

Probability of Ship on Collision Courses Based on the New PAW Using MMG Model and AIS Data

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ABSTRACT: This paper proposes an estimation method for ships on collision courses taking crash astern maneuvers based on a new potential area of water (PAW) for maneuvering. A crash astern maneuver is an emergency option a ship can take when exposed to the risk of a collision with other ships that have lost control. However, lateral forces and yaw moments exerted by the reversing propeller, as well as the uncertainty of the initial speed and initial yaw rate, will move the ship out of the intended stopping position landing it in a dangerous area. A new PAW for crash astern maneuvers is thus introduced. The PAW is developed based on a probability density function of the initial yaw rate. Distributions of the yaw rates and speeds are analyzed from automatic identification system (AIS) data in Madura Strait, and estimated paths of the maneuvers are simulated using a mathematical maneuvering group model.

1 INTRODUCTION

Tanjung Perak Port area is located in Madura Strait between Java Island and Madura Island, in Surabaya, East of Java, Indonesia. The port plays an important role as the central port of Indonesia. The port provides transportation services to and from the center of international trading in Singapore, as well as domestic trading services between the western and eastern parts of Indonesia. The port is expected to handle ships without transit in Singapore. Accordingly, larger ships could be handled. A multipurpose port was built in Lamong Bay near to the Tanjung Perak Port. The positions of the ports and anchorage zones are shown in Figure 1. The trajectory of a ship on the fairway is plotted in Figure 1 based on the automatic identification system (AIS) data. The positions indicated in blue are created as the limit of 6 areas representing 3 paths of course keeping A, C, and E, and 3 paths of turning B, D, and F.

Figure 1 shows that two anchored ships are located out of the anchorage zones and close to the fairway, indicating an increasing number ship calls. The increasing number of ship calls and the lack of traffic scheme in the developing port area will increase the number of collision candidates, and the causation probability, and subsequently will increase the number of ship collisions. The causation probability of ship collisions in Madura Strait is about 1.08×10^{-4} (Mulyadi et al., 2014). The probability represents the frequency of failing to avoid a collision when on collision course. The high causation probability also denotes the high probability of ships losing control. The high number of ship calls and ships losing control as well as the limited area will make course changes more difficult when the ships are exposed to a ship-ship collision situation. Besides course changes and course keeping, a crash astern maneuver may be chosen by the navigator to avoid accidents.

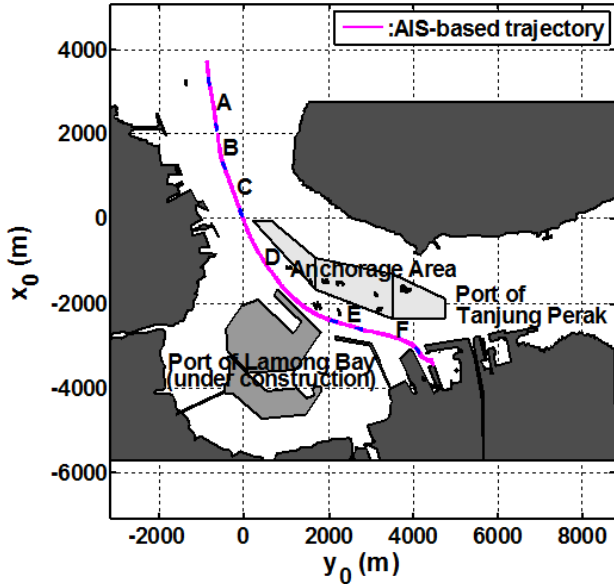


Figure 1. Ship trajectory in the research area.

This study aims at developing a method to estimate the probability of collision when using a crash astern maneuver. The proposed method was developed based on the combination of the two typical methods introduced by Fujii (1974) and Kristiansen (2005), and the concept of potential area of water (PAW) introduced by Inoue (1990). The frequency of a subject ship on a collision course is estimated based on the distributions of initial speed and initial yaw rates. The uncertainty of the initial conditions significantly affects the paths of the maneuvers (Asmara et al., 2012). The trajectories are estimated using mathematical maneuvering group (MMG) model and initial conditions of speed and yaw rate are analyzed from automatic identification system (AIS) data. The aim of this study is to propose a method for estimating the probability of collision resulting from crash astern maneuvers in the research area, of a ship on a collision course that attempts crash astern maneuvers.

2 LITERATURE REVIEW

The formula used for the assessment of collision risk is shown by Equation 1 (Goerlandt et al., 2011).

$$R = PC \quad (1)$$

where R is the collision risk; P , the probability of collision; and C , the factor representing the consequences of collision such as collision energy losses.

