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An alternative portable dynamic positioning system on a barge in short-crested waves using the fuzzy control

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Abstract. The paper described the nonlinear dynamic motion behavior of a barge equipped with the portable outboard Dynamic Positioning (DP) control system in short-crested waves. The DP system based on the fuzzy theory is applied to control the thrusters to optimally adjust the ship position and heading in waves. In addition to the short-crested waves, the current, wind and nonlinear drifting force are also included in the calculations. The time domain simulations for the six degrees of freedom motions of the barge with the DP system are solved by the 4th order Runge-Kutta method. The results show that the position and heading deviations are limited within acceptable ranges based on the present control method. When the dynamic positioning missions are needed, the technique of the alternative portable DP system developed here can serve as a practical tool to assist those ships without equipping with the DP facility.

Keywords: fuzzy control; time domain; dynamic positioning; short-crested waves

1. Introduction

The Dynamic Positioning (DP) control system can maintain the position and heading of a ship precisely in the ocean by using thrusters, which is very important to adjust ship's position relative to a mobile object such as the remotely operated vehicle (ROV). The first DP system was designed for a plane with the horizontal motion (surge, sway and yaw) by the single-input single-output (SISO) PID controller in the 1960s (Fay 1989). Generally, most vessels with DP system adopt azimuth thrusters and propulsion propeller to generate thrust forces to maintain the desired position and heading in the horizontal plane (Morgan 1978). DP systems incorporating with different control techniques based on linear optimal and Kalman filter theories were already applied to deal with the ship dynamic positioning problems by many authors, e.g., Balchen (1980) and Sørensen, *et al.* (1996). However, the Kalman filter generally needs to be combined with the other analytical technique for further practical applications (Saelid *et al.* 1983). Besides, Stephens *et al.* (1995) also successfully applied the nonlinear fuzzy controller to handle the ship dynamic positioning system. Inoue and Du (1995) brought a concept of the self-tuning fuzzy control system on a DP system that the control strategy is improved automatically according to the sea conditions

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of operation. Lee *et al.* (2002) also developed the DP system based on the fuzzy theory, which is applied to the control outputs including the rudder angle, propeller thruster and a lateral bow thruster to counteract the environmental forces, maintaining a ship in the desired position at sea. Tannuri and Donha (2000) used a H_∞ methodology in the controller design of a dynamic positioning system for a floating production storage and offloading vessels (FPSO) turret moored in deep water. Johansen (2005) reported a pilot study of Hardware-in-the-loop (HIL) testing on the DP computer system hardware and software. Perez and Donaire (2009) proposed a design based on a combined position and velocity loops in a multi-variable, anti-windup implementation. Tannuri *et al*. (2010) raised a vessel DP system which is based on a sliding mode conventional PID-type controller to overcome the nonlinearity of the system and environment. Sørensen (2011) indicated that incorporating PID controllers with output feedback control, nonlinear control or hybrid control can improve the performance and operability of the DP system on board, which makes the ship satisfy a variety of missions and environments.

The references stated above focus on two types of ships: (1) professional vessels which are already equipped with a DP system on board at the initial designed stage, (2) ships without DP devices, utilizing the rudder to control thrust vector. The objective of the present study is to apply the outboard thrusters with automatic controllers as a portable DP system to those vessels without DP devises, e.g., barges. It's an effective dynamic positioning tool, especially in executing the underwater ROV mission using the vessels without equipping the DP system. In order to simulate the real sea environment, the short-crested waves, ocean current, wind and nonlinear drifting force are also considered in the calculations.

The concepts of the portable thrusters feature in the present DP systems are similar to the "Dynamic Positioning System" of "Thrustmaster of Texas" company announced in 1988 (Maritime Reporter 2002). However, costly Azimuth thrusters are used in the DP system of "Thrustmaster of Texas," whereas general propeller thrusters are adopted in the present study, which will be more economical. Besides, the DP control algorithm of "Thrustmaster" is not publicly released, therefore the present study tries to develop a different type of DP system with optimal control based on the fuzzy algorithm.

The motives for using fuzzy control on the DP system are due to the uncertainty from the sea states and the nonlinear ship motion behaviors. Among many controllers, the PD or PID control is commonly adopted and the neural network algorithm is also applied to make the operation more efficient. For instance, Hemerly and Nascimento (1999) applied the neural network adaptive control algorithm to train the controller and simulate the related control parameters for PID controller. Fang and Zhuo (2010) also applied the self-tuning neural network PID controller to reduce the ship roll motion in random waves. Du *et al*. (2013) developed a neural controller using the vectorial backstepping technique for ship dynamic positioning with uncertainties and unknown disturbances. However, the neural network PID controller needs to be trained in many cases before work in the real condition and lacks of the physical intuition in the practical system adjustment.

The fuzzy control has no such limitations, e.g., Fang and Chiou (2000), Inoue and Du (1995) and Lee *et al.* (2002). The fuzzy control based on the fuzzy set theory is raised by Zadeh (1965). Fuzzy set is extended from traditional set and using infinite values of membership functions to describe one set. Mamdani (1974) then further applied the fuzzy set theory to the control technique based on the concept of Linguistic Approach and fuzzy inference. In order to obtain the best system parameters, several optimization techniques were also incorporated, e.g., self-tuning fuzzy controller (Fang and Chiou 2000, Inoue and Du 1995, Ho *et al*. 2013). Here the DP system based on the fuzzy algorithm is adopted, which system parameters are suitable and stable for the practical applications.

The present study applies the fuzzy system to control the revolutions per minute (R.P.M.) of propellers i.e., two stern thrusters and one bow thruster create the forces to counteract the environmental forces. The wave forces on the barge in the real sea state are based on the short-crested waves approach. The formulas of the wave spectrum expressed by International Towing Tank Conference (ITTC) (Michel 1999 and ITTC 2005) were adopted here, which contains the two parameters, significant wave height and average period. Depending on the irregular wave method based on the wave energy spectral analysis theory was closer the accurate ship motions and forces at sea than using the regular wave method.

The nonlinear mathematical model developed in the present paper, including seakeeping and maneuvering characteristics, has a set of ordinary differential equations (O.D.E.) which are needed to solve the six degrees of freedom (6 DOF) motions of the barge with the DP system in random waves. It is seen that the time domain approach is more direct and accurate and can include nonlinear contributions which are typically neglected in the linear frequency domain approach (Kang and Kim 2014). Hence the 4th order Runge-Kutta method is then applied to solve the time domain motion simulations of the barge. The portable outboard DP system consisting of one sideward bow thruster and two forward stern thrusters, and the operations controlled by applying the fuzzy algorithm with respect to different sea states are investigated. As the original design of the ship may not have the DP system, applying portable outboard thrusters as the DP system might be a good alternative idea which is suggested in the present study. The results show that the technique developed here can serve as an effective simulation tool to improve the stability and the safety for the ship with the portable dynamic positioning requirement at random sea.

