A Proposal for Standard Manoeuvres and Parameters for the Evaluation of Inland Ship Manoeuvrability

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Received: July 30, 2014.

ABSTRACT

Inland ship manoeuvrability has more complex features than that of sea-going ships due to constrains of inland waterways and complicated ship configurations. In order to clarify the complexity of manoeuvring, impact factors of navigation environment and ship particulars are first analysed to point out the determinants for evaluation. After reviewing existing standards of testing manoeuvres and criteria, it is concluded that there is a lack of knowledge to develop design guidance for manoeuvring in shallow/restricted water, which is the common sailing condition for inland vessels, making a proper evaluation more difficult. For the purpose of achieving more realistic judgement on manoeuvrability, benchmark manoeuvres are proposed for discussion. Conclusions are drawn on the need of validation for the effectiveness of testing manoeuvres and elaborate manoeuvring criteria for inland vessels.

Keywords: inland vessel manoeuvrability criteria, standard ship manoeuvres, manoeuvring capacity evaluation

1. INTRODUCTION

Primarily, ships are designed from an economical point of view focusing on the transport efficiency and construction cost, but manoeuvrability, including the capability of inland navigation on lakes, rivers and artificial waterways which are limited in size by width and depth of the channel, is also very important. In order to ensure navigation safety and smooth traffic, standard manoeuvres and parameters are needed for manoeuvrability prediction and evaluation to distinguish inappropriate ships before constructions.

However, impact factors on inland ship manoeuvres that correspond to limited channel breadth and shallow water are more or less ignored in initial ship design. David Clarke (2009) has claimed: “The difficulties of considering the ship behaviour in shallow water have so far been ignored, on the understanding that if the ship is made better in deep water then it is likely that some of its behaviour in shallow water will also be better”. Considering the differences between inland waterways and the open sea, a specific system of manoeuvrability evaluation methods for inland vessels, which is proposed to be different in testing manoeuvres and criteria, appears to be desirable.

Also, standard parameters and manoeuvres for design and testing of inland ship manoeuvrability are still not as elaborate as the IMO standards (International Maritime Organization, 2002a, 2002b) for sea-going ships. There is also a doubt on the effectiveness of existing testing methods to ensure a good manoeuvrability. For instance, good results for 20° zigzag tests may be achieved by a ship with poor manoeuvring capabilities. This leads to bad judgement on ship manoeuvrability (Y Yoshimura, Kose, & Hiraguchi, 2000). Thus, new guidance and criteria are needed for inland vessels to ensure good manoeuvrability for navigation safety.

This paper presents the state-of-the-art for standards for evaluation of inland vessel manoeuvrability. A discussion on the impacts of navigation environment and ship configurations is given in Section 2 to highlight the important parameters for manoeuvrability research. In Section 3, the testing manoeuvres and related standards are reviewed to find the gaps in knowledge regarding benchmark manoeuvres and specific criteria. After that, new benchmark manoeuvres are proposed for discussion in Section 4. Lastly, conclusions are drawn in Section 5.

2. IMPACTS ON INLAND VESSEL MANOEUVRABILITY

In order to judge the ship's manoeuvring capabilities, the navigation environment should be clarified according to the target waterways. Thus, the features of inland channels, such as shallow waters and narrow channels, are analysed first to find constraints and boundary conditions on ship manoeuvrability in Subsection 2.1. After that, ship configurations that are considered to compensate for the negative disturbances from navigation environment are discussed in Subsection 2.2.

2.1. Impacts of navigation environment

Due to the complexity of the navigation environment, inland waterways are commonly more susceptible to marine accidents than open seas. Meanwhile, inland ship accidents may also lead to heavy losses owing to the lengthy blockage of the whole channel in inland water transport. To point out the main impacts of the navigation environment on inland vessel manoeuvring, two specific navigation areas in the River Rhine are presented, namely the Lorelei rock in Germany and complex a T-junction near Nijmegen in the Netherlands.

As an example of natural sailing environment (Fig. 1), the narrow bend and strong currents caused by the Lorelei rock have serious impacts on ship manoeuvrability. In Fig. 2, the T-junction of the River of Rhine and the Mass-Waal Canal in Nijmegen shows the complexity of the inland navigation environment and heavy traffic in a combination of straight channels, bent channels, confluence of channels, terminals, and harbour basins. All the ships passing these areas have to be qualified with sufficient manoeuvring capabilities to ensure safe navigation.

