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Wheel over point mathematical model

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Abstract. This research proposes an improved mathematical model which can be used to calculate wheel over point (WOP) for a ship's route optimisation. WOP is a marking made on the charted course to demonstrate where the ship must initiate the course alteration to guarantee that it follows the route. The advance transfer technique (ATT) was used to determine WOP. Through practical exercise, two gaps were identified in ATT. From there, an improved mathematical model, namely ATMM, were developed. A preliminary manoeuvring analysis was then carried out in this study using a ship simulator for ATMM and the existing ATT. Then, the cross-track distance produced by both methods were compared to verify the difference. It was found that the ATMM produced better result in maintaining a ship on its course. This research's mathematical model is expected to be used onboard ship and used in the Electronic Chart Display and Information System to aid navigator in making more effective course alteration.

Keywords: cross track distance; manoeuvring analysis; passage planning; ship simulation; wheel over point

1. Introduction

It is essential for a ship to navigate by following one course line to another course line connected by waypoints (WPT), according to the ship's bridge team's agreed passage plan (Lušić *et al.* 2014, Skora and Wolski 2016). As shown in Fig. 1, the charted course is the course line drawn on the navigational chart connected by waypoints (ICS 2016, IMO 1999). WPT is where two different course lines are connected (ICS 2016, Skora and Wolski 2016, Swift 2018). When changing a course, alteration needs to be carried out at an ample distance, otherwise, the ship can overshoot from the track (Vujičić *et al.* 2018), which can result in a cross-track distance (XTD) (Lekkas and Fossen

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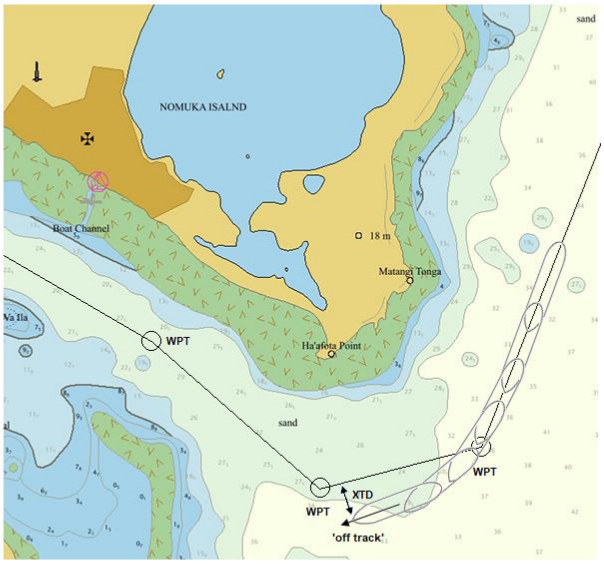

Fig. 1 Illustration for a charted course, WPT, and XTD

Table 1 WOP distance from WPT

Situation	Change of course (θ)	Advance (d_{adv})	Transfer (d_{trs})	$d_{CG\text{-}WPT}$
1	20°	0.24	0.108	- 0.057
2	50°	0.24	0.108	0.149

2014). The cross-track distance can bring a ship closer to land and expose the ship to danger (Briggs *et al*. 2003, Kristić *et al*. 2020). Thus, a wheel over point (WOP) or altering course (AC) position needs to be marked on the charted course as an indication of the point of alteration (Georgiana and Stefan 2010, Rutkowski 2018).

Although the purpose is the same, WOP and AC have slightly different definitions. WOP is a point where the rudder is set at maximum rudder angle (Anwar 2015), while AC position can be executed at any rudder angle for an alteration of course (ICS 2016). Both techniques contribute to energy efficiency in terms of fuel consumption (Chaal 2018) as they optimise the vessel's voyage in maintaining optimum route (Lu *et al*. 2015, Tiwari *et al*. 2020). Most importantly, these techniques can ensure the safety of the ship's navigation by maintaining the ship on its track (Vujičić *et al*. 2018).

1.1 The problem statement and research aim

The advance transfer technique (ATT) is a technique used to find WOP (Anwar 2015). To further understand the ATT usage, a practical exercise was carried out on a navigational chart in this study. During the practical session, two problems were identified.