2. Mathematical formulas

2.1 Equations of motions

The extensive nonlinear equations of 6-DOF ship motions with fuzzy DP control based on the mathematical model developed by Fang and Luo (2005) are shown as below

$$m\left(\dot{u}-v\dot{\psi}\right)=\left(m_y(\omega_e)-X_{v\dot{\psi}}\right)v\dot{\psi}-m_x(\omega_e)\dot{u}-m_x(\omega_e)z_G\ddot{\theta}-m_z(\omega_e)w\dot{\theta}+X_{FK}(\omega_0)+X_{WF}-R+X_D+F_{cx}+F_{Tx} \tag{1}$$

$$m\left(\dot{v}+u\dot{\psi}\right)=-m_x(\omega_e)u\dot{\psi}-m_y(\omega_e)\dot{v}+m_y(\omega_e)z_G\ddot{\phi}-Y_v v-Y_{\ddot{\psi}}\ddot{\psi}+Y_{\dot{\psi}}\dot{\psi}+Y_{v|v|}v\left|v\right|+Y_{v|\dot{\psi}|}v\left|\dot{\psi}\right|+Y_{\dot{\psi}|\dot{\psi}|}\dot{\psi}\left|\dot{\psi}\right|+Y_{FK}(\omega_0)+Y_{DF}(\omega_e)+Y_{WF}+Y_D+F_{cy}+F_{Ty} \tag{2}$$

$$m\dot{w}=-m_z(\omega_e)\dot{w}-Z_w(\omega_e)w-Z_{\ddot{\theta}}(\omega_e)\ddot{\theta}-Z_{\dot{\theta}}(\omega_e)\dot{\theta}-Z_\theta(\omega_e)\theta+Z_{FK}(\omega_0)+Z_{DF}(\omega_e)+mg \tag{3}$$

$$I_{xx}(\omega_e)\ddot{\phi}-I_{xx}(\omega_e)\dot{\theta}\dot{\psi}=J_{xx}(\omega_e)\dot{\theta}\dot{\psi}-J_{xx}(\omega_e)\ddot{\phi}-K_{\dot{\phi}}\dot{\phi}+m_y z_G\dot{v}+(Y_v v-Y_{\dot{\psi}}\dot{\psi})z_G+K_{FK}(\omega_0)+K_{DF}(\omega_e)+K_{WF}+N_{Tx} \tag{4}$$

$$I_{yy}(\omega_e)\ddot{\theta}+I_{xx}(\omega_e)\dot{\psi}\dot{\phi}=-J_{xx}(\omega_e)\dot{\phi}\dot{\psi}-J_{yy}(\omega_e)\ddot{\theta}-M_{\dot{\theta}}(\omega_e)\dot{\theta}-M_{\theta}(\omega_e)\theta-M_{\dot{w}}(\omega_e)\dot{w}-M_{w}(\omega_e)w- m_x z_G\dot{u}+M_{FK}(\omega_0)+M_{DF}(\omega_e)+N_{Ty} \tag{5}$$

$$I_{zz}(\omega_e)\ddot{\psi}-I_{xx}(\omega_e)\dot{\theta}\dot{\phi}=J_{xx}(\omega_e)\dot{\theta}\dot{\phi}-J_{zz}(\omega_e)\ddot{\psi}-N_{\dot{v}}\dot{v}-N_{v}v-N_{\dot{\psi}}\dot{\psi}+N_{\dot{\psi}|\dot{\psi}|}\dot{\psi}\left|\dot{\psi}\right|+N_{vv\dot{\psi}}v^2\dot{\psi}+ N_{v\dot{\psi}\dot{\psi}}v\dot{\psi}^2+N_{\phi}\phi+N_{v|\phi|}v\left|\phi\right|+N_{\dot{\psi}|\phi|}\dot{\psi}\left|\phi\right|+(-Y_v v+Y_{\dot{\psi}}\dot{\psi}+Y_{v|v|}v\left|v\right|+ Y_{v|\dot{\psi}|}v\left|\dot{\psi}\right|+Y_{\dot{\psi}|\dot{\psi}|}\dot{\psi}\left|\dot{\psi}\right|)x_H+N_{FK}(\omega_0)+N_{DF}(\omega_e)+N_{WF}+N_D+N_C+N_{Tz} \tag{6}$$

where m and I are the ship mass and ship mass moment of inertial about each axis of rotation, respectively. u, v and w are the surge, sway, heave velocities; ϕ, θ and ψ are roll, pitch and yaw displacements, respectively. ω_o and ω_e are the wave frequency and the encounter frequency. X, Y and Z represent external forces with respect to surge, sway and heave, whereas K, M and N are external moments respecting roll, pitch and yaw. The subscripts FK and DF represent Froude-Krylov force and diffraction force which are induced by waves; the subscript WF represents the wind force. R is the resistance of the ship; X_D, Y_D and N_D are the longitudinal and lateral drifting force, and the drifting moment in short-crested waves, respectively; F_{cx}, F_{cy} and N_c are current forces and moment, respectively; F_{Tx}, F_{Ty}, N_{Tx}, N_{Ty} and N_{Tz} are the thrust forces and moments due to the DP system for surge, sway, roll, pitch and yaw, respectively. The heave force due to the DP system is not considered in the motion equation. Since the thruster forces are mainly acting on the horizontal plane of the barge, and the vertical components of thrust that caused by ship motion are ignored. The definitions and derivations of the rest variables in Eqs. (1)-(6) can be referred to Fang and Luo (2005).

2.2 Short-crested waves

The irregular waves are encountered mostly at sea. In order to simulate the ship motions realistically in different sea states, the wave forces calculated in this study are based on the short-crested waves method, which are superimposed by many regular waves with respect to different directions. The dominate wave advances along the x_o-axis and two coordinate systems (frames) are used to describe the motion of a DP barge in the horizontal plane as shown in Fig. 1. Frame g-xy is fixed at the center of gravity of the barge and frame o-x_oy_o is the earth-fixed coordinate system.