The depth of water and the width of channels also limit the navigation environment. The shallow water effects are often considered as less important in ship design for sea-going ships because they do not often sail in shallow waters. While in fact, the smaller water depth to draft ratio ($1.5 < H/T < 3$) for inland vessels may significantly affect the turning and stopping abilities due to the change of hydrodynamic forces and different propeller/rudder efficiency (Koh & Yasukawa, 2012).

Another two impacts of the constrained conditions are the stronger ship-ship and ship-bank interactions. Due to the asymmetrical flow caused by ships sailing in the close proximity of the other ships, lateral forces and yaw moments which seriously affect the manoeuvring performance are induced (Lo, 2012; Vantorre, Verzhbitskaya, & Laforce, 2002). Also, the high traffic density of inland waterways increases the frequency of ship over-taking and passing. In combination with constrained channel width, this raises the concern on the ship-ship and ship-bank interactions.

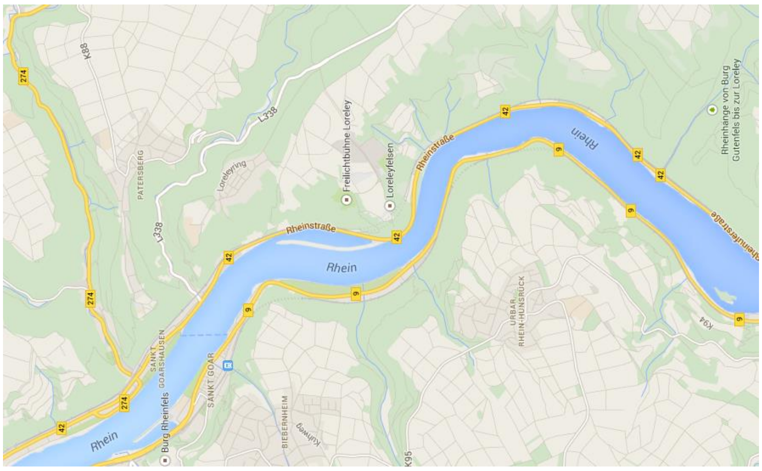

Fig. 1 Narrow bend channel near the Lorelei

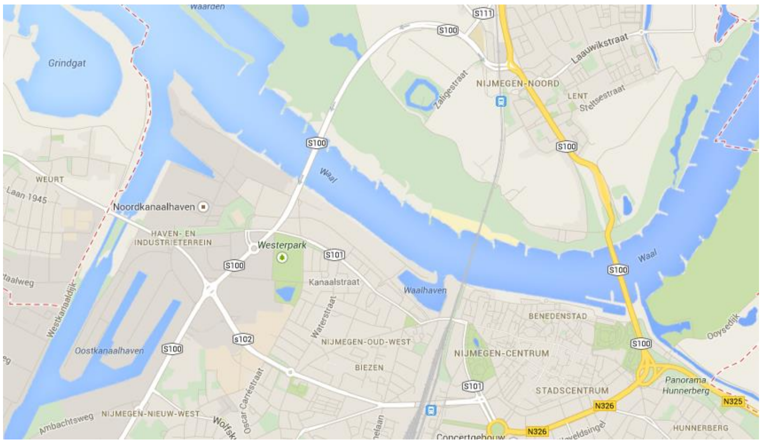

Fig. 2 Complex waterway environment in Nijmegen

Last but not least, unlike open sea, inland waterways are classified as different levels of channels according to the waterway dimensions such as width, water depth and traffic density (European Conference of Ministers of Transport, 1992). Apparently, a lower-level waterway may have more limits than a higher-level waterway, requiring a ship to have better manoeuvring capabilities. Thus, the requirements on inland ship manoeuvrability are proposed to be adapted to each level of the waterway classes. On the other hand, as a consequence of the commonly higher transport efficiency of larger ships compared to smaller ships, it is valuable to discuss the applicability of large vessels in a low level waterway under specific criteria.

