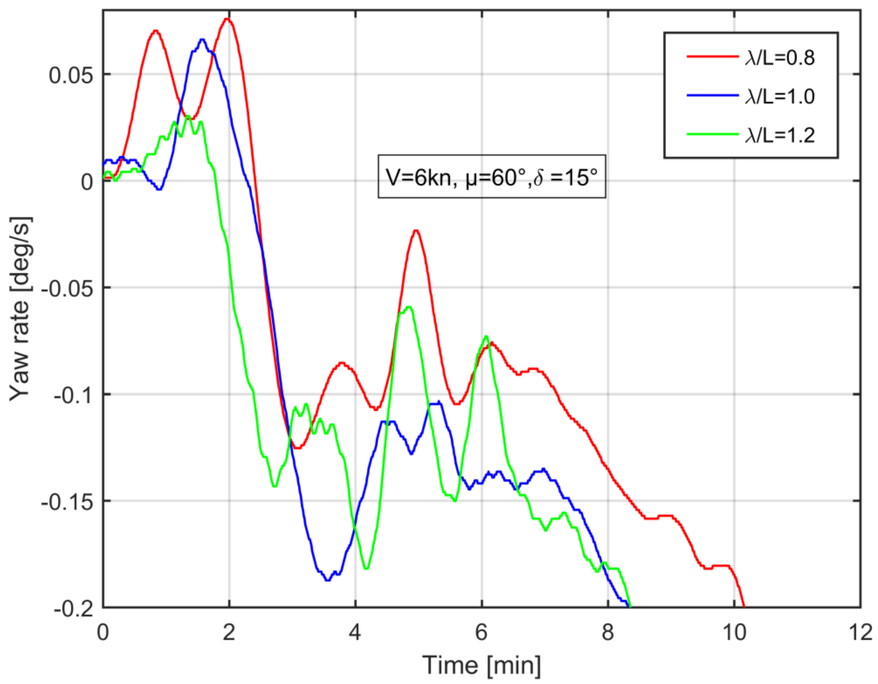

Figure 14 Yaw rate in turn at λ/L = 0.8, 1.0, 1.2, μ = 60°.

4.3 Effect of wave encounter angle

One of the significant factors in ship maneuvering in waves is the angle of encounter. The cases of entry into turning at values of μ = 30°, 45°, and 60° were investigated experimentally for the set of initial forward speed. The relevant resulting trajectories are illustrated in **Figures 15 - 17**.

The analysis of the graphs shows the following features:

- at the speed of 4 knots, for all speeds investigated, the turning motion became uncontrollable due to the prevailing effect of the mean wave drift force and yaw moment
- deviation from the initial course is more pronounceable at a 30° wave encounter angle for all speeds considered
- deformation of the trajectory is at maximum at a low speed of 4 knots
- running with 8 and 10 knot initial speeds, it is possible to make a turn with a 35° rudder in specified wave conditions.

4.4 Effect of rudder angle ordered

The required steering angle values for entry at very low speed were examined for the case of 4 knots. The response of the ship is shown in **Figure 18**.

It is very clear that only at maximum steering angle is turning possible, which is valid for the predominant number of low-speed cases. With the constant initial parameters of the test- wave encounter angle, speed, and wavelength- the result was expected, because the steering force depends only on the effective rudder angle, which did not reach stall value. By this, it can be emphasized that the perception of the maximum rudder angle of 35 in this study is not very sustainable. A margin of 5 degrees should be accepted, and a value of 30, for example, should be considered, even if we are assuming an idealized case of regular wave action.