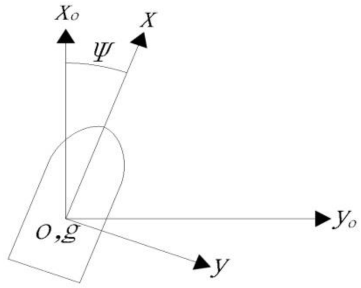


Fig. 1 Coordinate systems in the horizontal plane

The equation and wave pattern based on ITTC-1978 (Michel 1999 and ITTC 2005) wave energy spectrum are described as below

$$S_{aa}(\omega_i) = \frac{172.75 H_{1/3}^2}{\bar{T}^4 \omega_i^5} \exp\left(\frac{-691}{\bar{T}^4 \omega_i^4} \right) \tag{7}$$

$$S_{aa}(\omega_i, \mu_j) = S_{aa}(\omega_i) \times \frac{2}{\pi} \cos^2(\mu_j) \tag{8}$$

$$\zeta_{ij} = \sqrt{2 S_{aa}(\omega_i, \mu_j) \delta\omega \delta\mu} \tag{9}$$

$$\zeta_w = \sum_i \sum_j \zeta_{ij} \cos\left[k_i (X_0 \cos\mu_j + Y_0 \sin\mu_j) - \omega_i t + \varepsilon_{ij} \right] \tag{10}$$

where ζ_{ij} and ε_{ij} are the wave amplitude and the phase angle of the j_{th} wave direction in the i_{th} regular wave, respectively; $H_{1/3}$ is the significant wave height. The characteristic wave period $\bar{T}$ is usually taken as the zero crossing period $\bar{T}_Z$ (Phelps 1995); ω_i is the wave frequency of i_{th} regular wave; μ_j is the angle between the j_{th} wave direction and the dominate wave direction. The angle range is defined as $(-\pi/2 < \mu_j < \pi/2)$. The phase angles ε_{ij} are selected randomly from 0 ~ 2π. In order to approach the real wave pattern and avoid the repeated period, the simulating irregular waves superimposed by suitable numbers of regular wave components is necessary. However, if too many wave components are selected for every direction, the time computational demand would increase rapidly. Therefore, every two-dimensional irregular wave is constructed by 20 regular wave components from the same direction and the short-crested waves consist of two-dimensional irregular waves from 13 wave directions.

Because the complex wave pattern ζ_w is known, the diffraction force acting on the ship body can be obtained. For the short-crested waves built from the regular waves, we need to find the corresponding encounter frequency for calculating added mass and damping coefficient. Practically, the coefficients for a ship sailing in irregular waves can be obtained based on the average frequency $\bar{\omega}$ of the spectrum. (Crossland and Johnson 1998)

$$\omega_e = \bar{\omega} - \frac{\bar{\omega}^2 U}{g} \cos\psi \tag{11}$$

$$\bar{\omega} = 0.5 \left(\frac{2\pi}{1.296 \bar{T}} + \sqrt{\frac{2\pi g}{1.25 L}} \right) \tag{12}$$

where L is wave length. U is the ship speed (m/s), and ψ is the heading angle.

2.3 External environment forces

The related calculations of the external forces, including current force, wind force and wave drifting force are stated in the following.

2.3.1 Current forces (i.e., F_{cx}, F_{cy} and N_c)

The current forces and moment acting on the ship in the ocean with respect to the relative speed and direction between the ship and current can be expressed as

$$F_{cx} = \frac{1}{2}\rho[(V_c cos\alpha - \dot{x}_G)^2 + (V_c sin\alpha - \dot{y}_G)^2]BdC_{cx} \tag{13}$$

$$F_{cy} = \frac{1}{2}\rho[(V_c cos\alpha - \dot{x}_G)^2 + (V_c sin\alpha - \dot{y}_G)^2]L_{pp}dC_{cy} \tag{14}$$

$$N_c = \frac{1}{2}\rho[(V_c cos\alpha - \dot{x}_G)^2 + (V_c sin\alpha - \dot{y}_G)^2]L_{pp}^2 dC_{cn} \tag{15}$$

where F_{cx} and F_{cy} are current forces respecting surge and sway mode of the ship; N_c are yaw moment; V_c is the current speed; α is the angle between the current and ship heading; $\dot{x}_G$ and $\dot{y}_G$ are the ship speed horizontal components with respect to the center of gravity; B, D and L_{PP} are breadth, depth and length between perpendiculars, respectively. The corresponding coefficients C_{cx}, C_{cy} and C_{cn}, are obtained from the empirical formulas (Nienhuis 1986).

The similar concept can also be applied to estimate the wind forces and moment on the ship as shown below.

2.3.2 Wind forces (i.e., X_{WF}, Y_{WF} and N_{WF})

The estimation of the wind forces and moment on the ship based on the formulas developed by Isherwood (1973).

$$X_{WF} = X_W(\gamma_R)\frac{1}{2}\rho_a A_f V_R^2 \tag{16}$$

$$Y_{WF} = Y_W(\gamma_R)\frac{1}{2}\rho_a A_S V_R^2 \tag{17}$$

$$K_{WF} = K_W(\gamma_R)\frac{1}{2}\rho_a \left(\frac{A_S^2}{L}\right) V_R^2 \tag{18}$$

$$N_{WF} = N_W(\gamma_R)\frac{1}{2}\rho_a A_S L V_R^2 \tag{19}$$

where X_{WF}, Y_{WF}, K_{WF} and N_{WF} are the wind forces and moments regarding surge, sway, roll and yaw, respectively; X_W、Y_W、K_W and N_W are non-dimensional coefficients of the wind forces and moments with respect to the relative wind angle γ_R (Isherwood 1973); and ρ_a is the air density; A_f and A_S are the longitudinal and sideward projected area of the ship hull above the water surface, respectively; V_R is the ship speed relative to the wind. Here K_W is generally small; hence K_{WF} can be neglected.

2.3.3 Wave drifting forces (i.e., X_D, Y_D and N_D)

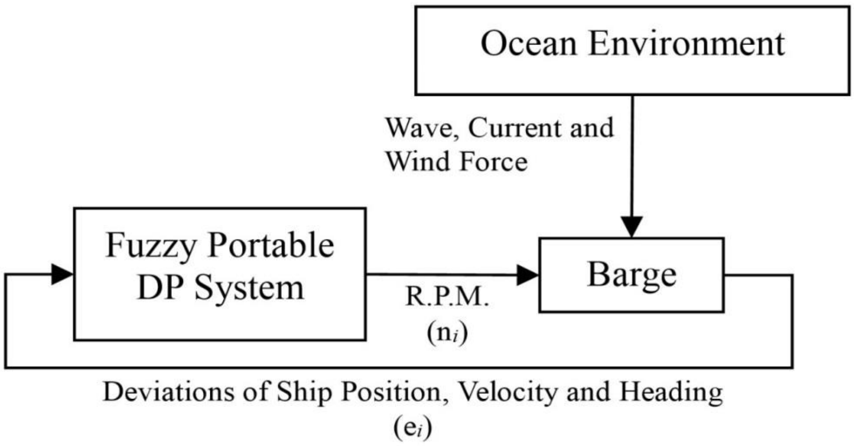


Fig. 2 Control loop of the DP system on the barge

Based on the "weak scatterer" assumption, the nonlinear hydrodynamic forces could be calculated by using the same technique as that of Salvesen (1974).

$$\overline{F}(\omega_e) = R_e\left\{-\frac{1}{2}\rho\iint_{S_B}\left[\phi_B\frac{\partial}{\partial n}-\frac{\partial\phi_B}{\partial n}\right]\nabla\phi_I^* ds\right\} \tag{20}$$

where ϕ_I^* is the complex conjugate of incident wave potential ϕ_I and ϕ_B is the body disturbance potential. The integral is around the ship body surface S_B.