In this subsection, the complex navigation environment of the Lorelei rock and that of the Nijmegen area are first presented as extreme examples of inland navigation environments. Inland waterways are roughly described as bendy, busy, shallow, and laterally constrained water. Regarding all these characteristics, the complexity of inland waterways requires more concern on ship configurations to ensure a sufficient level of navigation safety.

2.2. Impacts of ship configurations

Ships are equipped with multiple propulsion and manoeuvring devices. To ensure smooth manoeuvring and compensate for the negative disturbances from navigation environment, an adequate selection of ship arrangements should be made, for example the number of propellers and rudders, to achieve a balance between manoeuvring performance and cost.

Inland vessels are commonly designed with a large block coefficient and high width/ draft ratio in order to carry more cargo. As the ship width and draft are constrained by the waterways, the range of block coefficient among inland vessels is limited between 0.8 and 0.93, while those for sea-going ships between 0.4 and 0.85. On the other hand, inland vessels commonly sail at relatively slow speed around 5~15 knots compared to 10~25 knots for sea-going ships, affecting the hydrodynamic forces for manoeuvring performance (Yasuo Yoshimura & Sakurai, 1989). The blunt inland vessels at low cruise speed may perform better at turning related manoeuvres but worse at course keeping.

To improve the propulsion efficiency, inland vessels are commonly equipped with a hull tunnel in front of the propeller. These tunnels are useful to improve the propeller inflow as well as affecting the hull generated hydrodynamic forces and moments. However, the impacts of these tunnels on resistance and manoeuvring are still unclear. A more elaborated representation of the hull generated hydrodynamic forces and moments is needed to obtain a more accurate prediction of manoeuvrability.

Rudders are crucial to ship manoeuvring for starting and correcting manoeuvres. The span of inland vessel rudders is constrained by the draught which is limited by the water depth, thus the rudder chord is increased resulting in a small aspect ratio around 1 compared to a value of 2 for sea-going ships (Kim, Kim, Oh, & Seo, 2012). To generate sufficient turning forces, inland vessels are commonly designed with multiple rudders per propeller to increase the total rudder area (shown as Fig. 3). Additionally, inland rudders feature a much wider range of rudder profiles, as well as end plates to obtain better performance in changing the flow direction.

Fig. 3 An inland vessel equipped with 4 rudders and twin propeller

Characteristics of inland vessel configurations are compared to those of sea-going ships in this section. Among the differences are higher block coefficients, larger width to draft ratios, lower speed, and multiple rudders per propeller. The complexity of inland vessel configurations due to the various options of rudders, propellers, and hull form has been made clear. On the condition that most of the research is done for deep water, it is the necessary to adjust the existing hydrodynamic force prediction methods and manoeuvring models for inland vessels to shallow/constrained condition. Overall, the differences between inland navigation and sea-going navigation are made clear. Therefore, distinguish features of manoeuvrability testing and requirements are reasonably desirable.

3. STANDARDS OF MANOEUVRES AND CRITERIA

Considering the impacts on manoeuvrability discussed in the last section, the standards of ship manoeuvrability for sea-going ships and inland vessels are compared to find the effectiveness of testing methods and related criteria. In order to identify the missing knowledge in prediction and evaluation, a comparison of existing standards is shown in Table. 1.

Table 1： IMO standard manoeuvres and criteria for ship manoeuvrability (Central Commission for the Navigation of the Rhine, 2012; International Maritime Organization, 2002a, 2002b)

Standard Manoeuvres	Tests	IMO Criteria	CCNR Criteria
Turning ability	Turning test with maximum rudder angle (-35°/35°)	Advance < 4.5 L	None
		Tactical diameter < 5 L	
Initial turning ability	10°/10° zigzag test	Distance ship travelled < 2.5 L by the time the heading has changed by 10° from the original heading	
Yaw-checking and course-keeping abilities	10°/10° zigzag test	First overshoot angle:	20°/45° evasive test criteria vary for different ship dimensions
		$< 10^\circ$ ($L/V < 10\mathrm{s}$);	
		$< (5+0.5L/V)^\circ$ ($10\mathrm{s} \leq L/V < 30\mathrm{s}$);	
		$< 20^\circ$ ($L/V \geq 30\mathrm{s}$)	
		Second overshoot angle:	
		$< 25^\circ$ ($L/V < 10\mathrm{s}$);	
		$< (17.5+0.75L/V)^\circ$ ($10\mathrm{s} \leq L/V < 30\mathrm{s}$);	
		$< 40^\circ$ ($L/V \geq 30\mathrm{s}$)	
	20°/20° zigzag test	First overshoot angle $\leq 25^\circ$	Stop distance vary for different ship dimensions
Stopping ability	Full astern stopping	Track reach < 15 L	
		None for head reach	