Several researchers have introduced methods for estimating the number of collisions. Generally, the methods were developed based on Fujii's model (1974), where the number of expected collisions is calculated from the number of collision candidates multiplied by the probability of failing to avoid a collision when on a collision course, as shown by Equation 2.

$$N_{coll} = N_A P_C \quad (2)$$

where N_{coll} is the number of collisions for a given time period; N_A , the number of encounters during the time period; and P_C , the probability of failure of collision avoidance, generally known as causation probability. In this approach, the number of collision candidates is estimated using geometrical probability based on an encounter segment of the lateral distribution of the ship's trajectory. The probability of collision avoidance failure, the causation probability, is estimated based on specific error situation analysis of several factors leading to the probability of wrong action and steering failure.

In another approach, the probability of steering failure is defined as the probability of a loss of control. It estimates the collision probability by multiplying it with the probability of a ship collision upon the loss of vessel control (Kristiansen, 2005). In this method, the probability of loss control is determined from historical data. The probability of a collision upon the loss of vessel control is calculated using a geometrical probability based on dimensions of fairway and ships, traffic density, and ships' speed, as well as the type of collision. In this approach, first, the probability of collision P_a is determined based on the historical accident data, and second, the probability of collision upon the loss of vessel control P_i is calculated based on geometrical probability of collision. Finally, the probability of control loss P_c in the port area is determined. Collision probability is defined as the probability of a loss of control P_c multiplied by the probability of an incident (the probability of accident upon the loss of vessel control) P_i (Kristiansen, 2005) as follows:

$$P_a = P_c P_i \quad (3)$$

where the indexes denote accident (a), loss of control (c) and impact (i). In this approach, the probability of control loss seems to be treated as the collision candidate frequency, which is determined based on the historical statistic data. The probability of an incident, probability of accident upon the loss of vessel control, acts as the probability of failing to avoid accident. However, the method used for determining the incident probability is different from that used for estimating causation probability in the previous approach. It was used in the first approach to calculate the collision candidate frequency, which depends on the type of encounter, fairway dimensions, and the speed and dimensions of ships, based on a geometrical probability.

Figure 2 shows the approaches of the described methods and the proposed method. Both of the existing methods do not specifically show the probability of collision upon using crash astern maneuvers, which may be adopted by navigators to avoid a collision in dense traffic. The lateral deviation of the maneuvers may be considered as a wrong action included in the causation probability, and losing control in the first and second approaches, respectively. However, the specific estimation of probability of a ship on a collision course when performing crash astern maneuvers has not yet been analyzed.

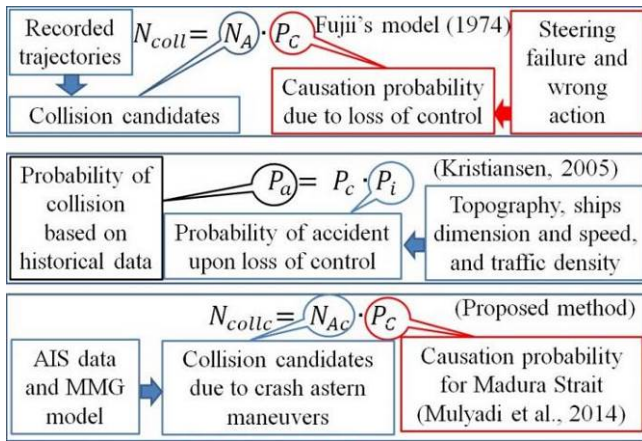


Figure 2. Flow chart of existing and proposed methods.

This paper proposes a method to estimate the probability of ship on a collision course, upon taking crash astern maneuvers, based on a new PAW for maneuvering. The PAW for maneuvering is defined as the water area that would be used before the intended ship's movement is achieved, assuming that the navigator will encounter an emergency involving the application of crash astern maneuver or such other emergency action as may be necessary should the ship encounter an unexpected situation during the maneuver (Inoue, 1990). The number of collision candidates due to a crash astern maneuver is the number of ships taking crash astern maneuvers multiplies by the probability of ships on collision courses performing crash astern maneuvers. The number of ships taking crash astern maneuvers is the number of ships entering the research area multiplies by the probability of them taking crash astern maneuvers. However, the probability of taking a crash astern maneuver is not discussed in this paper. The PAW was developed by superimposing the ship paths by their positions when crash astern maneuvers are ordered (Inoue, 1990). The new PAW developed in this study is developed not only by the positions when the maneuvers are ordered but also by the distribution of initial speed and initial yaw rate.

3 METHODS

3.1 AIS Data

The AIS data is taken from an AIS receiver installed at the Institut Teknologi Sepuluh Nopember (ITS) campus in Indonesia through a collaboration between ITS and Kobe University. The number of ship calls in the port area on a peak day in January 2011 was more than 120, as shown in Figure 3. The number of entering ships is higher than leaving ships because of the high number of anchored ships, as indicated by the ships anchoring out of the anchorage zones, as shown in Figure 1. The number of entering and leaving ships is identified from AIS data by distinguishing the ship courses in the research area. The average number of entering and leaving ships per day is 49 and 42, respectively.