The mean longitudinal and lateral nonlinear forces on the ship with respect to the wave heading μ in short-crested waves can be approximately estimated by

$$X_D = \left|\overline{F}_D\right|\cos\psi \tag{21}$$

$$Y_D = \left|\overline{F}_D\right|\sin\psi \tag{22}$$

where

$$\overline{F}_D = 2\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_0^{\infty}\frac{F(\omega)}{a^2}S_{aa}(\omega,\mu)\cdot d\omega d\mu \tag{23}$$

where $\overline{F}_D$ is the mean nonlinear hydrodynamic force on the ship in random waves; $S_{aa}(\omega,\mu)$ is ITTC-1978 wave energy spectrum of short-crested wave in section 2.2 (i.e., Eqs. (7) and (8)). The yaw drifting moment N_D can be integrated from the sectional Y_D with respect to the LCG along the whole ship length. The related introduction can be referred to Fang *et al.* (2013).

3. Fuzzy control for DP system

The DP systems based on the fuzzy theory, i.e., Fig. 2, is applied to control the thrusters for against the environmental forces, maintaining the ship position and heading at sea. The rule base and database of the fuzzy control are obtained from the experts' experience, which were adapted to different sea states. In the general process of fuzzy control can be divided as three parts: "Fuzzifier the Input Data," "Fuzzy Inference" and "Defuzzifier".

3.1 Input data and scaling mapping

The input data can be obtained from the deviations of the ship position (x, y) and heading ψ away from the desired station.

$$e_1(t) = x(t) - x(0) \tag{24}$$

$$e_2(t) = v_x(t) - v_x(t-1) \tag{25}$$

$$e_3(t) = y(t) - y(0) \tag{26}$$

$$e_4(t) = v_y(t) - v_y(t-1) \tag{27}$$

$$e_5(t) = \psi(t) - \psi(0) \tag{28}$$

$$e_6(t) = v_\psi(t) - v_\psi(t-1) \tag{29}$$

where $e_1(t)$ and $e_3(t)$ are the position deviations for x- and y-axis in the earth-fixed coordinate system, respectively. $e_2(t)$ and $e_4(t)$ are the velocity deviations from the surge and sway modes, respectively. $e_5(t)$ and $e_6(t)$ are the heading deviation and yawing velocity deviation. Scaling mapping is transferring the magnitudes of input data suitable for the range of the defined membership function.

$$X_i(t) = G_i e_i(t) \quad i = 1 \sim 6 \tag{30}$$

where G_i are scaling factors that obtained from the relationship between the input data and the domain of the membership function.

The linguistic values used to describe the scaled input data and output q were written as below:

PB: Positive Big
PM: Positive Middle
PS: Positive Small (output q only)
ZO: Zero

NS: Negative Small (output q only)
NM: Negative Middle
NB: Negative Big

3.2 Rule base

The experience or senses from realism can be selected as the fuzzy rules and collected as the rule base, which are described as below: (Note: the rule base shown in Table 1 is used in the later simulation calculations)

3.3 Fuzzifier, fuzzy inference and database

In the part of fuzzifier the input data, the membership functions of bell shape and fuzzy singleton type were adopted to fit the ship dynamic non-linear system and DP control in real-time. The combination of membership functions can generate the maximum output range in the fuzzy controller.

The bell shape function is selected as the membership function $f_{ij}(X_i)$ with Gaussian distribution that the value between in the interval [0, 1].

$$f_{ij}(X_i) = \exp\left[-\left(\frac{X_i - x_{bi,j}}{\sigma_{ij}}\right)^2\right] \quad i = 1 \sim 6, \quad j = 1 \sim 25 \tag{31}$$

where $x_{bi,j}$ is the location with maximum function value of f_{ij} and σ_{ij} is the bandwidth, respectively.

The membership function with singleton type for the output q in the j^{th} rule is defined as below

$$f_{qj}(q) = \begin{cases} 1, \text{ if } & q = q_j \\ 0, \text{ if } & q \neq q_j \end{cases} \tag{32}$$

Table 1 Rule base for DP system

X_{i+1} \ X_i	PB	PM	ZO	NM	NB
PB	NB	NM	NM	PS	PS
PM	NM	NM	NS	PS	PS
ZO	NM	NM	ZO	PM	PM
NM	NS	NS	PS	PM	PM
NB	NS	NS	PM	PM	PB

($i = 1, 3, 5$)

where q_j is the location with maximum function value of $f_{qj}(q)$

The database of the defined values for σ_{ij}, $x_{bi,j}$ and q in the membership function is shown in Tables 2 and 3, respectively, which will be used in the later simulation calculations. The system parameter (σ_{ij} = 5.09) in fuzzy rules is obtained from the experts' experience, which provide for the present fuzzy control.

The operation proceeding of the fuzzy inference from the corresponding output function based on the j^{th} rule is shown as below

$$f^{(1)}_{RO(j)}(q) = f_{ij}(X_i)\cdot f_{i+1,j}(X_{i+1})\cdot f_{qj}(q) \qquad i=1,\ j=1 \sim 25 \tag{33}$$

$$f^{(2)}_{RO(j)}(q) = f_{ij}(X_i)\cdot f_{i+1,j}(X_{i+1})\cdot f_{qj}(q) \qquad i=3,\ j=1 \sim 25 \tag{34}$$

$$f^{(3)}_{RO(j)}(q) = f_{ij}(X_i)\cdot f_{i+1,j}(X_{i+1})\cdot f_{qj}(q) \qquad i=5,\ j=1 \sim 25 \tag{35}$$

3.4 Defuzzifier

Using the defuzzifier of the height-defuzzification method to obtain the output q^*.

$$q^{(1*)} = \frac{\sum_{j=1}^{25} f^{(1)}_{RO(j)} q_j}{\sum_{j=1}^{25} f^{(1)}_{RO(j)}} = \frac{\sum_{j=1}^{25}\prod_{i=1}^{2} f_{ij}(X_i) q_j}{\sum_{j=1}^{25}\prod_{i=1}^{2} f_{ij}(X_i)} \tag{36}$$

$$q^{(2*)} = \frac{\sum_{j=1}^{25} f^{(2)}_{RO(j)} q_j}{\sum_{j=1}^{25} f^{(2)}_{RO(j)}} = \frac{\sum_{j=1}^{25}\prod_{i=3}^{4} f_{ij}(X_i) q_j}{\sum_{j=1}^{25}\prod_{i=3}^{4} f_{ij}(X_i)} \tag{37}$$

$$q^{(3*)} = \frac{\sum_{j=1}^{25} f^{(3)}_{RO(j)} q_j}{\sum_{j=1}^{25} f^{(3)}_{RO(j)}} = \frac{\sum_{j=1}^{25}\prod_{i=5}^{6} f_{ij}(X_i) q_j}{\sum_{j=1}^{25}\prod_{i=5}^{6} f_{ij}(X_i)} \tag{38}$$

In order to obtain the non-fuzzy values for the practical control required, the output values q^* would be scaled into the practical domain (the R.P.M. of the propellers).

where $G_i (i = 7 \sim 9)$ is the output scaling factor determined by the practical thruster capacity. Both n_1 and n_2 are calculated from $q^{(1*)}$ and $q^{(3*)}$ to correct the position deviation from the surge mode and the heading deviation, respectively; n_3 is calculated from $q^{(2*)}$ and $q^{(3*)}$ to correct the position deviation from the sway mode and the heading deviation, respectively.