For now, the most widely accepted criteria for ship manoeuvrability are issued by IMO including turning ability, initial turning ability, yaw-checking and course-keeping abilities, and stopping ability (Table 1). However, these standards are specified for ships longer than 100 m with traditional propulsion systems (propellers and rudders) in deep unconstrained waters. For shorter ships and vessels with other propulsion systems, the current rules are flexible. Also, the hydrodynamic (constrained water), meteorological (wind, wave, and current), navigational (other ships, artificial constructions) impacts are not included.

On the other hand, there are no universal applicable standards for inland vessels. The CCNR standards are only issued for ships on the River Rhine. Meanwhile, regarding the impact factors discussed in Section 2, the standards do not cover all the characteristics of inland ship manoeuvring. Even if a ship satisfies all the required criteria, it is still hard to tell if this ship is capable to safely pass the bendy channel in Lorelei (Fig. 1) or enter the sub channel of Nijmegen (Fig. 2) in any condition. Thus more practice related manoeuvres are needed for manoeuvring evaluation.

After reviewing the existing standards, it is concluded that more specific criteria for different navigation conditions are needed that define the minimum requirements. Furthermore, emergency situations, such as strong wind and waves, need to be studied to predict the manoeuvring capabilities in the worst scenario. Because of the differences in navigation environment and ship particulars between sea-going ships and inland ships, it is proposed to develop new and different standards for the evaluation of inland ship manoeuvrability.

4. BENCHMARK MANOEUVRES FOR INLAND VESSELS

As discussed in the last section, the existing criteria and manoeuvres are not sufficiently elaborate and suitable for inland vessels. As criteria are based on the performance of manoeuvres, revised benchmark manoeuvres are proposed in this section for discussion.

4.1. Hard turning manoeuvre

The classic turning manoeuvre consists of both a starboard and a port turning circle with 35 degree or maximum rudder angle (Fig. 4). The target test parameters are the advance (the distance travelled by the midship when the direction changed 90 degrees from the original course) and the tactical diameter (the distance travelled by the midship when the direction changed 180 degrees from the original course). This kind of manoeuvring tests can give a good representation of the ship’s turning ability. However, the full circle turning test requires so much space that sometimes it is not feasible to be carried out for operation in real inland navigation. Furthermore, it is not a manoeuvre that an inland ship is likely to make.

Inland vessels sail in constrained waterways with limited operational space. Therefore, designers have to take more concern on the manoeuvring space requirement for inland vessels than sea-going ships. Inland vessels are commonly configured with bow thrusters and sometimes with stern thrusters. It is better to take a full turning manoeuvre with the help of those thrusters to save more space. On the other hand, the maximum rudder angle for inland vessels can be set to almost 90 degrees. With the help of multiple rudders, inland ships can redirect most of the propeller outflow fully aside. Thus, with the help of thrusters and multiple rudders, the performance of full circle turning for inland vessels could be quite different from sea-going ships.

Considering the bendy conditions in inland navigation (Fig. 1), the classic turning manoeuvres are proposed to be carried out in different conditions, specifically selfmanoeuvring with rudders and manoeuvring with thrusters. More focus is suggested to be laid on the first quarter of the full turning circle under large rudder angles, named as hard turning manoeuvre, as it is much more related to real navigation. The location of the pivot point, around which the ship is turning, is expressed as a function of the ship speed, acceleration, rudder angle, etc. to give an estimation of the required turning space. With this hard turning manoeuvre, capacity of altering the original course by 60 to 90 degrees at bent channels may be more clearly described.