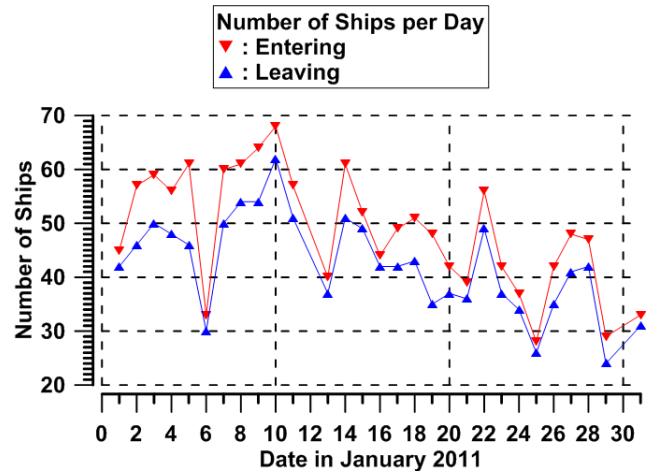


Figure 3. Number of ship calls in the port area.

Table 1. Distribution of speed

Area Distribution		Parameter of Distribution	
		Mean (kt)	Standard Deviation (kt)
A	Normal	9.8139	3.3600
B	Normal	9.6653	3.4433
C	Normal	9.4936	3.0687
D	Normal	7.7335	3.9185
E	Normal	6.0941	2.8388
F	Normal	5.6742	2.4777

The distribution of ship speeds in the 6 areas is presented in Table 1. The distribution fits to normal distributions with a mean of between 10 to 5 knots decreasing from area A to area F. The average ship speed is more than 9 knots before entering the anchorage zones in area A, B and C. It is more than 7 knots in the area between the new port and anchorage zones, area D, and about 6 knots in the existing port area, area E and F.

3.2 MMG Model

The mathematical model for the simulation of ship maneuvering was developed based on Yoshimura's model for medium high-speed merchant ships and fishing ships (Yoshimura & Masumoto, 2012). The coordinate system for this model is shown in Figure 4. The equations of surging, swaying and yawing motion are expressed by Equations 4 to 6. The subscripted H, P, and R for longitudinal force X, lateral force Y, and yaw moment N, represent the hull, propeller and rudder, respectively. The hull, propeller, and rudder forces and moments are calculated based on Kijima's and Yoshimura's regression equations and empirical forms for medium high-speed merchant ships and fishing ships (Yoshimura & Masumoto, 2012).

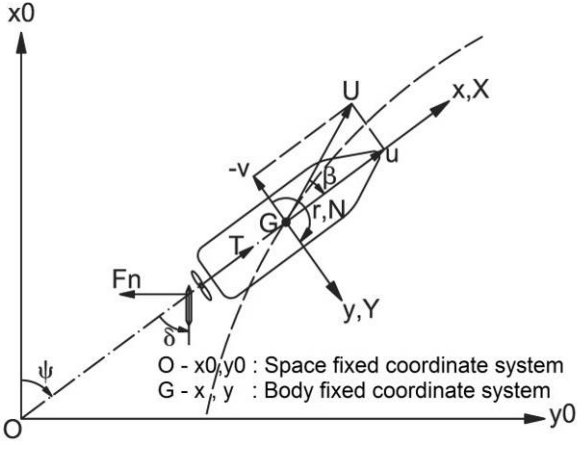


Figure 4. Coordinate system of MMG model.

The model also considers the effect of the shallow water on ship maneuvering (Kobayashi, 1995).

Surge:

$$(m + m_x)\dot{u}_G - (m + m_y)v_G r_G = X_H + X_P + X_R \quad (4)$$

Sway:

$$(m + m_y)\dot{v}_G + (m + m_x)u_G r_G = Y_H + Y_P + Y_R \quad (5)$$

Yaw:

$$(I_{zz} + J_{zz})\dot{r}_G = N_H + N_P + N_R - x_G Y \quad (6)$$

Hull forces and moment are expressed in Equations 7 to 9.

$$X_H + m_y v_G r_G = 0.5 \rho L d U^2 \{ X'_0 + X'_{\beta\beta} \beta^2 + (X'_{\beta r} - m'_y) \beta r' + (X'_{rr} - x'_G m'_y) r'^2 + X'_{\beta\beta\beta\beta} \beta^4 \} \quad (7)$$

$$Y_H - m_x u_G r_G = 0.5 \rho L d U^2 \{ Y'_\beta \beta + (Y'_r - m'_x) r' + Y'_{\beta\beta\beta} \beta^3 + Y'_{\beta\beta r} \beta^2 r' + Y'_{\beta r r} \beta r'^2 + Y'_{r r r} r'^3 \} \quad (8)$$

$$N_H = 0.5 \rho L^2 d U^2 \{ N'_\beta \beta + N'_r r' + N'_{\beta\beta\beta} \beta^3 + N'_{\beta\beta r} \beta^2 r' + N'_{\beta r r} \beta r'^2 + N'_{r r r} r'^3 \} \quad (9)$$

where:

