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Analysis of Berthing Safety using Maneuvering Simulation and Berthing Aid System

I.P.S. Asmara[1*], M.A. Mustaghfirin[2], K. Abdullah[3], C.A. Firmansyah[4]

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***Abstract*— Collisions of ships to cranes in container terminals are attracting attention from the maritime safety community. This paper provides a berthing safety analysis using the berthing aid and automatic identification systems. First, a berthing aid system is developed to measure berthing safety, as speed and angle indicate. The berthing aid system installed in a berth consists of two laser sensors to measure ships' distances, speed, and heading during the berthing maneuver. Second, a berthing maneuver simulation is conducted to determine tugboat elements, consisting of the number and capacity of tugboats, using a time series of thrust power and direction. The elements are simulated to achieve the berthing safety indicated by the time series of speed over the ground, course over the ground, and the ship's heading angle relative to the berth. The monitoring of ship trajectory using an automatic identification system in the port area and berthing safety parameters along the end stage of the berthing maneuver using the berthing aid system has been implemented in this research. The measurement proved that the berthing maneuvers comply with the requirements.**

Keywords—pilotage, container ship, berthing speed, berthing angle, collisions

Corresponding Author : putusindhu@ppns.ac.id

I. INTRODUCTION

Tug handling operation is one of the elements contributing to port operations' safety. Pilotage performance depends on information and recommendations a marine pilot delivers to the captains of vessels and tugboats. The pilot is responsible for ensuring the success of the berthing operation by following the route planned to avoid stranding in shallow water and finally berthing at the jetty by complying with the requirements of maximum berthing speed and approaching angle. Complying with the requirements means preventing collision with the port facilities and complying with the allowable impact energy between the hull and fender. Accordingly, the bigger the vessel, the lower the berthing speed allowed. The captain should minimize the berthing angle to decrease the collision probability between the bow and the facility installed at the harbor.

Ishikura et al. introduced three elements for tugboat handling: percentage, direction, and duration of propelling tugboat power [1]. The implementation of optimum tugboat elements in ship handling operations will ensure the achievement of safety and efficiency. Compliance with the Permanent International Association of Navigation Congresses (PIANC) requirement on a maximum berthing speed and a maximum berthing angle at the end of the berthing maneuver indicates safe operation. Toward the position at the distance of 0 m from the jetty, the port operator should control the two parameters during the end stage of the maneuver. The phase started at the ship position, which had distances of 80 m, 60 m, 40 m, and 20 m apart from the fender of the jetty. It will effectively control the swaying motion of the vessel to the jetty. The optimum handling elements are intended to improve the bollard pull efficiency or minimize the pilotage time. The speed follows the port's approaching channel until the position of 80 m from the jetty, which also contributes to the tugboat's usage efficiency.

Kang et al. used a docking aid system (DAS) to measure the berthing speed and analyzed the data to categorize pilots [2]. Berthing speed is one of the variables used to calculate berthing operation risk. Hejun et al. proposed a method of berthing operation risk using the berthing speed and distance between the ships [3]. Hejun classified the risk into six levels: extremely safe, safe, slightly safe, slightly dangerous, dangerous, and extremely dangerous. Lee et al. grouped the berthing speed into safety, warning, and critical [4]. Lee and Kang used the DAS to measure the berthing speed. Berthing velocity leads to the kinetic energy of the berthing operation. Gucma et al. assessed maneuvering safety based on kinetic energy [5]. The berthing speed is controlled by tugboats or bow thrusters. In this research, the tugboats are simulated to control it. Gerigk et al. introduced the deficiency of bow thrusters on the safety of the quay structure [6].