1.1.1 The first observation – Negative value for alteration less than 20°

The formula for ATT that was proposed by Anwar (2015) is shown in (2). Below is an example of the calculation of WOP for 20° and 50° course alteration.

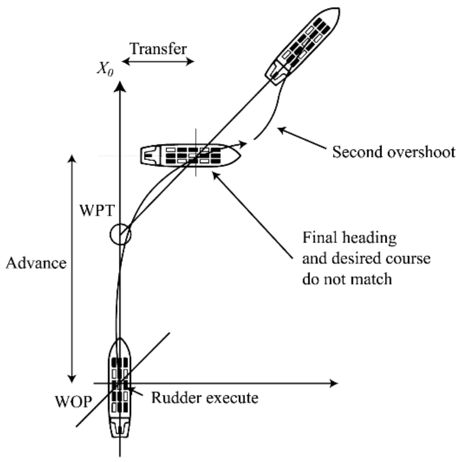

Fig. 2 Advance transfer technique principle (Anwar 2015)

The negative value of WOP for situation 1 in Table 1 implies that the ship has to make the course alteration 0.057 nm after WPT, which means that the ship has overshot the planned track.

1.1.2 Second observation – The final heading of the ship does not match the charted course

The principle of the technique works as shown in Fig. 2. It can be observed that the final heading of the ship is 090°T, which do not match the 045°T desired course. This can cause a second overshoot.

2. Methodology

The research started with a review on the ATT to further understand WOP's concept. Through the review, a research gap was identified and then an approach of restructuring the application of manoeuvring characteristic in determining WOP was made. From there, a new advance transfer mathematical model (ATMM) was developed.

After developing the mathematical model, both ATT and ATMM were tested against observations from the physical system that they represented, which in this case, was a ship simulator. This process is usually called validation (Voit and Voit 2020).

Using the Wartsila ship simulator, a manoeuvring analysis was carried out to test both methods to validate the model by determining its impact on the cross-track distance (XTD). When two models of the same system are available, researchers may want to compare them to choose one for future use (Voit and Voit 2020). Therefore, after simulation analysis was carried out, XTD results for both methods were compared to determine whether ATMM is better than ATT in determining WOP.

2.1 Review on advance transfer technique (ATT)

The manoeuvring characteristic of a vessel is subjected to the rudder angle ordered for a particular manoeuvre (Kim e*t al*. 2005). A constant turning circle can be achieved by fixing the ship's rudder at a certain angle (Drachev 2012). Upon ship delivery, a sea trial manoeuvre will be carried out, resulting in a specific manoeuvring characteristic for that ship where manoeuvring details are recorded, including a turning circle for every particular rudder angle (Duman and Bal 2017, IMO 2002).

This method of fixing rudder at hard over rudder angle during turning is also known as the advance transfer technique (Anwar 2015, Lušić *et al*. 2014), and it is widely used while navigating in inland water and during pilotage. Other techniques for determining WOP, such as constant radius turn (CRT) and constant rate of turn (CROT), require the vessel's speed as a variable in their respective formulas (Jithin 2019). However, as the turning circle's characteristic is unaffected by the vessel's speed (Kim *et al*. 2005), ATT allows WOP to be calculated without having to include the ship's speed, which can be seen in equation (2). In open sea navigation, the speed of a ship can be considered as constant and predictable according to the previous voyage's service speed. Thus, it is possible for any technique to be applied under such condition. Comparatively, in inland water, the ship's speed is frequently adjusted depending on the traffic density, the state of visibility, water depth, manoeuvrability, navigation hazards (House 2004a), and as per the pilot's advice (TTEG 2008). As a result, CRT and CROT are difficult to be used during navigation in inland water and pilotage. For this reason, ATT is preferable in such situations.

The basic concept of determining WOP can be derived from a few methods and techniques (Anwar 2015, Georgiana and Stefan 2010, Jithin 2019, Schlemmer 2020); however, this study focuses only on the identification of the ship's WOP according to the advance transfer technique by Anwar (2015), which requires two variables from the manoeuvring characteristic as shown in Fig. 3, namely 1) advance and 2) transfer distance, hence its name.