- r'_G = dimensionless yaw rate = $r (L/U)$
- x'_G = dimensionless longitudinal center of gravity = x_G / L
- ρ = density of water
- L = ship length
- d = mean draught
- m'_x, m'_y = dimensionless added mass = $m_x, m_y / 0.5 \rho L^2 d$
- X'_0 = dimensionless resistance = $X_0 / 0.5 \rho L d U^2$

The relation between trust coefficient and apparent advance constant for a reversing propeller is adopted from K_T - J_S diagram for container ship (Yoshimura & Nomoto, 1978; Yoshimura, 1980).

$$\begin{aligned} (1-t)T/\rho D^4 n^2 &= -0.336 J_S + 0.486 & (J_S > 0) \\ (1-t)T/\rho D^4 n^2 &= -0.335 & (-0.6 < J_S < 0) \\ (1-t)T/\rho D^4 n^2 &= 0.51 J_S + 0.19 & (J_S < -0.6) \end{aligned}$$

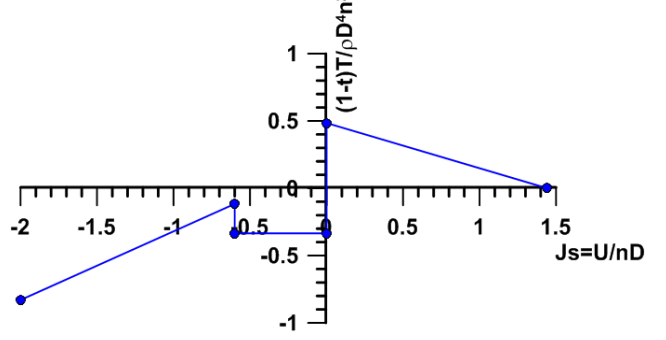


Figure 5. K_T - J_S diagram for a container ship.

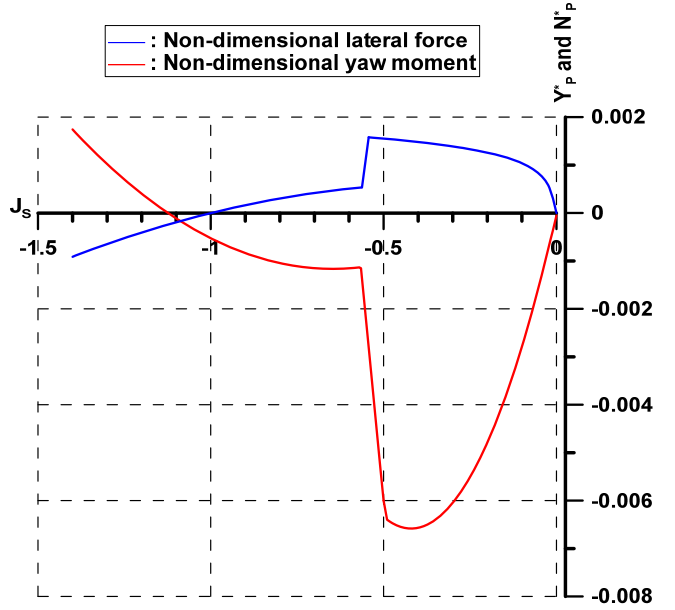


Figure 6. Lateral force and yaw moment exerted by a reversing propeller.

The trust coefficient for a reversing propeller is presented in the fourth quadrant of Figure 5.

Lateral force and yaw moment exerted by a reversing propeller are taken from Yoshimura graphs (1980). The graphs are fit to Equations 10 to 15 and are shown in Figure 6.

$$Y_P^* = 0.005125 J_S^2 + 0.006629 J_S + 0.000978 \quad \text{for } J_S \leq -0.5653 \quad (10)$$

$$Y_P^* = -0.074153 J_S - 0.043076 \quad \text{for } -0.5653 < J_S \leq -0.5 \quad (11)$$

$$Y_P^* = 0.037007 J_S^2 + 0.031084 J_S - 0.000054 \quad \text{for } -0.5 < J_S \leq 0 \quad (12)$$

$$N_P^* = -0.001255 J_S^2 - 0.000734 J_S + 0.000519 \quad \text{for } J_S \leq -0.5625 \quad (13)$$

$$N_p^* = 0.049018J_s + 0.028116$$

for: $-0.5625 < J_s \leq -0.5429$ (14)

$$N_p^* = 0.000319 \ln(-J_s) + 0.001774$$

for: $-0.5429 < J_s \leq 0$ (15)

Y_p^* and N_p^* are typical non-dimensional form of lateral force and yaw moment exerted by reversing a propeller as presented by Equations 16 and 17 below.

$$Y_p^* = Y_p / \frac{\rho}{2} L d (nD)^2$$
 (16)

$$N_p^* = N_p / \frac{\rho}{2} L^2 d (nD)^2$$
 (17)

where n is propeller revolution and D is propeller diameter.