Pilotage in a new port or a case port handles a vessel with a capacity higher than usual; the port authority will ask the port operator to do a berthing and un-berthing analysis and present the results regarding the tugboat elements or steering system and thruster capability. The maneuvering analysis is conducted by doing simulations using bridge simulators. Although the facility is

I.P.S. Asmara, Ship Building Engineering Dept., Politeknik Perkapalan Negeri Surabaya, Jalan Teknik Kimia Kampus ITS Sukolilo Surabaya, 60111, Indonesia, E-mail: putusindhu@ppns.ac.id
M.A. Mustaghfirin, Marine Engineering Dept., Politeknik Perkapalan Negeri Surabaya, Jalan Teknik Kimia Kampus ITS Sukolilo Surabaya, 60111, Indonesia, E-mail: mustaghfirin@ppns.ac.id
K. Abdullah, Ship Building Engineering Dept., Politeknik Perkapalan Negeri Surabaya, Jalan Teknik Kimia Kampus ITS Sukolilo Surabaya, 60111, Indonesia, E-mail: kharis.abdullah@ppns.ac.id
C.A. Firmansyah, PT Terminal Peti Kemas Surabaya (TPKS), Surabaya, Indonesia, E-mail: cahya.ardie@ymail.com

relatively expensive, almost all nautical study programs are equipped with a simulator. Unfortunately, the port maps data installed at the simulator do not cover several domestic ports in Indonesia. The authors developed a 2D plot of a berthing and un-berthing simulator based on the 3 DOF of the Maneuvering Modeling Group (MMG). The iterations of surging force, swaying force, and yawing moment due to the percentage of bollard pull usage and its direction to comply with PIANC requirements are the main problems for the tug operator who has not had experience with pilotage operation.

This research aims to propose a method of berthing safety by developing a framework for enhancing the determination of tugboat elements toward the implementation of automatic pilotage, to determine the maximum environmental conditions on the port operation manual, and to measure if the berthing criteria comply with the PIANC requirements.

II. LITERATURE REVIEW

Wu et al. developed a linear mathematical model of tugboat cable force in a study to simulate a berthing maneuver assisted by two tugboats [7]. The mathematical model of 3 DOF maneuvering equations for tugboat handling was developed. The study assumed the vessel had no propelling power and thruster and neglected the hydrodynamic interaction between the ship and the tugs. The derivative equation of MMG was solved using the Runge-Kutta method. This study analyzed the different time domain speeds between the ship and the tugboats, achieving the final speed of 0.45 m/s. This study considered the effect of wind disturbance on the surging, swaying, and yawing motions.

A study by Wakita et al. has introduced their work in developing Neural Network identification for low-speed maneuvering models [8]. The proposed prediction of the maneuvering model focused on developing optimization methods using a loss function. The function evaluated the position and velocity derived from the numerical simulation instead of directly evaluating the instantaneous accelerations performed by other researchers. The study improved the precision of the prediction model by avoiding the usage of measured accelerations in the loss function containing noise due to the actual environment. The research compared the predicted trajectory to two other trajectories from the experiment and the MMG Model. The MMG model in the study was introduced by Yasukawa and Yoshimura [9]. Yasukawa introduced the Maneuvering Modeling Group (MMG) standard method equipped with the hydrodynamics coefficient of the KVLCC2 tanker as the case study. Wakita performed the research using the model of the M.V. ESSO OSAKA tanker. The hydrodynamic coefficient of the vessel was derived from Yoshimura et al. [10].

Yoshimura et al. introduced a new mathematical model of hydrodynamic hull force in the ocean and harbor [11]. The maneuvering model is equipped with the hydrodynamics coefficient derived from the Pure Car Carrier (PCC) model and the research ship model, with a block coefficient of less than 0.547 and 0.5743, respectively. The coefficients are appropriate for maneuvering in the ocean and harbor. The coefficient should be evaluated because of the effects of the ship's bottom vessel and seabed surface interaction. Kobayashi has developed the effects of shallow water on the hydrodynamic coefficient [12]. The effects are significantly dependent on the block coefficient and beam-to-length ratio. Yoshimura and Masumoto published the hydrodynamic coefficients of two Japanese fishing vessels, two European fishing vessels, five fishery research vessels, one PCC, two container ships, and one research vessel [13] [14].