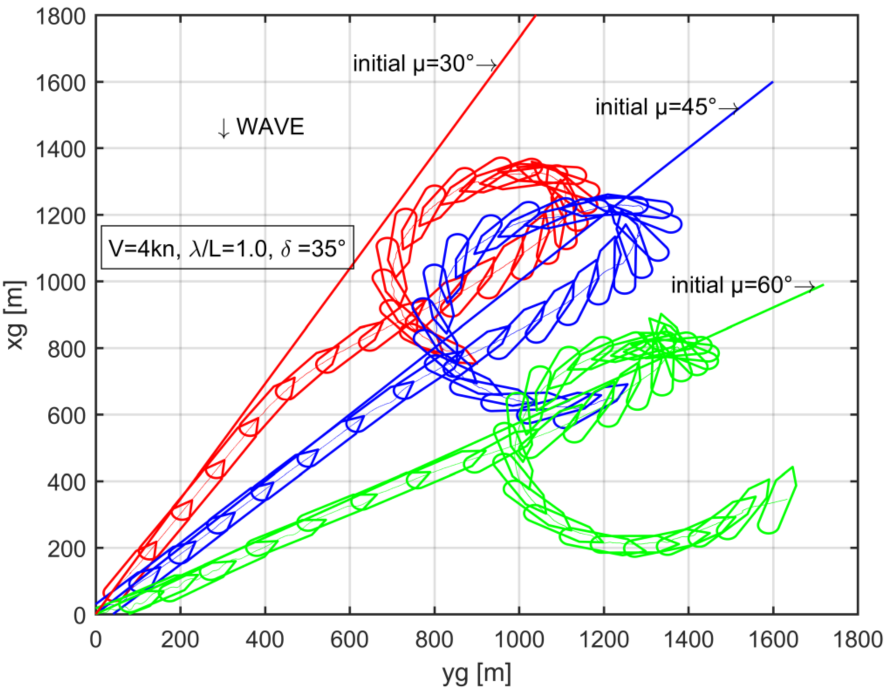

Figure 15 Trajectories at $V = 4$ kn, $\mu = 30°$, $45°$, $60°$.

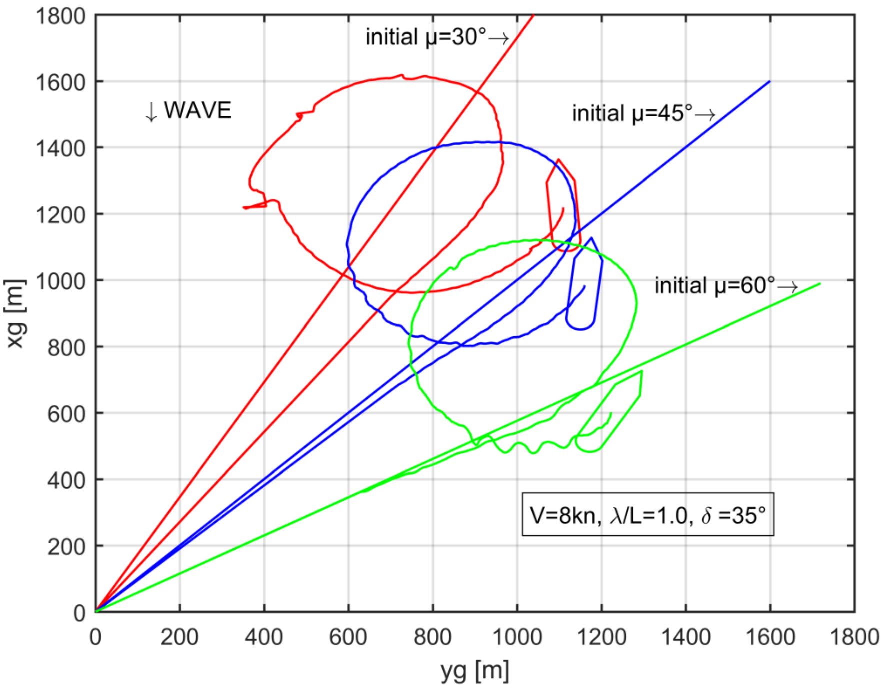

Figure 16 Trajectories at $V = 8$ kn, $\mu = 30°$, $45°$, $60°$.