3.3 Subject Ship Selection

A pure car carrier (PCC) ship was selected as the subject ship based on the maximum size of ships voyaging in the research area. In addition, the ship's primary dimensions fit the requirement of the nonlinear hull derivatives for the MMG model, including the beam to length (L/B), beam to draught ratio (d/B) and block coefficient (C_b). The principle dimensions of the subject ship are presented in Table 2. The subject ship is simulated to follow the AIS based trajectory of an entering ship using the MMG model. The distributions of yaw rate in the 6 areas are analyzed based on the time series of yaw rate resulted from the simulation.

Table 2. Principle dimension of PCC ship.

Ship Particulars	Dimension
Length (L_{pp})	180 m
Breadth (B)	32.2 m
Draft (d)	8.2 m
Coefficient Block (C_b)	0.548
Displacement (Δ)	26,650 tons
Speed (V_s)	18 kt
Propeller Diameter (D_p)	5.7 m
Rudder Area (A_R)	37.76 m ²

3.4 PAW for Crash Astern Maneuvers

Originally, the concept of PAW for crash astern maneuvers was introduced as an area covered by possible paths of a ship upon taking several emergency actions of crash astern maneuvers. The possible paths are developed based on the positions when maneuvers are ordered (Inoue, 1990). Each position actually represents a specific course, speed, and yaw rate. However, a PAW is introduced as the superposition of the paths of the maneuvers ordered at several initial positions. This paper proposes a new PAW that is developed based on not only the

positions when maneuvers are ordered but also the distributions of speed and yaw rate in an area of the positions. The distribution of a ship's speed is analyzed from AIS data. However the distribution of yaw rate is not provided in the AIS data. Accordingly, a method is proposed to estimate the distribution of yaw rate in the research area as follows:

- 1 The subject ship is simulated in the research area to follow the trajectory of a ship belonging to the same class derived from AIS data.
- 2 The trajectory and time series of the subject ship's yaw angle should be similar to those derived from AIS data.
- 3 The trajectory is divided into several paths of areas. The distribution of yaw rate of the subject ship in the area calculated in the MMG model is analyzed. The distribution is treated as a random initial condition of crash stern maneuvers taken in the area.

4 RESULTS AND DISCUSSIONS

The distributions of the yaw rate of the subject ship in the 6 areas were estimated in the simulation using the MMG model to follow the trajectory of an entering ship plot based on the AIS data.

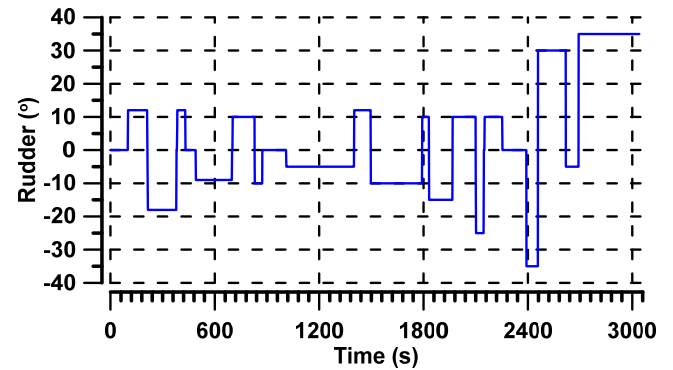


Figure 7. Time series of rudder angle.

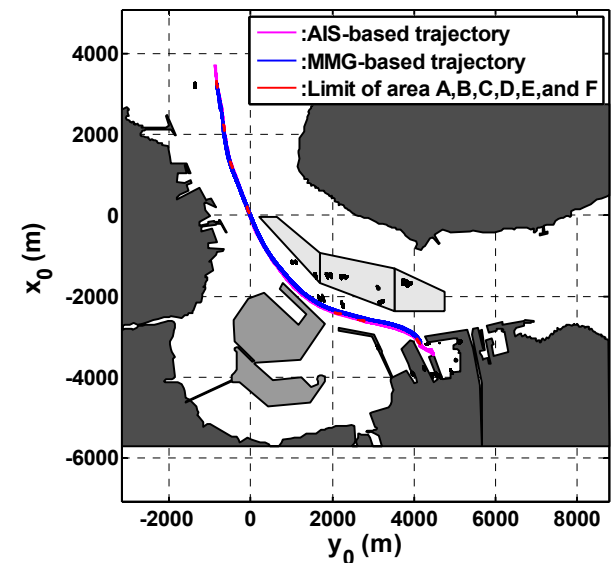


Figure 8. Trajectory of subject ship.

The time series of rudder angles of the subject ship following the trajectory of the entering ship is shown

in Figure 7 and the comparison of the trajectories are presented in Figure 8. Figure 8 shows that subject ship's trajectory is almost the same as the entering ship's trajectory. The subject ship's time series of yaw angle results from the MMG model are also almost the same with the entering ship's true heading derived from AIS data, as presented in Figure 9.