Researchers defined automatic berthing as the vessel achieving the target point at a speed of 0.2 m/s at maximum and a heading angle of 250 to 270 degrees Yoshimura and Masumoto [14]. That allowable berthing speed is the same as the PIANC requirement for a vessel with a displacement of 50,000 tons or more. The standard direction of the jetty in that definition is 270 degrees, so the maximum allowable relative heading to the jetty is 20 degrees. This researcher proposed a berthing control system using ANN's back-propagation algorithm to achieve minimum error between the system outputs and the teaching data of rudder angle, propeller revolutions, tugboat configuration, and thruster forces. The MMG model used in this research was a mathematical model developed by Ogawa and Hamamoto [15].

A study by Bui et al. designed a berthing system for unactuated ships assisted by four tugboats [16]. The effectiveness of actuator forces in a low speed of maneuvering in the harbor is low, so the tugboats eliminated it. This research optimized the configuration of thrust and direction of each tug using the redistributed pseudo-inverse (RPI) algorithm. The approach lane was designed to be about 45 degrees relative to the direction of the jetty, and the berthing length is about one ship length. This research used a mathematical model with a mass/inertia matrix and a linear damping matrix. The values of matrix elements were derived from the Cyber ship I model, an offshore supply vessel model. The vessel has four thrusters, but they are inactivated in this research. The design was implemented in the approaching and berthing phases to optimize tugboats' power and increase their controllability. Recently, the mathematical model of MMG used the nonlinear differential equation with nonlinear hydrodynamics coefficients representing the damping matrix, but this research used the linear model.

Tomera designed a controller of a ship autopilot based on the nonlinear mathematical maneuvering model using a PID controller [17]. The research used the numerical hydrodynamics model of Cybership II, which considered the disturbances of waves. Time domain analysis results were compared to similar controllers in calm and disturbances water. A cost function consisting of heading angle deviation and rudder deflection was implemented to compare the controller's performance. In this research, the mathematical maneuvering model considered the matrix of damping forces consisting of linear and nonlinear hydrodynamic coefficients according to Fossen's model published in a book [18]. The book described and discussed the 6 DOF and 3 DOF motion equations of marine vehicles, which were completed with the description of the hydrodynamic damping coefficient and the models of wind, wave, and ocean currents.

Gil et al. determined a critical maneuvering area to avoid collision based on a numerical ship motion model called the LaiDyn model, the 6 DOF allowing the analysis of maneuvering and seakeeping in regular and irregular waves, but the research was applicable in negligible weather conditions [19]. This research introduced a minimum maneuvering area in an encounter between two vessels. The target vessel was assumed to have taken a straight path, and the own ship took a turning maneuver for collision avoidance. The maneuvering was started at the position of the Minimum Distance to Collision (MDTC). The concept is called the Collision Avoidance Dynamic Critical Area (CADCA) simulator, using an added mass matrix based on strip theory and retardation function depending on the damping matrix.

Wu et al. published the berthing maneuver of catamaran unmanned surface vehicles using a maneuvering model consisting of linear and nonlinear hydrodynamic derivatives. They considered a complex port condition with the model's disturbances of wind, wave, and current [20]. The catamaran vessel with the left and right propellers was simulated to perform the stopping distance by reversing the propeller revolution. The non-dimensional hydrodynamic forces and moment with the hydrodynamic derivatives used in the model were adopted from Kijima [21]. Kijima introduced the approximate formula for the hydrodynamic forces in any loading condition. The formula was derived from the model test data of 13 general cargo, car carriers, and RORO ships.

Authors have contributed to the simulation of tugboat handling ships' maneuverability in customized new ports and developing ports in Indonesia [21][22][23]. This research enhanced the determination of tugboat elements as a preparation stage for implementing automatic pilotage. As a case, a simulation of a container ship in Surabaya Container Port yielded tugboat elements in the maximum wind, wave, and sea current speed conditions.