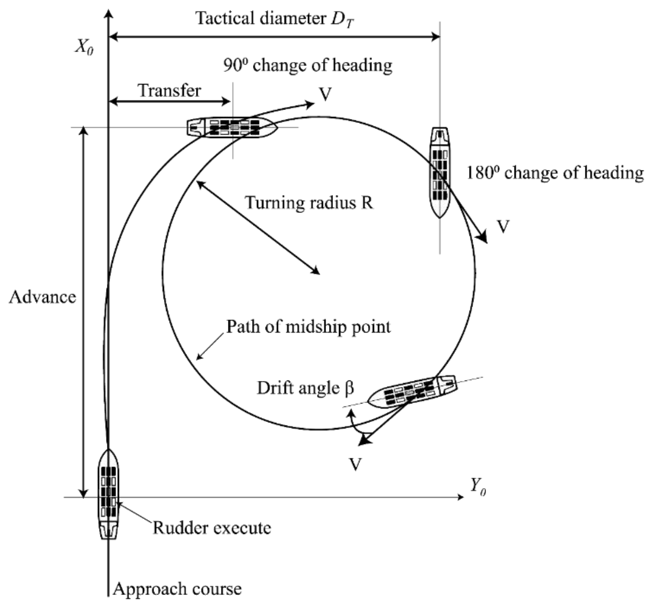

Fig. 3 Typical manoeuvring characteristic of a ship (ITTC 2002)

Advance is the distance covered during the forward motion of the ship from the point that the vessel initiates the turn and transfer is defined as the distance covered when the vessel moves perpendicular to the fore and aft line at the commencement of the turn (House 2004b). In other words, advance and transfer distance can be measured from the moment the vessel initiates the turn by hard over the rudder until the ship's heading changes by 90° from the initial heading, where the distance of advance is on the X_0 axis and the distance of transfer is on the Y_0 axis, as shown in Figure 3 (ITTC 2002). Both distances are measured by referring to the positioning of the ship's centre of gravity (CG) (ITTC 2002).

The advance and transfer distance are usually expressed in nautical miles (nm) and they can be extracted from the manoeuvring characteristic. The usage of the aforementioned information to determine the WOP is as explained below.

With references to Figs. 4-6, the symbols abbreviations used for explaining the formula are as follows:

d_{adv} = Advance distance from manoeuvring characteristic
d_{trs} = Transfer distance from manoeuvring characteristic
d_{CG-WPT} = Distance from ship's centre of gravity to WPT
d_{WOP} = Distance of WOP' from WPT

Based on the understanding of the technical concept shown in Fig. 4, the formula to calculate the position of WOP can be constructed. The course alteration (difference between next course and present course) will be represented as θ. The WOP, as defined by Anwar (2015), is the distance from the ship's centre of gravity (CG) to the WPT, thus it will be named as d_{CG-WPT}. To obtain d_{CG-WPT}, the advance distance, d_{adv}, needs to be subtracted with d_a, therefore

$$d_{CG-WPT} = d_{adv} - d_a \tag{1}$$

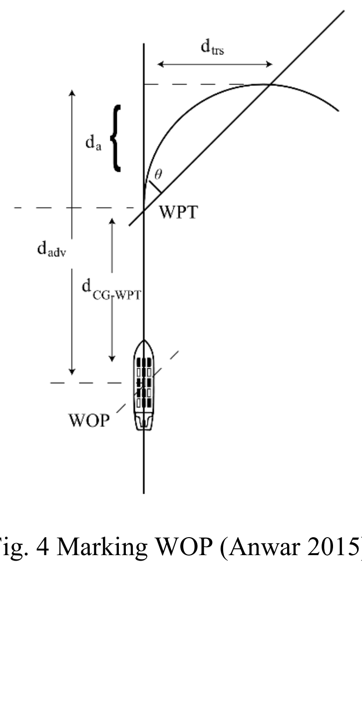

Fig. 4 Marking WOP (Anwar 2015)