The time series of yaw rates of the subject ship based on the MMG model is shown in Figure 10, and the distribution of the yaw rates in the 6 areas are fit to normal and uniform distributions, as listed in Table 3. Based on the distribution of yaw rates presented in Tables 3, the initial of yaw rate, at the time of reversing the propeller, is randomized.

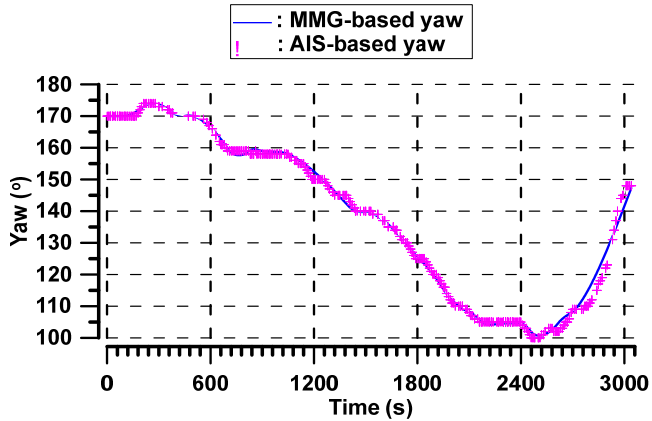


Figure 9. Time series of yaw angle.

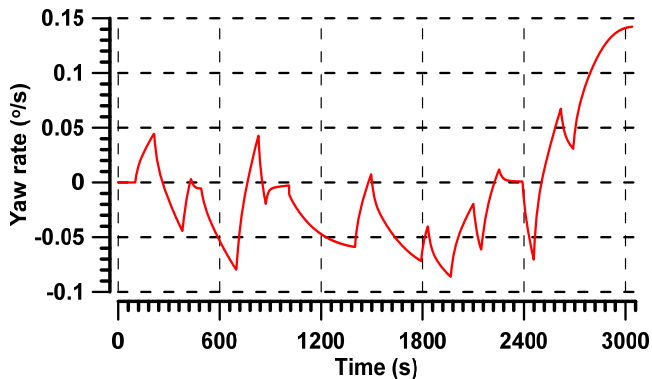


Figure 10. Time series of yaw rate.

Table 3. Distribution of yaw rate.

Area	Distribution	Distribution Parameters (rad/s)	
A	Normal	$\mu = 4.8582E-5$	$\sigma = 4.0774E-4$
B	Uniform	$a = -0.00141$	$b = 1.5265E-4$
C	Normal	$\mu = 6.5377E-5$	$\sigma = 3.8861E-4$
D	Normal	$\mu = 7.9368E-4$	$\sigma = 3.4995E-4$
E	Uniform	$a = -6.2509E-4$	$b = 3.6763E-4$
F	Uniform	$a = -0.00148$	$b = 0.00239$

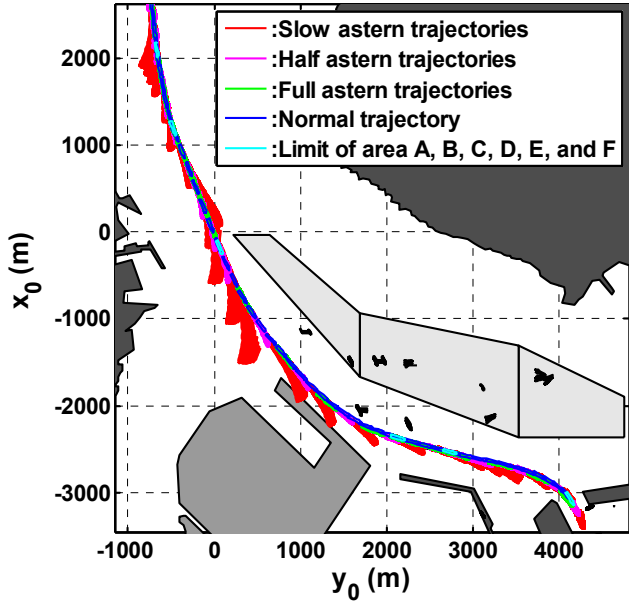


Figure 11. PAWs by position and initial yaw rate.