TABLE 1.
SUGGESTED APPROACH VELOCITY (MEAN VALUES, M/S)

Vessel Displacement in tons	Favorable Conditions	Moderate Conditions	Unfavorable Conditions
Under 10,000	0.30 – 0.16	0.45 – 0.30	0.60 – 0.40
10,000 – 50,000	0.12 – 0.08	0.30 – 0.15	0.45 – 0.22
50,000 – 100,000	0.08	0.15	0.20
Over 100,000	0.08	0.15	0.20

The approach velocity is the perpendicularly measured vessel speed at initial berthing contact with the port Motora [24]. It depends on the ship's displacement, as shown in Table 1.

The berthing angle also reduces the energy absorption capacity of fenders. The suggested berthing angle for vessels larger than 50,000 DWT is at most 6 degrees based on measurements in Japan. The berthing angle for smaller ships is 10-15 degrees. It is 8-10 degrees for feeders/coasters, and for barges, it is 15 degrees.

III. METHOD

In this study, we use a 3 DOF MMG model proposed by Yoshimura and Masumoto (2011, 2012) [13], [14], which includes the forces of tugboats and external disturbances such as wind and sea currents. Equations 1 to 3 described in Asmara et al. [22], [23], [25] added new variables of tug surging force X_T, tug swaying force Y_T, and tug yaw moment N_T. The tugboat elements are simulated to meet the requirements of PIANC 2002 [26] [27]. Applying Newton's law, the 3 DOF MMG model expressed the surging, swaying, and yawing motion of vessels represented in Equations 1 to 3. The equations consider the forces of wind disturbance. The model adopted the MMG model with the approximation of the linear and nonlinear hull derivatives published by Yoshimura and Masumoto [13], [14]. The equations consisted of tugboat forces eliminating the forces and moment of the propeller and rudder.

$$(m+m_x)\dot{v}_G-(m+m_y)v_G r_G = X_H+X_P+X_R+X_W+X_C+X_T \quad (1)$$

$$(m+m_y)\dot{v}_G+(m+m_x)u_G r_G = Y_H+X_P+Y_R+Y_W+Y_C+Y_T \quad (2)$$

$$(I_{zz}+J_{zz})\dot{r}_G = N_H+N_P+N_R+N_W+N_C+N_T \quad (3)$$

In the left part, m and I_{zz} are the ship's mass and moment of inertia for yawing motion, respectively. m_x, m_y, and J_{zz} denote added mass for surging motion, added mass for swaying motion, and added moment of inertia, respectively. u_G, v_G, and r_G are surging velocity, swaying velocity at the canter of gravity, and yawing rate, respectively. x_G is the longitudinal canter of gravity of the ship from mid-ship. In the right part, X, Y, and N denote surging force, swaying force, and the yawing moment, respectively. Subscript H, P, R, W, C, and T denote the ship's hull, propeller, rudder, wind, current, and tugs, respectively.

Figure 1 shows the body-fixed and space-fixed coordinate systems. β, δ, and ψ denote the drift angle, rudder angle, and the ship's true heading, respectively. The added mass and added mass moment of inertia are calculated according to diagrams from Motora [24], [28], [29]. The ship mass, m, is calculated based on the density of the water in Tanjung Perak, 1.021 gr/cm^3 Williams [30]. The model covers the effects of shallow water according to equations from Kobayashi [12]. The effects of wind on ship maneuvering are estimated using equations from Fujiwara et al. [31]. The current effect is calculated based on the relative velocity [32]–[34].