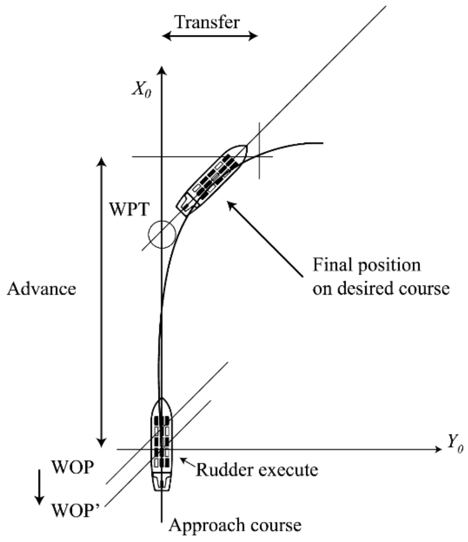

Fig. 5 This study's concept (ship's heading and course are the same at the end of alteration)

d_a can be obtained by utilising the tangent rule as follows

$$tan\,\theta = \frac{d_{trs}}{d_a}$$

$$d_a = \frac{d_{trs}}{tan\,\theta}$$

Hence, the formula of advance transfer technique (Anwar 2015) is obtained as below

$$d_{CG-WPT} = d_{adv} - \frac{d_{trs}}{tan\ \theta} \tag{2}$$

2.2 Restructure the application of manoeuvring characteristic

To improve the usage of advance and transfer distance in determining WOP, this study intends to improvise the ATT technique so that the ship's final course matches the charted course in the passage plan.

Therefore, to match the final course with the ship's heading, this research intends to redesign the technique as shown in Fig. 5 to ensure that the final heading of the ship will match the desired next course.

2.3 Development of research mathematical model (ATMM)

The mathematical model can be constructed from the existing equation that is published in the related study (Voit and Voit 2020). Therefore, the ATT equation by Anwar (2015) can be used as the

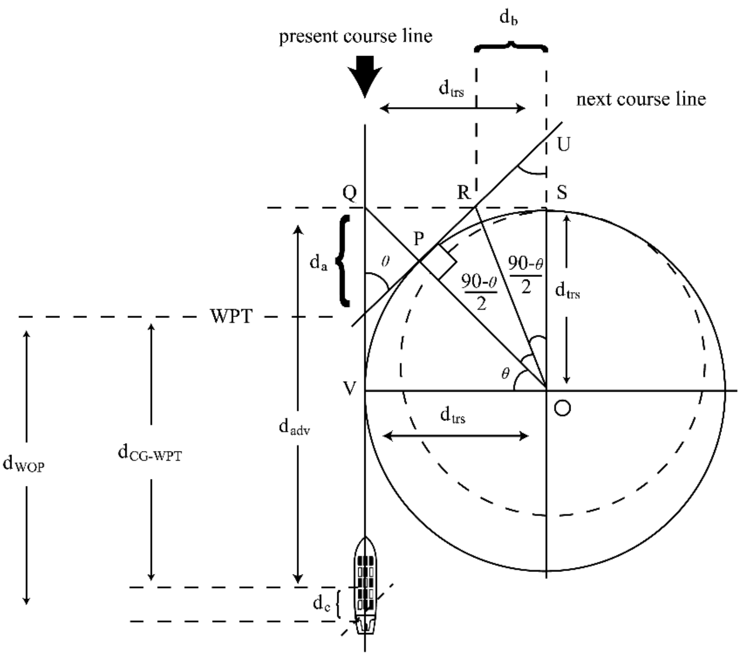

Fig. 6 Distribution details

foundation of the mathematical model, which will be constructed for the calculation of the WOP position. Fig. 6 is constructed according to the generic diagram of a ship turning circle and it will be used to assist the explanation on the development of ATMM.

As shown in Fig. 6, the development of ATMM will also include the distance from the ship's bridge to the ship's centre of gravity (CG). Therefore, in addition to (1), the distance of WOP' from WPT, also known as d_{WOP}, will consist of 1) d_{CG-WPT} and 2) d_c, hence

$$d_{WOP} = d_{CG-WPT} + d_c$$

With reference to the existing ATT formula in (1), $d_{CG-WPT} = d_{adv} - d_a$, the equation can be re-written as

$$d_{WOP} = d_{adv} - d_a + d_c \tag{3}$$

The next step is to find the value of d_a and d_c.