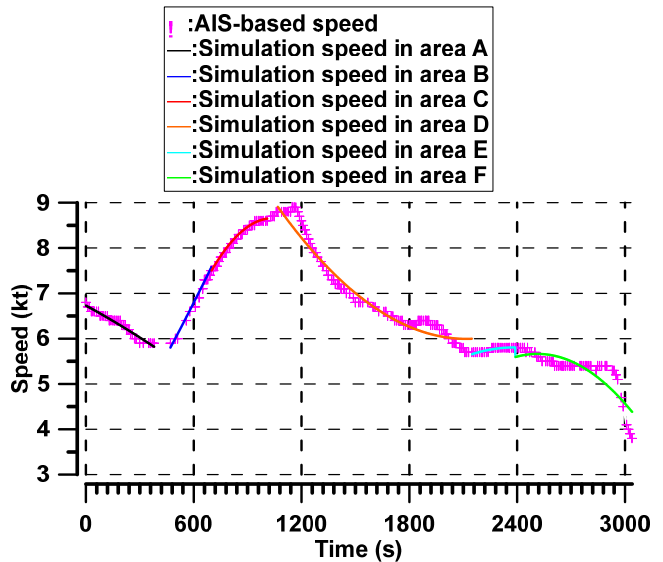


Figure 12. Time series of ship speed.

The reversing of the propeller is ordered at 4 positions in each area. Three types of crash astern maneuvers including slow, half, and full are simulated for the subject ship. The PAW of slow, half and full astern maneuvers based on the random value of initial yaw rate are presented in Figure 11.

Figure 11 shows that the PAW becomes smaller when entering the area of Tanjung Perak Port, areas E and F, because the speed significantly decreases. The time series of ship speed is presented in Figure 12. In area B, the PAW of a slow crash astern maneuver covers the opposite line of the fairway lying at the port side of the entering ship. Some of the possible paths enter the exiting lane of the 100 m wide fairway. In areas C and D, the PAWs do not cover the opposite lane but enter the area of Lamong Bay Port. In area D, the paths cross the line of port structure, which means the ship collides with the structure. The probabilities of the ship on collision course in the danger areas of B and D is analyzed as follows:

4.1 Probability of Ship on Collision Course upon Taking Crash Astern Maneuvers in Area B

Area B is the area where a course alteration is taken before a short straight path of area C and the long turning path of area D. Four positions are selected in area B as initial positions, which are when the crash astern maneuvers are ordered at the simulation times t , of $t = 410$ s, $t = 500$ s, $t = 590$ s, and $t = 680$ s. In area B, taking a slow crash astern at the last initial position, $t = 680$ s, caused a PAW covering the opposite lane, as shown in Figure 13.

However, if a half or a full astern maneuver is ordered, the lateral deviation is not significant. The maximum lateral deviation was only 0.24 times the ship width B , and $0.13B$, for the half and full astern maneuvers, respectively. It is a small deviation when compared to the width of the lane, which is 100 m, or about $3B$. Dangerous situations will occur if a slow crash astern is ordered. The distribution of lateral deviation from the normal position is shown by the bar chart presented in Fig. 14. The distribution fits to a uniform distribution with maximum deviation of $4.165B$ and minimum deviation of $2.114B$. About 77% of the possible paths will enter the opposite line by considering that the allowable lateral deviation is half of lane width, which is about $2.5B$.

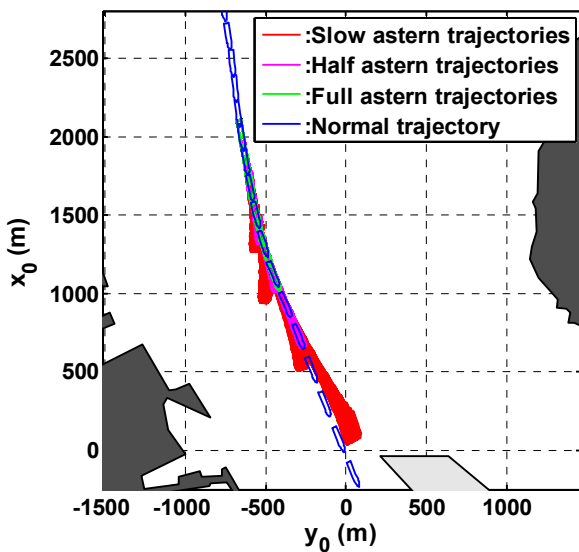


Figure 13. PAWs by initial yaw rate in area B.

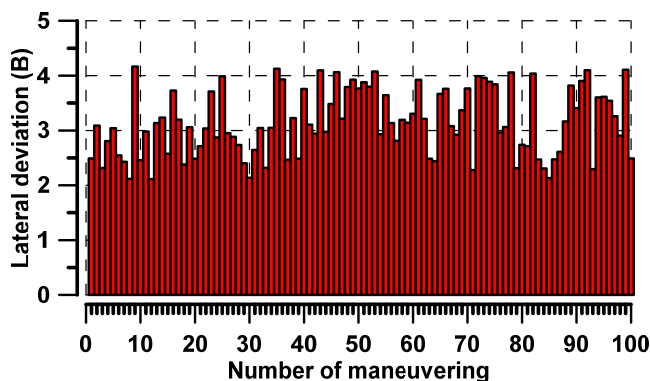


Figure 14. Bar chart of lateral deviation for slow crash astern at $t=680$.