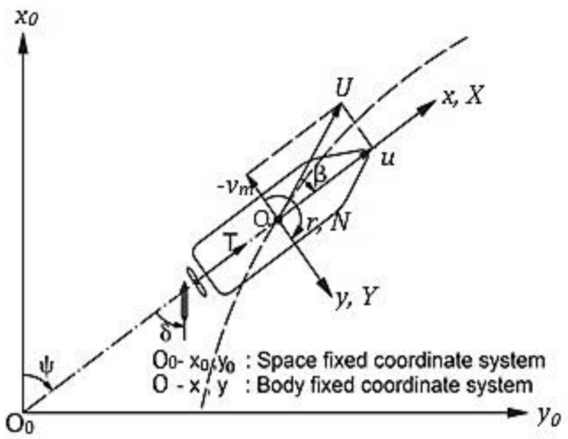


Figure. 1. Coordinate System of MMG

Surabaya Shipbuilding State Polytechnic, Politeknik Perkapalan Negeri Surabaya (PPNS), has installed an AIS receiver in the Surabaya Container Terminal, Terminal Petikemas Surabaya (TPS). The PPNS-AIS is one of the counterparts of vesselfinder.com. The AIS data is also collected and derived from the PPNS-AIS server. In the pilotage operation, the vessel following the western part of the Surabaya channel is monitored from vesselfinder.com. The berthing aid system equipped with lasers has been installed in dock 4 of TPS to monitor the berthing speed and berthing angle. Figures 2 (a) and (b) show a vessel berthing in dock 4 of TPS and the monitor of the PPNS Berthing aid system (BAS).

IV. RESULTS AND DISCUSSION

The subject ship is a container ship with a capacity of 2872 TEUs, as seen in Table 2. The vessel berthed in dock 4 of the Surabaya Container Terminal, Terminal Petikemas Surabaya (TPS).

TABLE 2.
SHIP DIMENSIONS

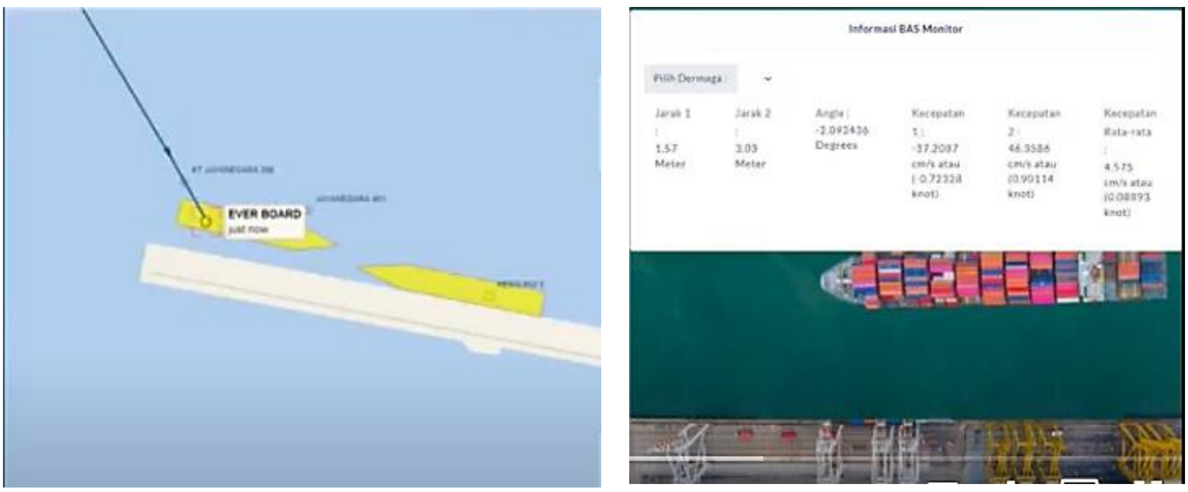
Ship Dimensions	Value
LOA (m)	210.98
DWT (t)	36972
Capacity (TEUs)	2872
Beam (m)	33
Draught (m)	10.5
Block Coefficient	0.65

According to data from Meteorology, Climatology, and Geophysics Council in Tanjung Perak Station, the high current speed of up to 0.87 m/s, the low tide is -1,2 m, the high tide is 0.6 m, and the maximum wind speed is 12 knots as seen in Table 3. The water depth of the turning basin is 15 m. The vessel berthed on the starboard side in condition 1 and on the port side in condition 2.