Table 2 Database for σ_{ij} and $x_{bi,j}$ in the membership function

Input	Linguist Notion	σ_{ij}	$x_{bi,j}$
	PB		8
	PM		4
X_i	ZO	5.09	0
	NM		-4
	NB		-8

$(i = 1 \sim 6)$

Table 3 Database for q in the membership function

Output	Linguist Notion	q
	PB	8
	PM	4
	PS	2
q	ZO	0
	NS	-2
	NM	-4
	NB	-8

$$n_1 = G_7 q^{(1*)} + G_9 q^{(3*)} \tag{39}$$

$$n_2 = G_7 q^{(1*)} - G_9 q^{(3*)} \tag{40}$$

$$n_3 = G_8 q^{(2*)} + G_9 q^{(3*)} \tag{41}$$

3.5 Thrusters forces and moment

The fuzzy system controls the R.P.M. of propellers i.e., the two stern thrusters and the bow one, to create the forces applied to counteract the environmental forces. Based on the revolution speeds n_i in Eqs. (39)-(41), the thrust forces can be calculated by

$$T_i = \rho n_i^2 D_P^4 K_T \tag{42}$$

where ρ, D_P and K_T are the water density, the propeller diameter and thrust coefficient, respectively. Then the resultant thrust-induced forces and moments on the ship can be obtained by

$$F_{Tx} = (T_1 + T_2)(1 - t_p) \tag{43}$$

$$F_{Ty} = T_3(1 - t_p) \tag{44}$$

$$N_{Tx} = T_3(1 - t_p) \times d \tag{45}$$

$$N_{Ty} = (T_1 + T_2)(1 - t_p) \times d \tag{46}$$

$$N_{Tz} = (T_1 - T_2)(1 - t_p)\frac{RB}{2} + T_3(1 - t_p)\frac{RL}{2} \tag{47}$$

where t_p (= 0.06) is the thrust deduction coefficient, d is the draft; RB (= 5 m) is the distance between two forward stern thrusters; RL (= 15.24 m) is the distance between two port or starboard thrusters.

3.6 PD control for DP system

In order to compare the efficiencies between fuzzy control and PD control for DP systems, the model of PD control for DP system are also described in this section and the related results are carried out in the simulations.

The PID controller is usually expressed in the following equation.

$$y(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \tag{48}$$

where $y(t)$ is the output in the controller, e.g., thruster's R.P.M; $e(t)$ means the system error, e.g., position and heading deviations. In the present study, only two control gains (i.e., proportional (K_P) and derivative (K_D)) are considered in the PD controller, whereas the control gain of the integral (K_I) is not included because the desired goals are fixed and independent of time (i.e., there are no steady-state error existed in the control system).

In the present study, the thrusters T_1 and T_2 depend on the position and heading deviations whereas T_3 only depends on the position deviation in sway direction. In the PD control, the thruster's R.P.M. n_i of the thruster T_i are shown in the below:

$$n_1(t) = K_{P,x}\left[x(t) - x(0)\right] + K_{D,v_x}\left[v_x(t) - v_x(t-1)\right] + K_{P,\psi}\left[\psi(t) - \psi(0)\right] \tag{49}$$

$$n_2(t) = K_{P,x}\left[x(t) - x(0)\right] + K_{D,v_x}\left[v_x(t) - v_x(t-1)\right] - K_{P,\psi}\left[\psi(t) - \psi(0)\right] \tag{50}$$

$$n_3(t) = K_{P,y}\left[y(t) - y(0)\right] + K_{D,v_y}\left[v_y(t) - v_y(t-1)\right] \tag{51}$$

where n_1 and n_2 are for the forward thrusters' R.P.M., whereas n_3 is for the sideward thruster's R.P.M.; $K_{P,x}$ and K_{D,v_x} are the related control gains for surge and surge rate; $K_{P,y}$

and K_{D,v_y} are the related ones for sway and sway rate, and $K_{P,\psi}$ is the control gain for heading deviation.

In order to obtain the optimal PD control, the above control gains must be suitably adjusted to obtain the maximum control effect with respect to different sea states. If no optimal algorithm or good experience is applied, the optimal gains need to be obtained by trial and error method, which are complex and takes a lot of time. The procedures of trial and error method are described here. Firstly, it can be set all the control gains are identical at the same time and try to increase or decrease the each gain depending on the simulation results. Lastly, we can find the regularity that the control gains "K_D" is usually bigger one or two orders of magnitude than the control gains "K_P". However, the gains obtained from the trial and error method may not be optimal although it is better. Therefore, the PD control needs to be incorporated with other algorithms, i.e., neural network, for the optimal control effect.

4. Results and discussion

In order to verify the DP system proposed in the present study, a barge is adopted and its principal dimensions are shown in Table 4. And the thruster data, e.g., thruster capacity, turning rate and maximum R.P.M., are shown in Table 5 and considered in the DP simulations. Three portable thrusters, i.e., two stern thrusters and one bow thruster, are assumed to install on board of the barge as shown in Fig. 3.