To find d_a, the following trigonometry function can be used

$$\tan\theta = \frac{QR}{d_a}$$

$$d_a = \frac{QR}{\tan\theta} \tag{4}$$

To get QR, subtract RS from QS. QS is equal to d_{trs}. For now, RS will be represented as d_b as shown in Fig. 6. Thus, $QR = d_{trs} - d_b$. Consequently, (4) can be written as follows

$$d_a = \frac{d_{trs} - d_b}{\tan\theta} \tag{5}$$

ΔROS is a right-angled triangle; therefore, the value of d_b can be obtained by utilising the trigonometry tangent function

$$\tan \angle ROS = \frac{d_b}{d_{trs}}$$

$$d_b = d_{trs} \cdot \tan \angle ROS \tag{6}$$

To determine ∠ROS, first, it needs to be noted that TU is a tangent line to OP, TU ⊥ OP, which makes UPO equal to 90°, $\llcorner UPO = 90°$. According to the rules of a triangle, the total inner angle of a triangle must be equal to 180°, ΔPUO = 180°. The total inner angle of triangle PUO is the sum value of ∠UOP, $\llcorner UPO$, and $\angle PUO$. This can also be written as

$$\angle UOP + \llcorner UPO + \angle PUO = \Delta PUO$$

$$\angle UOP + 90° + \theta = 180°$$

$$\angle UOP = 180° - 90° - \theta$$

$$\angle UOP = 90° - \theta$$

According to the rule of the tangent to a circle, RP and RS will be the same, | RP | = | RS |, since both distances are tangent to the circle. Thus, the angle of POR and ROS are also the same, ∠POR = ∠ROS. Hence, $\angle ROS$ is half of the value of $\angle POS$. For this reason, $\angle ROS$ can be expressed as

$$\angle ROS = \angle \frac{POS}{2}$$

$$\angle ROS = \frac{90° - \theta}{2} \tag{7}$$

With reference to (6) and the input from (7), the following is obtained

$$d_b = d_{trs} \cdot \tan \angle ROS$$

$$d_b = d_{trs} \cdot \tan\left(\frac{90° - \theta}{2}\right) \tag{8}$$

Inserting (8) into (5), d_a can be obtained as

$$d_a = \frac{d_{trs-} \; d_{trs} \cdot \tan\left(\frac{90° - \theta}{2}\right)}{\tan\theta} \tag{9}$$

A turning circle is constructed with reference to the ship's centre of gravity (CG) (ITTC 2002). For this reason, Anwar (2015) used the CG to locate the WOP. However, while navigating, the ship's position is monitored using the global navigation satellite system (GNSS), which is located at the ship's bridge. To be precise, it is located at the location where the GNSS antenna is mounted.

Therefore, the actual alteration shall be carried out by monitoring the GNSS position while taking into account the moment when the CG will be at the WOP position. Thus, the actual WOP marked on the chart shall include the distance between the bridge, hence $d_{CG} = d_c$, and this is applied as follows.

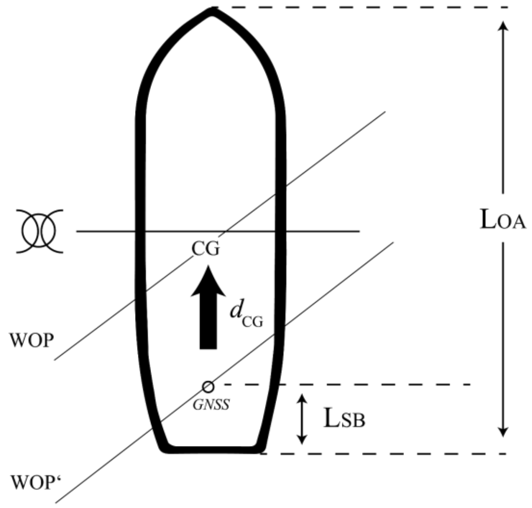

Fig. 7 d_{CG} is the distance between the ship's bridge (L_{SB}) and the ship's longitudinal Centre of gravity (L_{CG})