TABLE 3
ENVIRONMENTAL CONDITIONS

Environmental Condition	Condition-1	Condition-2
Maximum wind speed (knots)	12 (NW to SE)	12 (NW to SE)
Maximum current velocity (m/s)	0.87 (East to West)	0.87 (West to East)
Maximum tidal (m)	0.6 (High Tide)	-1.2 (Low Tide)
Water Depth (m)	15	15

Figure 3 presents the berthing simulation of the subject ship handled by three tugboats with a 2x45 tons bollard pull capacity in condition 1. Figure 3 shows the ship's trajectory in blue, and the simulation plotted the vessel's movement every 60 seconds. The jetty of Surabaya Container Terminal has four docks, as seen in Figure 3, and the ship is berthed at dock four on the starboard. In the berthing simulation, according to a discussion with the port pilot, the initial speed of the vessel is at most 3 knots in condition 1, and the current speed is 0.87 m/s. Figure 3 shows that at the first stage of the un-berthing maneuver the bow moved and turned to follow the center of the port channel.



(a) (b)

Figure. 2. PPNS monitoring system: (a) AIS (vesselfinder.com), (b) BAS

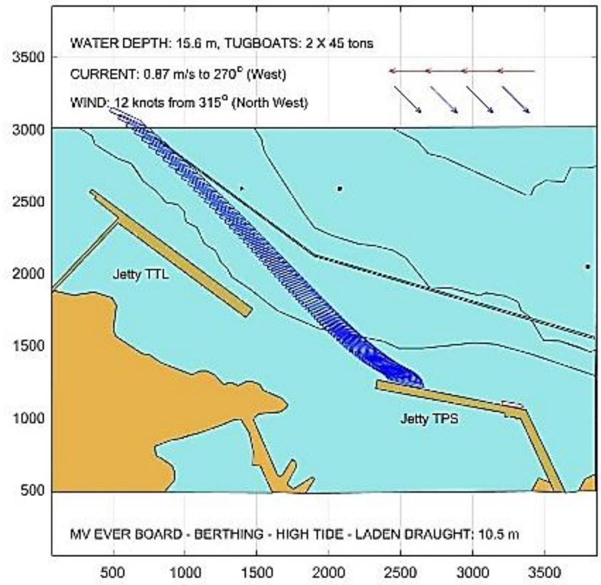


Figure. 3. Berthing Trajectory Simulation in Condition 1

Figure 4 shows that the berthing speed is 0.4923 knots or 0.25 m/s. It does not comply with the moderate requirement of PIANC for the favorable condition where the maximum berthing speed is 0.3 m/s for vessels having a displacement of less than 50,000 t and more than 10,000 t. The berthing angle is 107.5 degrees or 7.5 degrees relative to the jetty, which also complies with the PIANC requirement of not more than 15 degrees. Figure 4 shows the ship's speed, heading, and trajectory time series. The initial speed for the un-berthing maneuver is the same as the current speed, which means that the ship drifted to the West, but the dock structure stopped her.