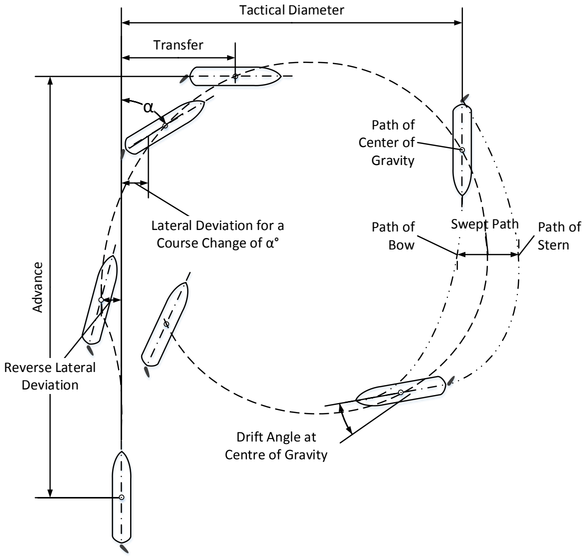

Fig. 4 Turning circle manoeuvre

4.2. T-junction turning

The confluence of Rhine and the Maas-Waal Canal in Fig. 2 is simplified as a T-Junction with an angle α shown in Fig. 5. Either the main channel or sub-channel is ruled by a Traffic Separation Scheme (TSS), which is used to regulate the traffic at busy, confined waterways. The traffic-lanes (or clearways) indicate the general direction of the ships in that zone. Normally, a ship navigating in a TSS should sail in its traffic-lane without disturbing ships in the other lane.

For the T-Junction channel illustrated in Fig. 5, extreme ship trajectories (all possible trajectories trough the T-junction lie within these extremes) are shown in Fig. 6. The purple ships are the start and end position of the manoeuver. The green vessels in the figure are indicated as ships with the worst manoeuvrability, which bring the channel dimension into full play but have the minimum safety margin. In comparisons with the green ones, the blue ships are shown with the best manoeuvrability, however, which may be too sensitive for stable control and energy conservation.

This simplified T-junction turning can give a good representation of the T-junction turning ability. It may also be associated with the hard-turning manoeuvre for estimation of hard turning ability. To achieve suitable manoeuvrability criteria, safety and efficiency should be taken into synthetically consideration. In this case, the optimal trajectory will be found within the range of green and blue lines. This trajectory is performed by a series operation of speed changing, course altering, turning, and course keeping. Each manoeuvring step need to be defined and judged by suitable criteria established through benchmark case study.