To determine the d_{CG}, firstly, the location of CG needs to be verified. Longitudinal Centre of Gravity (L_{CG}) is equal to the sum of longitudinal moment divided by the ship's final displacement (House 2004b, Latorre 2003). Let Xi be the longitudinal distance of cargo spaces and tanks measured from the amidships, and Wi be the amount of weight loaded on each cargo space and tank. As a result, $\sum_i x_i w_I$ is the sum of the longitudinal moment exerted on the ship. The formula for a ship's L_{CG} is as follows

$$L_{CG} = \frac{\sum_i x_i w_i}{\Delta}$$

LOA is the overall length of the ship, and L_{SB} is the length from the ship's stern to the ship's bridge (Molland 2008). L_{CG} is measured from the midship, which is half of LOA (House 2004b). The symbol $+L_{CG}$ indicates that the position of L_{CG} is at the forward of midship, and $-L_{CG}$ indicates that the position of L_{CG} is at the aft of midship (Mucha *et al*. 2019). With reference to Fig. 7, the d_{CG} can be located as follows

$$d_c = d_{CG} = \frac{LOA}{2} + L_{CG} - L_{SB}$$

$$d_c = d_{CG} = \frac{LOA}{2} + \frac{\sum_i x_i \; w_i}{\Delta} - L_{SB} \tag{10}$$

However, in real-world applications, L_{CG} can also be obtained directly from the ship's cargo loading computer (House 2004b). L_{CG} can also be considered to be the same as the position of the Longitudinal centre of buoyancy (L_{CB}), which can be obtained from the ship's stability booklet (Molland 2008).

In summary, with reference to (3), d_{WOP} can be constructed using the input from (9) and (10) as follows

$$d_{WOP} = d_{adv} - d_a + d_c$$

$$d_{WOP} = d_{adv} - (9) + (10)$$

$$d_{WOP} = d_{adv} - \left(\frac{d_{trs-}\ d_{trs}\ .tan(\frac{90°-\theta}{2})}{tan\,\theta}\right) + \left(\frac{LOA}{2} + \frac{\sum_i x_i\ w_i}{\Delta} - L_{SB}\right) \qquad (11)$$

3. Simulator test

A ship simulator is a dependable piece of technology that can be used to aid in the study on manoeuvring (Duarte *et al*. 2016). Additionally, researchers utilise it to analyse the effects of shallow water and bank on a ship's turning circle (Du *et al*. 2018, Duarte *et al*. 2016, Kobylinski 2012, Mucha *et al.* 2019).

In this study, the developed ATMM was evaluated using the Wartsila Ship Simulator. The Wartsila Ship Simulator focuses on supplying main modules with new technologies to enable specialised training applications. It offers actual navigation simulation for more than 100 ship types and can configure the sea conditions according to user requirements (Wärtsilä 2020).

There are three major techniques that can be used to anticipate the manoeuvrability of a vessel and consequently validate the vessel's turning circle (IMO 2002, Yiew *et al.* 2019). The first one is by performing simulations using computational fluid dynamics (CFD) to parameterise the various hydrodynamic coefficients, while taking into account the vessel's 6 degree-of-freedom (6-DOF) motions and control responses (Taimuri *et al*. 2020). The second method is through the assessment of the hydrodynamic derivatives using manoeuvring models and system identification methods (Yiew *et al*. 2019). Finally, the third technique is through a full-scale trial method whereby an actual ship is manoeuvred to obtain its turning circle (IMO 2002). This study used the full-scale trial method. However, instead of using an actual ship, the manoeuvring was carried out using a ship simulator.

The simulation was performed using a bulk carrier type of ship with a total length of 182.9 m and a width of 22.6 m. The ship was in laden condition, with a displacement of 33089 tonnes and a 10.7m draught. The simulator recorded that the advance distance for this ship was 0.283 nm for port turning circle and 0.296 nm for starboard turning circle. On the other hand, the transfer distance was 0.137 nm and 0.144 nm for port and starboard turning circle, respectively. The ship L_{CG} was 0, and the L_{SB} was 30.5 m. Using Eq. (10), the d_{CG} was calculated to be 0.0329 nm.