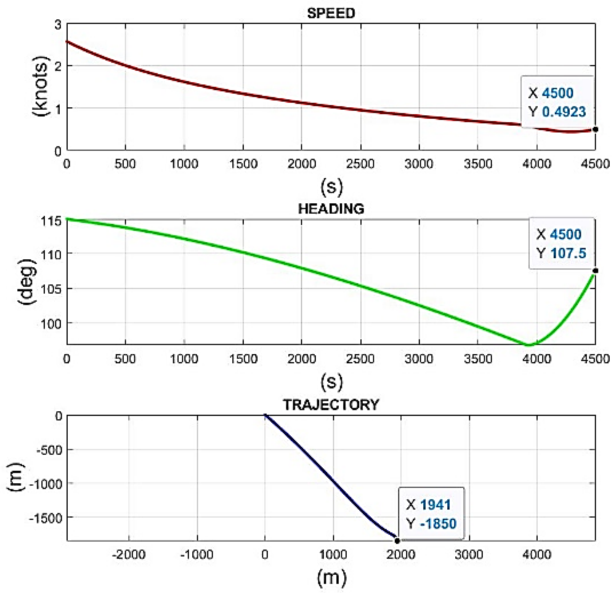


Figure. 4. Berthing Speed, Heading, and Trajectory in Condition 1

TABLE 4.
BERTHING PROCEDURE OF TUGBOATS IN ENVIRONMENTAL CONDITION 1

Step		1	2	3	4
Time (s)		0 to 2900	2900 to 3200	3200 to 3600	3600 to 4500
Engine Status		off	off	off	off
Rudder Angle		0°	0°	0°	0°
Astern Tug, 45 tons BP	Force	20%	20%	60%	60%
	Direction	180°	-160°	90°	180°
Forward Tug, 45 BP	Force	60%	20%	60%	60%
	Direction	-1.5°	20°	90°	-90°

According to the Regulation of the Indonesian Transportation Ministry, the capacity of tugboats to handle a ship having a length of 150 m to 250 m is a minimum 65 t bollard pull. Table 4 presents two tugboats handling the vessel with a total capacity of 60% of 2x45 or 54 t bollard pulls. The berthing maneuver has four steps: pulling, turning, pushing, and stopping. In the first step, the forward tugs pulled the vessel from the initial position at the center of the channel to approach the jetty. In the second step, the forward and astern tugs turned the ship into a heading of about 100 degrees to parallel the ship with the dock. At the position about 100 m apart from the jetty, at step 3, both tugs pushed the vessel to the starboard, and at step 4, the tugs took a correction by pulling to the portside to decrease the speed of stopping action. The tugs start the task from 3 nm at the jetty, but in this simulation, the initial position is at the channel with the same latitude as the north side of the jetty of Terminal Teluk Lamong (TTL). The maneuver takes 4500 seconds or 1 hour and 15 minutes from the initial to dock 4 of TPS.

In condition 2, the vessel is berthing following the current direction. Berthing maneuver in this condition is more complex than in condition one due to the difficulty of controlling the maneuvering speed. The port pilot suggested that the speed at the initial condition is at most 2 knots. Figure 5 shows vessels entering the anchorage area between the green and red buoys due to difficulty controlling the drifting motion. The speed decreased when the vessel was turned and pushed to dock 4. Figure 6 shows that the speed of the berthing maneuver decreased at the end stage. The berthing speed is 0.2796 knots or about 0.14 m/s, which complies with the PIANC favorable condition. The berthing heading is 274.5 degrees, and the berthing angle is only 5.5 degrees.

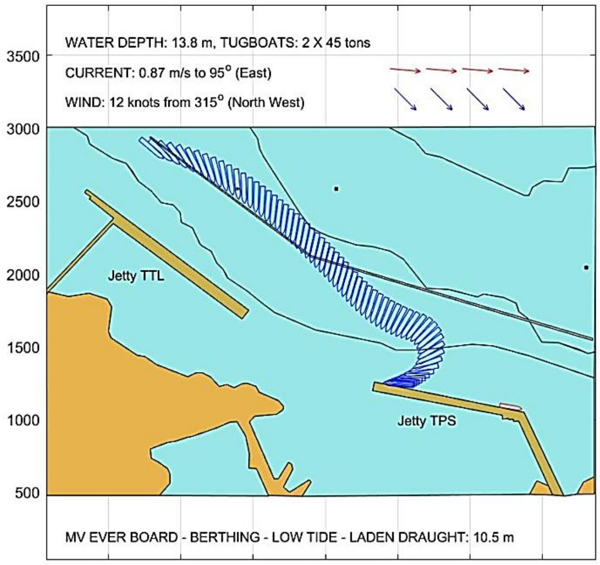


Figure. 5. Berthing Trajectory Simulation in Condition 2

The berthing maneuver in condition 2 has four steps and uses three tugboats, as seen in Table 5. In the first step, the forward and mid-ship tugs use their full power (85%) to decrease the drifting motion. At the second step, the mid-ship tug moved to the astern and pulled the vessel backwards to decrease the speed. The maneuvering speed can be decreased significantly by pushing the vessel to the starboard side at step 4, and at the final step, the vessel is pushed to dock 4.