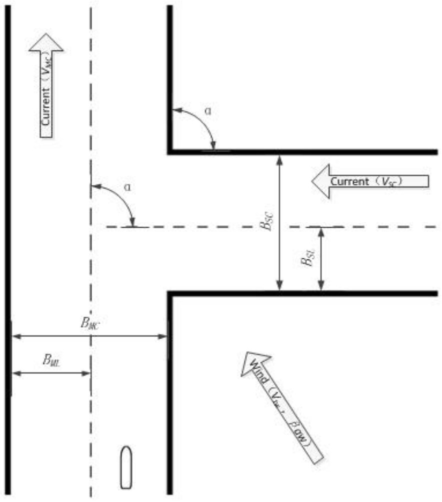

Fig. 5 An illustration of the T-Junction channel of Nijmegen

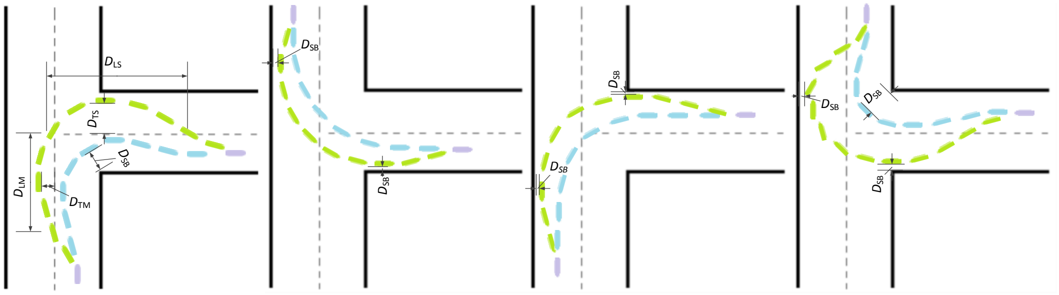

Fig. 6 Turning in the T-Junction channel

4.3. Lane-changing manoeuvre

One of the most important aspects of inland vessel manoeuvrability is the capability to change lanes in ship encountering and overtaking (Dijkhuis, Toorenburg, & Verkerk, 1993). However it is not covered in the existing standards. The capability of changing lanes is related to the initial turning ability and yaw-checking ability, which can roughly be presented by the classic zigzag test. However, the zigzag tests may lead to a wrong estimation of ship manoeuvring performance. The larger overshoot angle may be caused by the larger inertia of large ships or by the larger rate of turn of small ships. New dimensionless criteria are needed to express the course changing ability.

A revised zigzag test and related criteria are proposed by (Dijkhuis et al., 1993), which is based on the change of rate-of-turn. However, it is more realistic to emphasize the capability of a single lane-change or overtaking manoeuvre instead of continuous lane-changing like the zigzag test. An illustration of overtaking lane-changing is shown as Fig. 7. The blue ships represent the overtaking ship, while the purple ones are the positions of the ship being overtaken. The distance before overtaking (D_{BO}), the distance after overtaking (D_{AO}), and lateral distance (D_{LO}) are expressed in dimensionless forms of both ships' properties and parameters of waterways.

Considering the small relative speed in overtaking operations, it is may be less critical than the case of ship encountering. In more serious cases of collision avoidance, ships have to make large course altering to avoid the encountering ship and correct the course as soon as possible to prevent from grounding or a ship-bank collision. In that case, large angle of zigzag tests are needed, for instance 45°/45° zigzag test or even larger. To evaluate the effectiveness of large zigzag tests, further understanding of rudder performance is needed.

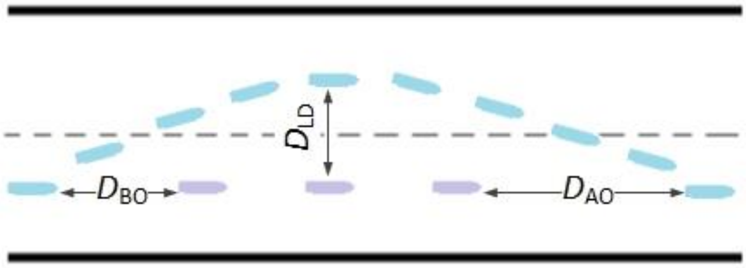

Fig. 7 An illustration of lane change manoeuvre

4.4. Stopping with rudder correction

Stopping ability in a straight channel is important for emergency operation. As the channel is constrained in width, inland ship stopping scenario is different from the sea going one. The basic IMO criterion on stopping ability is that the track reach should be limited within 15 ship lengths (except impracticable cases for large displacement ships) in the full astern stopping test (International Maritime Organization, 2002a, 2002b). In emergency of collision avoidance, sea-going ships commonly choose the more efficient operation of hard turning, while due to the constrain of the waterways, inland vessels have to carry out the crash stop raising up the importance of stopping ability.

For now, there are no criteria for the head reach (L_{HD}) and especially the lateral deviation (B_{LD}) yet, which are more crucial for inland navigation safety (Fig. 8). The Lateral deviation (B_{LD}) determines the distance between the ship and the bank. This distance (D_{SB}) is the dominant factor of the ship bank interaction influencing the safety. In this benchmark case, focus is proposed to be laid on the dimensionless relation of stopping reach and deviation with ship particulars.

In the existing standards, there is no description about the rudder in the stopping test. The rudder angle is commonly regarded as 0 degree during the whole operation, i.e. from the time when the full astern order is given till the ship stops in the water. However, for inland ships, the advance is not the only concern but also the lateral deviation. Thus, the classic stopping test is revised to find the lateral distance as Fig. 9. On the other hand, in order to reduce the lateral deviation, inland vessels have to get the assistance from rudder correction force as the proposed manoeuvre in Fig. 10. In this case, there is the question about when to start this correction rudder order and when to stop it.

In this section, revised manoeuvres, namely hard turning manoeuvre, T-junction manoeuvre, lane-changing manoeuvre, and stopping with rudder correction are proposed to achieve a more realistic judgement of the inland vessel manoeuvring performance. These manoeuvres need to be tested and validated through systematic research in the future.