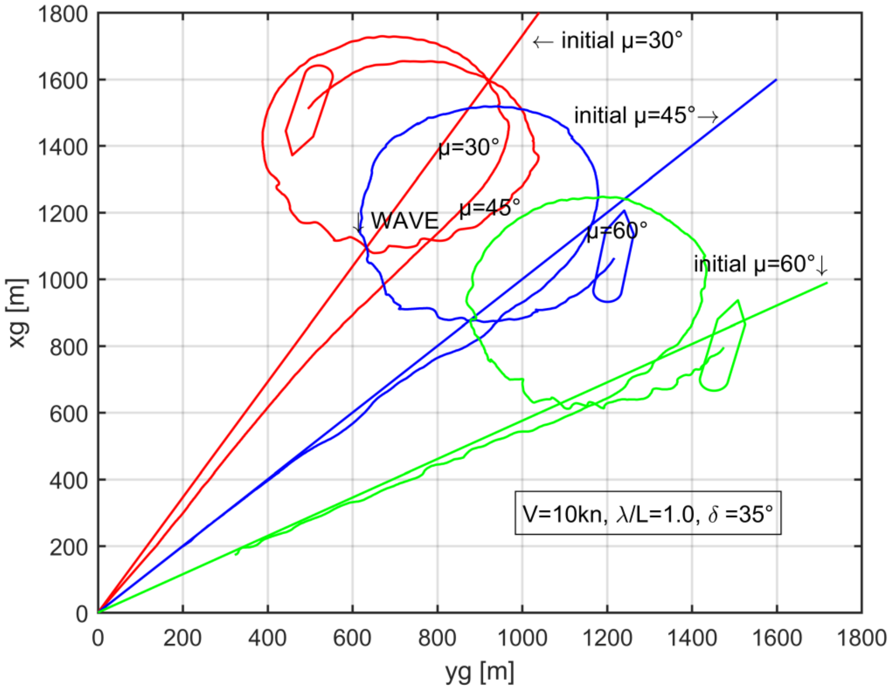

Figure 17 Trajectories at $V = 10$ kn, $\mu = 30°, 45°$.

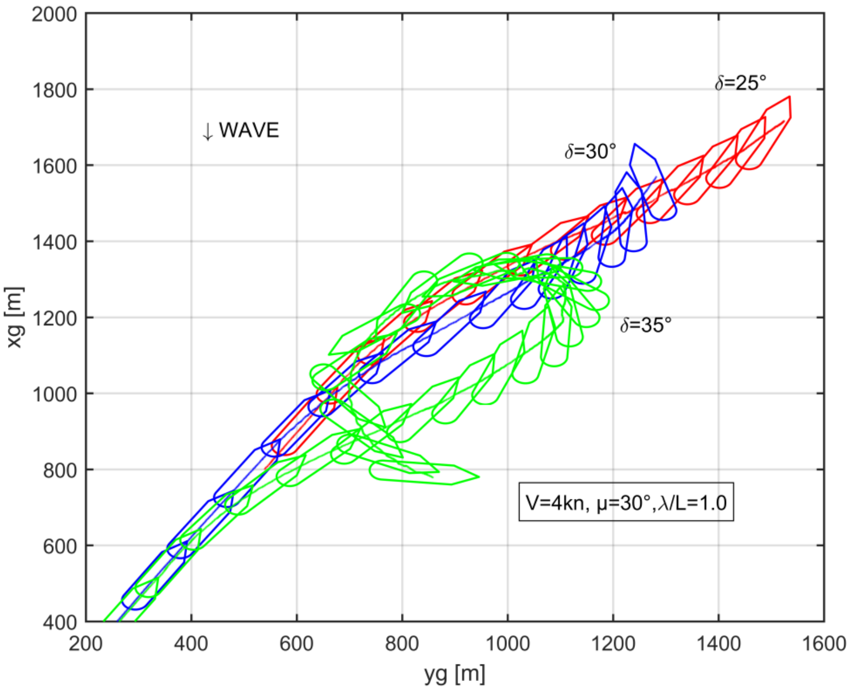

Figure 18 Initial turning with δ = 25°, 30°, 35°, $V = 4$ kn.

5. Brief analysis of KCS initial turning ability in regular waves

Regarding the criteria for vessel maneuverability in waves, as mentioned, a year ago, an approach was proposed by some Japanese scientists to assess ship maneuverability in severe sea conditions, which consisted of the introduction of 2 indicators: ship turning in wave drifting distance and related drifting angle. Later, many authors applied this method (Lee et al., 2009; Milanov et al., 2014; Kim et al., 2019). The first index is related to the distortion of vessel trajectory during maneuvers under consideration, expressed as magnitude of the vector between 2 ship positions for a pair of consecutive cumulative headings, i.e., < 360° - 720° >, < 720° - 1080° >, etc. The second index is related to the vector direction between these 2 ship positions, which in some studies is considered with the wave encounter angle μ. However, there are several considerations related to the implementation of this approach, namely:

- although the method is relatively simple, the processing of the experimental data is quite difficult
- the acquisition of the data is related to the long-term model turning motion in wave conditions, which requires a relatively large-size basin compared to those available in the research centers
- last but not least, this type of maneuver does not have much practical value in ship handling, because one of the main goals in the scenarios under consideration is to change course to achieve a favorable ship position on the wave propagation direction. Because of the latter conclusion, we consider it very important to investigate and normalize the ability of a ship to change course and maintain a new one in adverse sea conditions. Therefore, the initial course change, which is an entry into turning at different wave encounter angles at reduced speeds and for a set of sea states, should be one of the tasks.

The IMO (2002) *Standards for Ship Maneuverability* criteria are valid for calm water conditions and are used below for reference only.