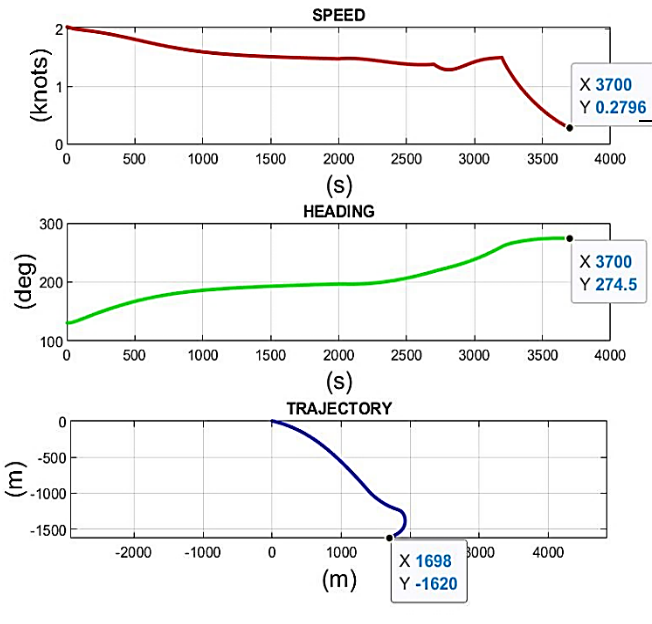


Figure. 6. Berthing Speed, Heading, and Trajectory in Condition 2

TABLE 5.
BERTHING PROCEDURE OF TUGBOATS IN ENVIRONMENTAL CONDITION 2

Step		1	2	3	4
Time (s)		0 to 2000	2000 to 2700	2700 to 3200	3200 to 3700
Engine Status		off	off	slow	off
Rudder Angle		0º	0º	0º	0º
Astern Tug, 45 tons BP	Force	-	60%	-	60%
	Direction	-	180º	-	180º
Mid-ship Tug, 45 tons BP	Force	85%	-	-	-
	Direction	90º	--	-	-
Forward Tug, 45 BP	Force	85%	60%	-	60%
	Direction	75º	90º	-	90º

Table 6 shows the berthing speed and angle of five vessels derived from the berthing aid system. The table indicates that the TPS's berthing maneuvers in dock 4 comply with the requirements.

TABLE 6.
COMPILATION OF BERTHING PARAMETERS MEASURED BY BERTHING AID SYSTEM

Name of Ships	Displace-ment (tons)	Berthing Speed (m/s)	Berthing Angle (degrees)	Status
MV EVER BOARD	36,972	0.45	2.49	Pass
MV. EVER BASIS	37,561	0.37	0.83	Pass
MV. BRIGHT LAEM C	17,852	0.10	2.00	Pass
MV. SPIL NATA	33,742	0.10	0.17	Pass
MV. YM HORIZON	19,104	0.17	3.49	Pass

V. CONCLUSION

This study simulated the elements of tugboat handling for the berthing procedure of a container vessel in the Surabaya Container Terminal based on two scenarios of environmental conditions. The simulation confirms that the berthing maneuver in condition 1, against the current, has a better trajectory than condition 2. Berthing in condition 2, following the current speed of 0.87 m/s, has an opportunity to drift to the anchorage area. The simulation has determined the number and capacity of tugboats, the time series of tugboat bollard pull, and the time series of tugboat force direction to achieve the berthing speed and angle requirement. The study of berthing speed and angle in the study area has been validated by the measurement using a monitoring system based on laser sensors called the Berthing aid system (BAS). The Automatic Identification System (AIS) has been installed in the port of TPS and provided data to monitor the vessel entering and following the West part of the Surabaya Channel in Madura Street. The simulation is operated by iterating the tugboat elements and takes a long time to comply with the PIANC criteria. Future work will develop an algorithm to optimize the elements

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