For the manoeuvring simulation, two charted routes were created on the simulator. One course was for port course alteration and another one was for starboard course alteration, which can be seen in Figs. 8 and 9. The WOPs were calculated using the ATT formula in Eq. (2) and the ATMM formula in Eq. (11), and recorded in Table 2 below. Then, the simulations were carried out by manoeuvring

Table 2 WOP calculated using ATT and ATMM equation

Side	θ	d_{adv} (nm)	d_{trs} (nm)	d_{CG} (nm)	WOP	
					ATT	ATMM
PORT	30°	0.283	0.137	0.0329	0.046	0.216
STBD	30°	0.296	0.144	0.0329	0.047	0.223

Using ATT method Using the ATMM

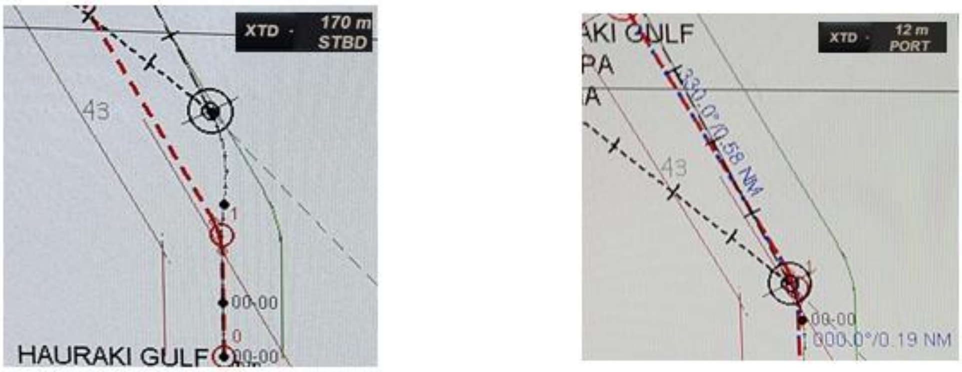

Fig. 8 Port alteration

Fig. 9 Starboard alteration

the ship on the charted course. When the ship arrived at the WOP, the course alterations were executed. The same process was repeated four times where two manoeuvring operations were carried out with reference to the WOP calculated using ATT while another two operations were executed based on the WOP calculated using ATMM. During the analysis, the XTD were carefully monitored.

4. Results and discussion

It is noteworthy to emphasise again that the objective of the analysis is to build a mathematical WOP model that improves course tracking by monitoring the XTD. The simulation results are as follows.

With reference to Fig. 8, when applying the ATT for port alteration, XTD is found to be 170 m to the starboard side of the vessel's track. Meanwhile, alteration to port using the ATMM successfully reduces the XTD to 12 m to the vessel's track.

With reference to Fig. 9, the same simulation is applied to starboard alteration, where alteration using ATT results in 181 m to port of the vessel's track. However, after applying the ATMM, the

XTD is reduced to 17 m to the vessel's track.

It can be inferred that ATMM provides improved XTD in terms of its distance to the charted course.

5. Conclusions

The ship must remain on the expected course line because of many reasons. Other than reducing fuel consumption, the most significant reason is that it can keep the vessel safe as many instances of collisions arise due to XTD ignorance (Kristić *et al*. 2020). After all, safety is the priority for a ship's operation (Kamis *et al*. 2020). It was observed that the ATT procedure could be further enhanced after studying and analysing the ATT process of evaluating WOP. A mathematical model, namely ATMM, was successfully developed and tested through manoeuvring simulation using the Wartsila ship simulator.

Contribution

It can be inferred that the ATMM built in this study significantly reduces the XTD as one of the techniques for deciding WOP. However, the simulation study is still at preliminary stages and further manoeuvring analysis will be carried out using various type of cargo ships.

Few cases of accidents had happened due to a lack of knowledge regarding WOP (TAIC 2016). With ATMM used as an algorithm in the ECDIS, it can automatically generate the WOP for each course alteration for passage planning to provide extra safety measures in case navigators are unaware of it.

Suggestion for future research

Additional tests using a different type of ship and various turning angles can be carried out to verify the mathematical model's effectiveness. Other than that, ensuring that the ship is staying on the course line will help to minimise fuel consumption in this study. Perhaps this study can be expanded to evaluate the effect on energy efficiency due to the reduction of XTD.

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