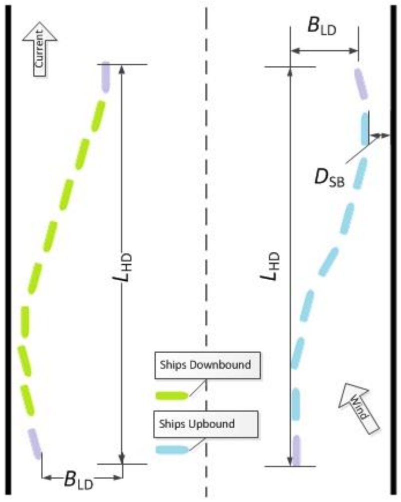

Fig. 8 An illustration of inland vessel stopping test

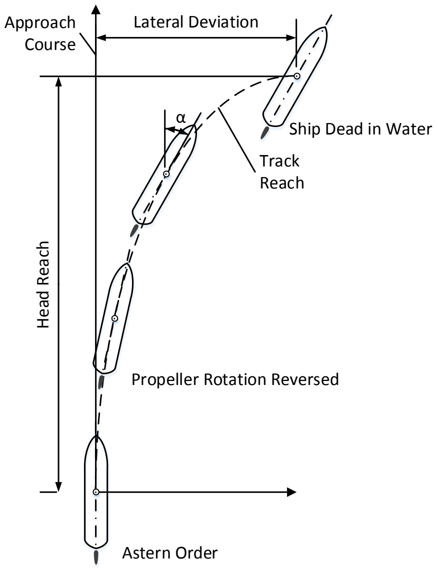

Fig. 9 Crash stopping test

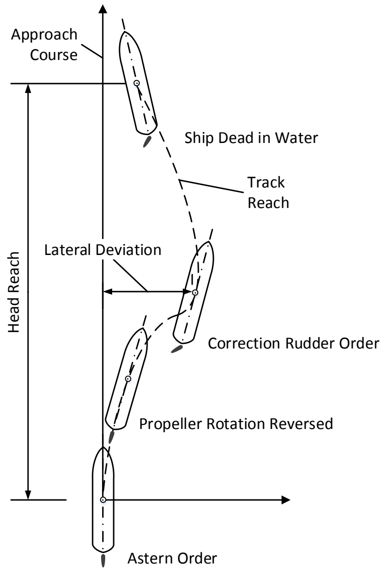

Fig. 10 Crash stopping test with rudder correction

5. CONCLUSIONS

In order to have a further insight of the prediction and evaluation methods on inland manoeuvrability, this paper first analyses the main impact factors on manoeuvring performance. Through this analysis, clear differences are found in the navigation environment and ship configurations between inland vessels and sea-going ships. After that, standards of manoeuvres and criteria on ship manoeuvrability are compared. There is a lack of knowledge of suitable manoeuvres to evaluate the manoeuvring performance of inland ships in real-world navigation. Therefore, new benchmark manoeuvres are proposed for further discussion. After all, following conclusions are drawn:

- Compared with sea-going ships, the navigation environment and ship configurations for inland vessels are clearly more complex. The most crucial factors are the shallow water effects and multiple rudder/propeller configurations.

- Manoeuvring criteria for inland vessels should be adapted according to the waterway level and specified with ship configurations. It is not appropriate to issue uniform criteria for all kinds of inland vessels. More concerns are needed for the applicability of larger ships in lower level of waterway class.
- Considering constrains of inland waterways, it is proposed that the classic manoeuvres are revised for the characteristics of inland navigation. Innovative manoeuvres are needed to evaluate the manoeuvring performance in more realistic cases.
- The effectiveness of existing manoeuvres needs to be discussed. There is also the need of more concern on the validation of the proposed manoeuvres in this paper.
- More study is suggested to be drawn on the hydrodynamic features of inland vessels in shallow water condition to improve the accuracy of manoeuvring prediction.

For the future, modifications of rudder modelling will be done for multiple rudder/propeller configurations to have a more accurate estimation of rudder forces and moments. The manoeuvring prediction models can be updated with the help of the revised rudder models. After that, the revised manoeuvres can be tested and validated. These are the next research topics for the authors.

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