In this study, for comparative analysis of the influence of external conditions on low-speed initial maneuvers in waves, the NATO team-developed criteria for ship maneuvering in waves, STANAG 4721 (2011), were applied. By definition, the STANAG criterion- initial turning time in waves *ta*- is related to the time to change course to a certain check value at a given rudder angle.

The basis for this choice is the following arguments:

- the rate of ship course response to steering action is of interest
- the criterion should be simple
- the method of estimating and related benchmarking (by model tests or full-scale trials) must also be accessible and possible.

To estimate the value of the above criterion, we provisionally introduced 2 cases of rudder/course ratios: *ta10* for the case δ/ψ = 15°/10° and *ta20* for δ/ψ = 20°/20°, as check values for the steering angle and the course. For the first case, the experimental data were processed in the following test conditions:

- three cases of wave encounter angles: μ = 30°, 45°, and 60°
- three relative lengths of regular wave: λ/L = 0.8, 1.0, and 1.2, with wave slope s = 0.02
- three speeds: V = 6, 8, and 10 knots; parameter L/V, that took into account the influence of the speed.

The results of the estimations of *ta10* values for different regular waves are given by **Figures 19 - 21**.

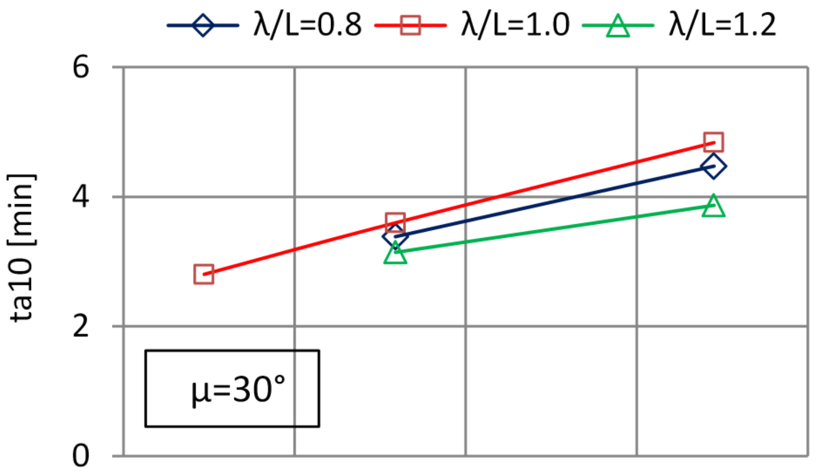

Figure 19 Index *ta10* versus *L/V*, $\delta = 15°$, $\mu = 30°$.

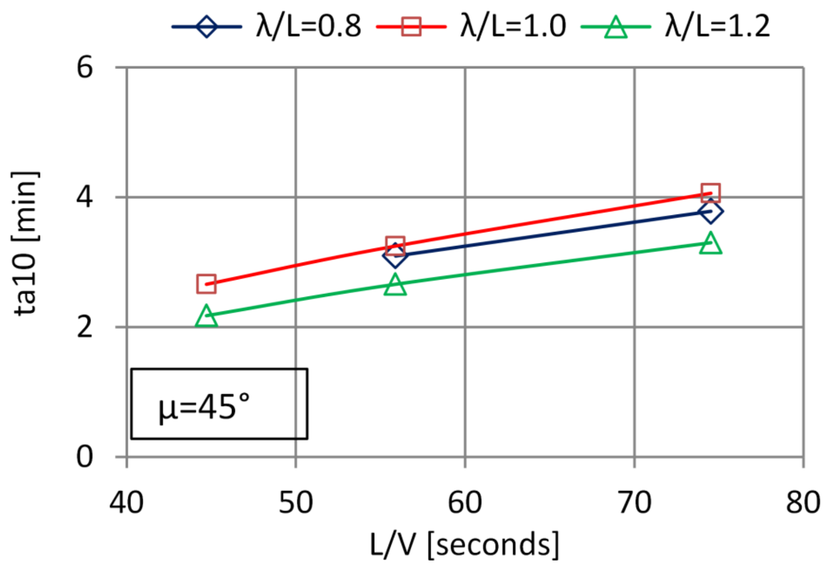

Figure 20 Index *ta10* versus *L/V*, $\delta = 15°$, $\mu = 45°$.

As can be seen, the behavior of the investigated dependencies is quite stable. From the graphs, it follows that, with speed increase, the time required to reach the normalized value of the course (*ta10* in this case) decreases. The conclusion is that the influence of the encounter angle is negligible, while the wavelength is predominant. As is well known, the wave drift forces are greater in short waves.