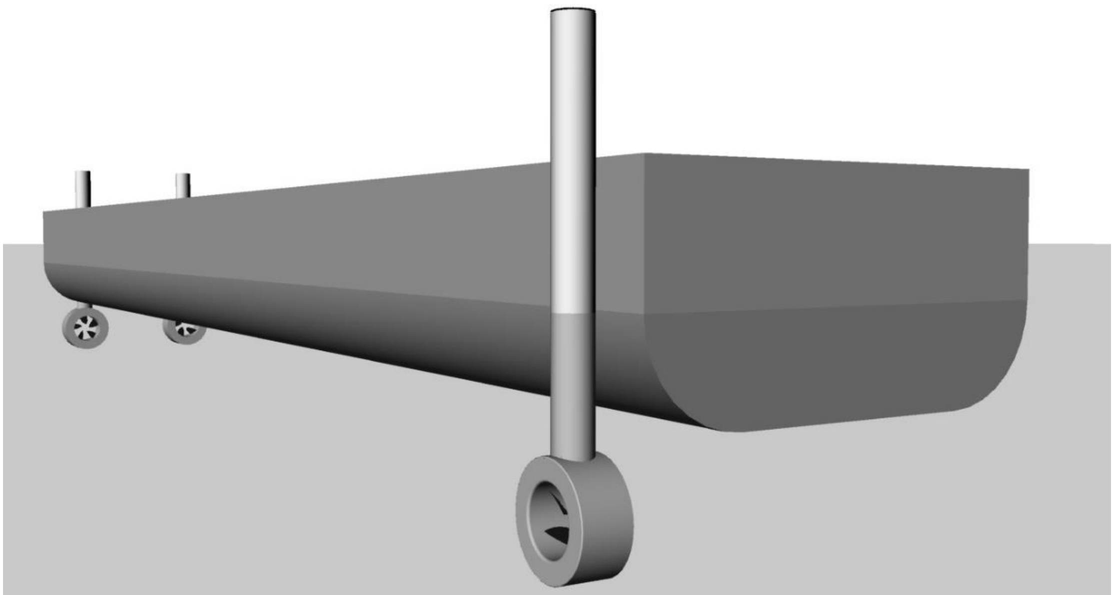


Fig. 3 Arrangement of the three portable outboard thrusters

Table 4 Principal dimensions of the barge

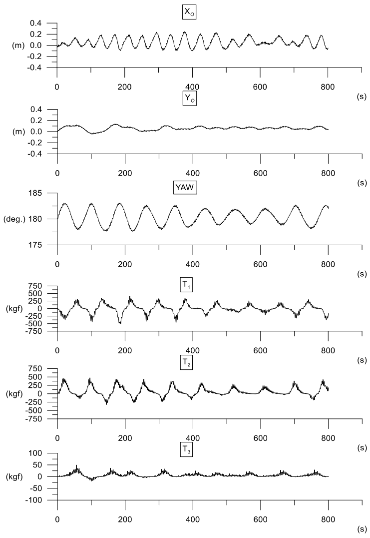
Displacement (tonne)	630
Length (*m*)	30.48
Breadth (*m*)	9.0
Draft (*m*)	2.45
KG (*m*)	4.0
LCG (*m*)	0
Longitudinal GM (*m*)	31.85
Transverse GM (*m*)	0.31
Radius of Gyration for Pitch (*m*)	7.62
Radius of Gyration for Roll (*m*)	3.15
Water plane Area (m^2)	274.32
Length between stern thrusters (*m*)	5
Wetted Surface (m^2)	370.392
C_b	0.9145

Table 5 Thruster data for DP simulation

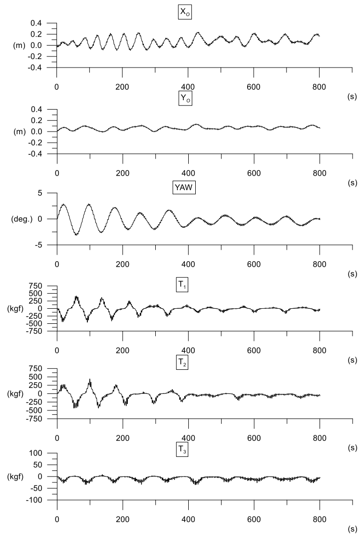
Propeller Diameter (m)	1.7
Pitch ratio	0.7
Turning rate	±30 R.P.M.
Maximum R.P.M.	300 R.P.M.
Each Thruster Capacity (kW) (Beaufort scale number = 3)	450

In the present simulation results, the DP barge was initially set to be at rest with a fixed position and heading, and then encountered the different sea states including the wave, the wind and the current. The objective of the control is to keep the barge at the initial setting position and heading. The wind speed and current speed are assumed to be constant with 4.37 m/s and 0.3 m/s, respectively. The short-crested random waves based on ITTC-1978 wave spectrum with $H_{1/3} = 0.3$ m and $T = 2.4$ *s* (Beaufort scale number 3) is adopted and start with existing wave amplitude in the simulations. Four different dominate wave headings (i.e., ψ = 180°, 0°, 135° and 45°) are considered here. Based on the regulation of International Marine Contractors Association (IMCA 2000), the DP system is often set against a scale of wind force with wind speed, the fixed current force, and the wave force with corresponding wave height. All three environmental forces are acting from the same direction and there is the relation between wind speed and the wave height which depends on the sea area. The time domain simulations of the present results are carried out by the 4th order Runge-Kutta method.

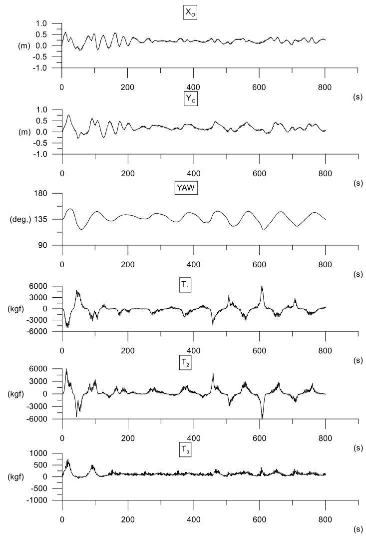
The results of the time history simulations with the fuzzy control adopt the rule base and database as Tables 1-3, respectively. And the values of the input and output scaling factors G_i are listed as below: G_1=0.15, G_2=0.45, G_3=0.15, G_4=45, G_5=1.5, G_6=45, G_7=1500, G_8=1500 and G_9=500.



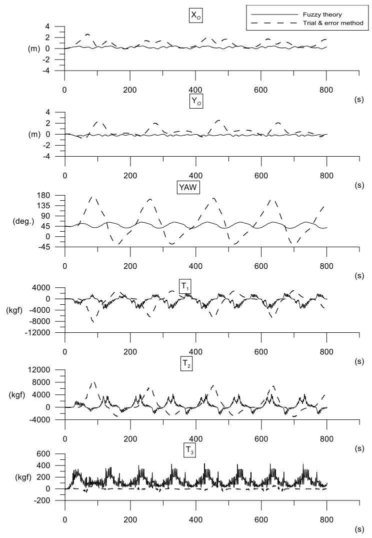
(a) Wave heading ψ = 180°



(b) Wave heading ψ = 0°



(c) Wave heading ψ = 135°



(d) Wave heading ψ = 45°

Fig. 4 Time history of the ship horizontal motions and thrust forces with respect to the different dominate wave headings