4.2 Probability of Ship on Collision Course upon Taking Crash Astern Maneuvers in Area D

Area D depicts a long turning path located between anchorage area and the new port. If a slow crash astern maneuver is taken at positions between the first and second initial positions of area D, at $t = 1250$ s and $t = 1500$ s, the PAWs will cover the structure of Lamong Bay port. The ship's speeds at the initial positions are 7.98 and 7.00 knots, respectively.

Figure 15 shows, at the same yaw rate distribution, the lower the initial speed the smaller the PAW. The bar chart of lateral deviations from the normal position of simulation of the PAW of initial position at $t = 1250$ s is shown in Figure 16. The distribution of the lateral deviation at this position fits to a normal distribution with the mean of $-5.894B$ and the standard deviation of $0.342B$. The distance between the fairway and the Lamong Bay port's structure is about $4.9B$ and all of the possible paths on the PAW attack the port structure. However, the maximum lateral deviation for half and full crash astern are $1.9B$, and $0.23B$, respectively.

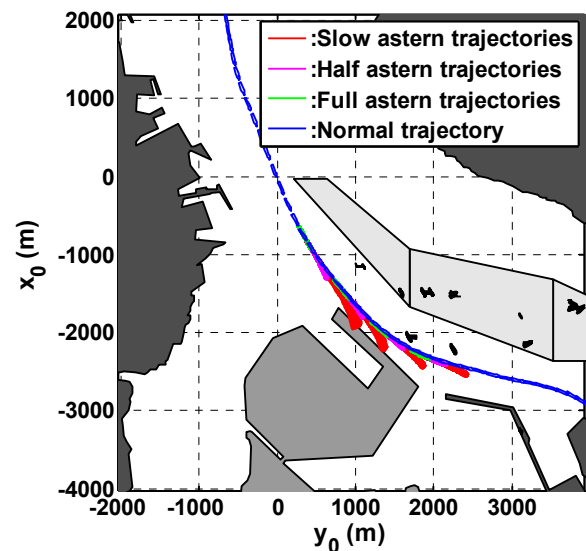


Figure 15. The PAWs by initial yaw rate in area D.

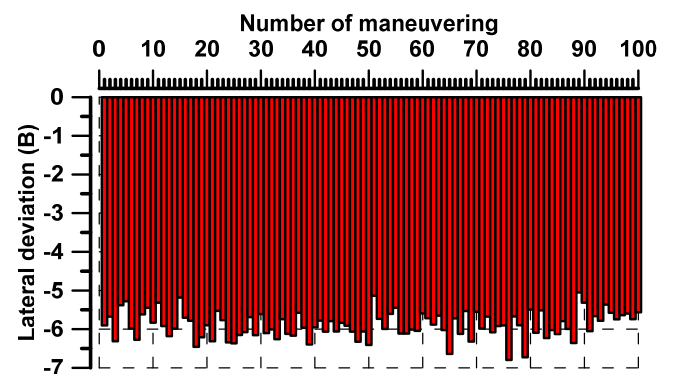


Figure 16. Bar chart of lateral deviation for slow crash astern at $t=1250$.

The initial speeds at the two other initial positions, at $t = 1750$ s, and $t = 2000$ s, are 6.35 and 6.03 kt. The maximum lateral deviations at these positions are $3.14B$ and $1.64B$. The deviations are less than the distance between the fairway and port structure. It means that

the safe speed at this area is around 6 kt. The probability of ships on collision courses of attacking the new port structure upon taking a slow crash astern maneuver is about 50 %. It is estimated based on the probability of ships having speed higher than the safe speed upon entering the existing port area, area E, as presented by Table 1.

5 CONCLUSIONS AND FUTURE WORKS

A new method of developing the PAW is introduced. The method was developed based on the position when the maneuver is ordered and the distribution of yaw rate in the area of the position. The distribution of yaw rate is estimated using a maneuvering simulation and AIS data. The new PAW is implemented to propose a method to estimate the probabilities of ship on collision course upon taking crash astern maneuvers. The methods were implemented in Madura Strait and conclusions obtained from the analysis of PAW in the research area are as follows:

- 1 Area B, the area located before the anchorage zones, and area D, the area between the anchorage zones and the new port of Lamong Bay, are considered danger areas.
- 2 The accident probability of the subject ships on collision courses upon taking a slow crash astern maneuver at the end part of area B will be 77% if the initial speed of the maneuver is about 8 knots.
- 3 The subject ship will attack the structure of the new port upon performing the maneuver at the first half of area D.
- 4 The maximum safe speed of the subject ship to avoid collision with port structure is about 6 knots.
- 5 The probability of ships on collision courses at the port area is estimated based on the distribution of ships' speed in the area, and the probability of ships to attack the new port structure upon taking the slow crash astern maneuver is 50 %.

The subsequent phase of this research will analyze the probability of ships taking a crash astern maneuver, develop the PAW for maneuvering of other types of ships, and analyze the implementation of the method in any other developing port areas.

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