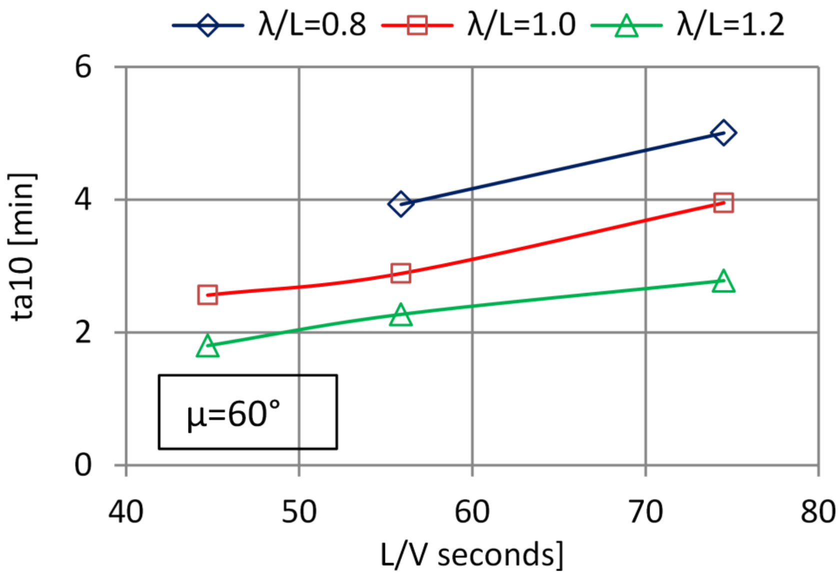

Figure 21 Index *ta10* versus *L/V*, δ = 15°, μ = 60°.

For the second case, when initial turning time index *ta20* is used, the test results for the relative wavelength of 1.0 were processed. The graphical illustration of the dependency of the initial turning time is shown in **Figure 22**. In the graph, the limit value according to the IMO (2002) requirement for calm water is given for information only.

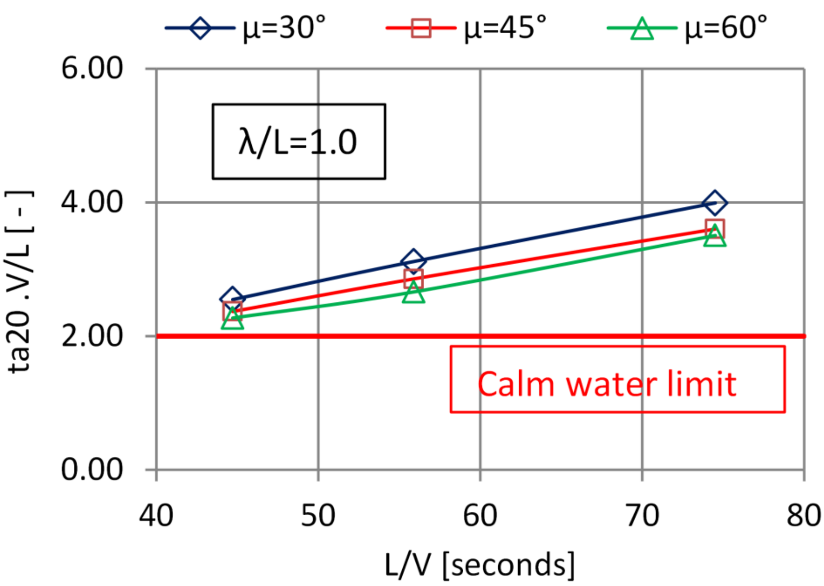

Figure 22 Index *ta20* versus *L/V*, μ = 30°, 45°, 60°.

Similar to the first case, the time required to reach the set course is shorter for long waves at higher speeds.

6. Conclusions

The main results of this study can be summarized as follows:

- as expected, the effect of linear velocity in the initial period of the turning motion is significant
- at 4 knots, the speed under the considered conditions of regular waves means it is impossible to change the course
- short wave influence on the initial turning characteristics are more pronounced compared with long wave influence
- a simple criterion for the assessment of ship capability to change course in wavy conditions was formulated. This approach can be applied for description of turning maneuver dependency on speed and wave encounter angle, indicating critical combinations and, correspondingly, including the results in a "Maneuvering Information" booklet.