The horizontal motions and yaw motion at ψ =180°, 0°, 135° and 45°, are shown in Figs. 4(a)-4(d), respectively. In Fig. 4(a), i.e., ψ =180°, with the fuzzy control, we find the barge moves only a little distance, i.e., 0.23 *m* (0.75% ship length) in x_o-direction away from the original position due to the environmental forces whereas the y_o-direction deviation is 0.14 m (0.46% ship length) and yaw motion is 3.1°. All the deviations approach steady states finally, which means that the fuzzy control works well in this case. As to the following sea condition (Fig. 4(b)), i.e., ψ =0°, the results are similar to those in head sea (ψ =180°). The maximum position deviation, i.e., 0.24 m (0.79% ship length) in x_o-direction, 0.11 *m* (0.36% ship length) in y_o-direction and about 3.1° in yaw motion. In Fig. 4(c), i.e., ψ =135 °, the position deviations in x_o- and y_o-directions are less than 0.61 m and 0.76 m (2.00% and 2.49% ship length), respectively. In this case, because of the oblique environmental forces, the barge heading turns significantly and the maximum heading deviation is about 19° which is practically accepted because the position state is finally steady. Similar results also occur at ψ =45 ° (i.e., Fig. 4(d)), which has maximum position deviations of 0.48 m and 0.37 m (1.57% and 1.21% ship length) in x_o- and y_o-directions, respectively, and smaller maximum heading deviation, i.e., about 18°. The results indicate that the position deviation is acceptable for the barge operation, which means that the controller based on the fuzzy algorithm works satisfactorily in the present DP system. The message of the motion behaviors shown in Figs. 4(c) and 4(d) indicates the ocean environmental state might be the worst, however the DP system proposed here still proves its availability in these cases. The comparisons with the traditional PD control using the trial and error method are also shown in Fig. 4(d), which indicates the results based on the fuzzy algorithm are obviously steady and better.

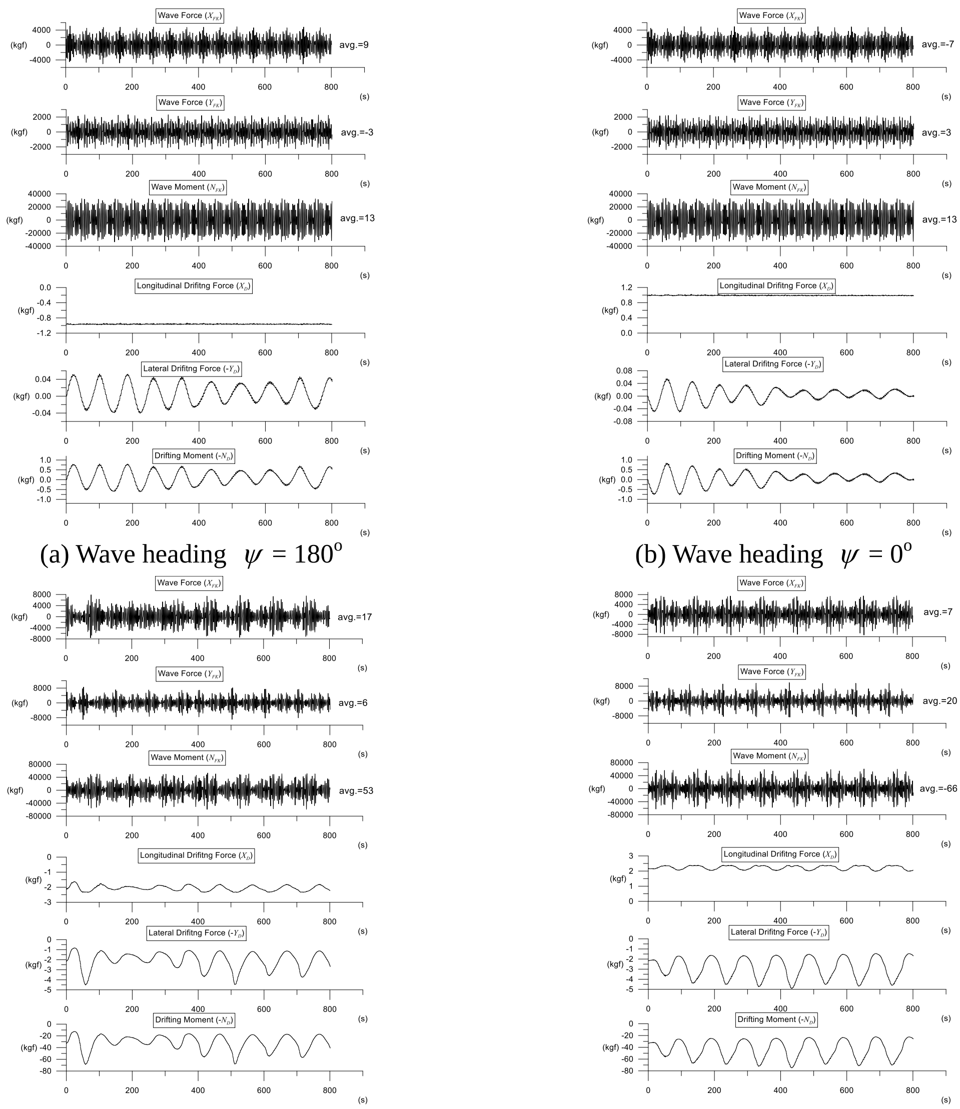
The thrust forces for the DP system thrusters with respect to the different wave headings are also shown in Figs. 4(a)-4(d) for reference. The stern thrusters (i.e., T_1 and T_2) can produce the moment to resist the heading deviations by adjusting different rotational directions. For example, in Fig. 4(c), the maximum required thrust forces, about 6,063 *kgf*, occurs at ψ =135°, produced by T_1 and T_2 are opposite and consequently cause the anti-yaw moment. The bow thruster, T_3, only needs to contribute a small thrust force, i.e., 748 *kgf*, in this case. The similar phenomenon is also observed at ψ =45°. In other words, it's only added a secondary portable outboard thruster at the bow of a twin-screw ship without a DP system.

The force contributions due to the first-order waves (Froude-Krylov force) and short-crested waves are illustrated in Figs. 5(a)-5(d). In the figures, the drifting forces are smaller than first-order wave forces. However, the positive values of the first-order wave forces and the negative values of those are nearly equal. (See the wave's average forces in Figs. 5(a)-5(d)). In ψ =135° and 45°, the short-crested waves become obvious, especially the drifting moment.

Figs. 6(a)-6(d) are the time history of other external forces, such as the wind and current forces. In the most DP cases, the wind forces are major factor, which also cause waves, whereas the current forces are notable in ψ =135° and 45°. In summary, the external forces acting on the ship hull turn into complex and significant in oblique sea, which the worst environmental states while the present DP simulations.

The trajectories of the barge at the different sea states are also shown in Figs. 7(a)-7(d) for reference. The original position of the center of gravity (*CG*) is set to be at the origin, i.e., (0, 0). The solid line and the arrow sign represent the path of the *CG* and heading, respectively. It can clearly investigate the present technique for the DP system practically works well. Moreover, in ψ =45° with PD control based on the traditional trial and error method is shown in Fig. 8 for comparison with Fig. 7(d). The results reveal that the DP system that based on the fuzzy algorithm was indeed better than the traditional trial and error method, which indicates the yaw deviation using the fuzzy algorithm can constrain the barge heading in a smaller range.