We consider the experimental data obtained to be valuable for the benchmarking of numerical simulations of KCS maneuvers in regular waves. Besides the benchmarking of CFD simulations, the approach can be developed in the field of research and the formulation of criteria for ship steerability in waves.

Acknowledgments

This work was performed under the BSHC research project B201106 "Ship Maneuvering in Waves and Wind". The authors are grateful for the assistance of the experimental team involved in the project.

References

IMO Resolution MSC.137(76). (2002). IMO Standards for Ship Manoeuvrability.

IMO MEPC.203(62). (2011a). *Amendments to the annex of the protocol of 1997 to amend the international convention for prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto.*

IMO MEPC 62/INF.21. (2011b). *Minimum propulsion power to ensure safe manoeuvring in adverse conditions.*

IMO MSC-MEPC.2/Circ.11. (2012). *Interim guidelines for determining minimum propulsion power to Maintain the manoeuvrability of ships in adverse conditions.*

IMO Res. MEPC.232(65). (2013). *Interim guidelines for determining minimum propulsion power to maintain the manoeuvrability in adverse conditions.*

IMO MEPC 75/6/3. (2019). *Finalization of the revised 2013 interim guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions.*

Kim, D. J., Yuna, K., Park, J. Y., Yeoa, D. J., & Kim, Y. G. (2019a). Experimental investigation on turning characteristics of KVLCC2 tanker in regular waves. *Ocean Engineering, 175*, 197-206. doi:10.1016/j.oceaneng.2019.02.011

Kim, D. J. (2019b). *Initial and steady turning characteristics of KRISO Container Ship (KCS) in regular waves*. In Proceedings of the 5th MASHCON Conference (pp. 230-239). Ostend, Belgium.

Kim, D. J., Yun, K., Choi, H., Yeo, D. J., & Kim, Y. G. (2019c). *Turning characteristics of KVLCC2 tanker in long-crested irregular head waves*. In Proceedings of the 6th International Conference on Advanced Model Measurement Technology. Rome, Italy.

Lee, S. K., Hwang, S. H., Yun, S. W., Rhee, K. P., & Seong, W. J. (2009). *An experimental study of a ship manoeuvrability in regular waves*. In Proceedings of the International Conference on Marine Simulation and Ship Maneuverability 2009 (pp. 518-527). Panama.

Milanov, E., Chotukova, V., Efremov, D., & Stern, F. (2014). *Systematic experimental investigation of maneuvering characteristics of free running Delft372 Catamaran in still water and* *regular waves*. In Proceedings of the 30th Symposium on Naval Hydrodynamics. Hobart, Australia.

North Atlantic Treaty Organization (NATO) Standard STANAG 4721. (2011). *Common Framework for Naval Surface Ship Manoeuvring Performance and Requirements*.

SHOPERA (Energy Efficient Safe SHip OPERAtion) Project. (2016). Retrieved from https://cordis.europa.eu/project/id/605221

Shigunov, V., & Papanikolaou. (2014). *Criteria for minimum powering and manoeuvrability in adverse weather conditions*. In Proceedings of the 14th International Ship Stability Workshop ISSW. Kuala Lumpur, Malaysia. doi:10.1080/09377255.2015.1104090

Shigunov, V. (2018). *Assessment of manoeuvrability in waves*. In Proceedings of the 32nd Symposium on Naval Hydrodynamics. Hamburg, Germany. doi:10.5957/JOSR.09180048

SIMMAN'2019. (2019). *Workshop on verification and validation of ship manoeuvring simulation methods*. Retrieved from http://www.simman2019.kr

Sprenger, R., Hassani, V., Maron, A., Delefortrie, G., Zwijnsvoorde, T., Cura-Hochbaum, A., & Lengwinat, A. (2016). *Establishment of a validation and benchmark database for the assessment of ship operation in adverse conditions*. In Proceedings of the 35th International Conference on Ocean, Offshore & Arctic Engineering. Busan, South Korea. doi.org/10.1115/OMAE2016-54865

Sprenger, F., Maron, A., Delefortrie, G., van Zwijnsvoorde, T., Cura-Hochbaum, A., Lengwinat, A., & Papanikolaou, A. (2017). Experimental studies on seakeeping and maneuverability of ships in adverse weather conditions. *Journal of Ship Research, 61*(3), 131-152. doi:10.5957/JOSR.170002

Ueno, M., Nimura, T., & Miyazaki, H. (2003). *Experimental study on manoeuvring motion of a ship in waves*. In Proceedings of the International Conference on Marine Simulation and Ship Maneuverability 2003. Kanazawa, Japan.