All the results reveal that the DP system adopted here can be concluded to be efficient. It can always constrain the barge to move in a limited acceptable area and help the barge to achieve the mission smoothly in random waves.



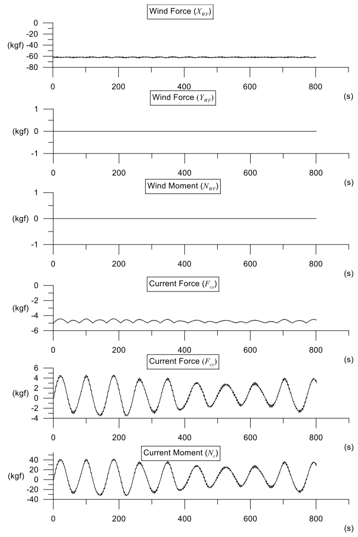
(a) Wave heading ψ = 180°

(b) Wave heading ψ = 0°

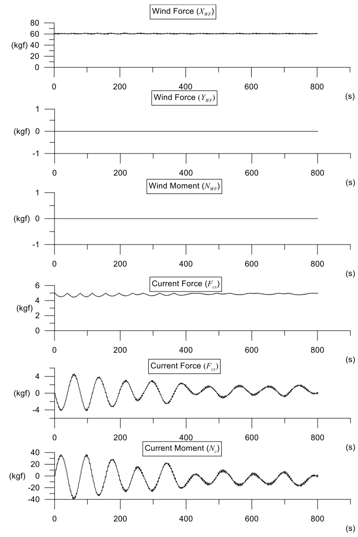
(c) Wave heading ψ = 135°

(d) Wave heading ψ = 45°

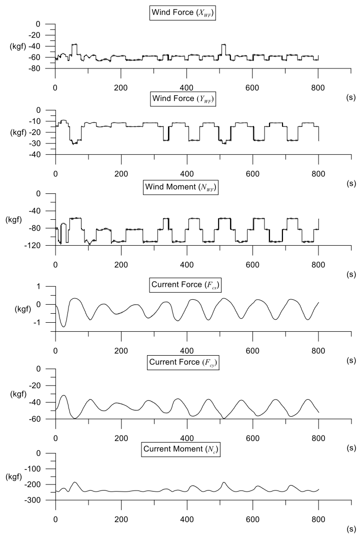
Fig. 5 Time history of the first-order wave forces and drifting forces with respect to the different dominate wave headings



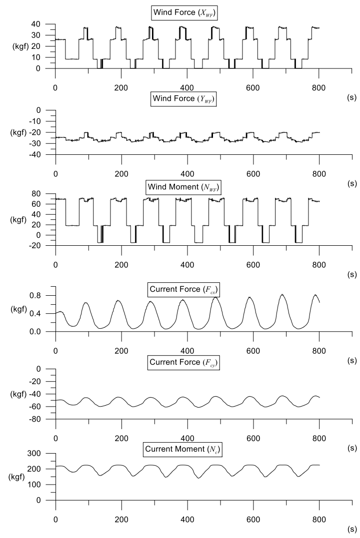
(a) Wave heading $\psi = 180^{o}$



(b) Wave heading $\psi = 0^{o}$

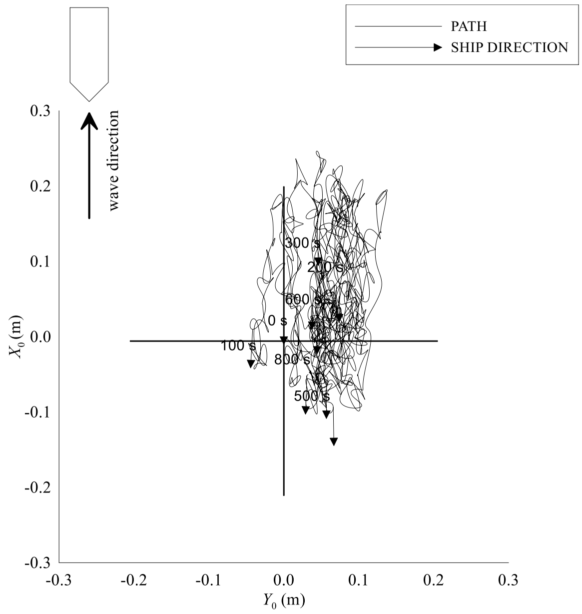


(c) Wave heading $\psi = 135^{o}$

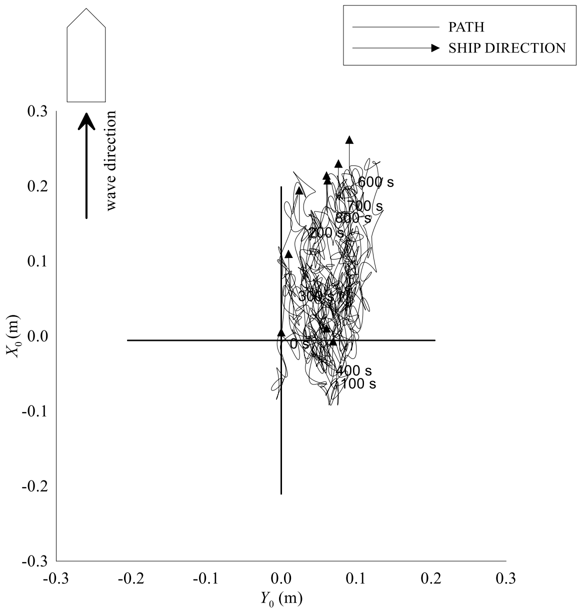


(d) Wave heading $\psi = 45^{o}$

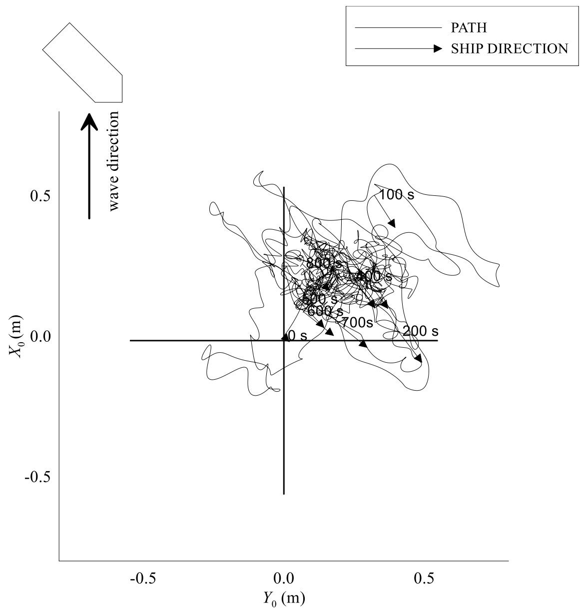
Fig. 6 Time history of the wind forces and current forces with respect to the different dominate wave headings



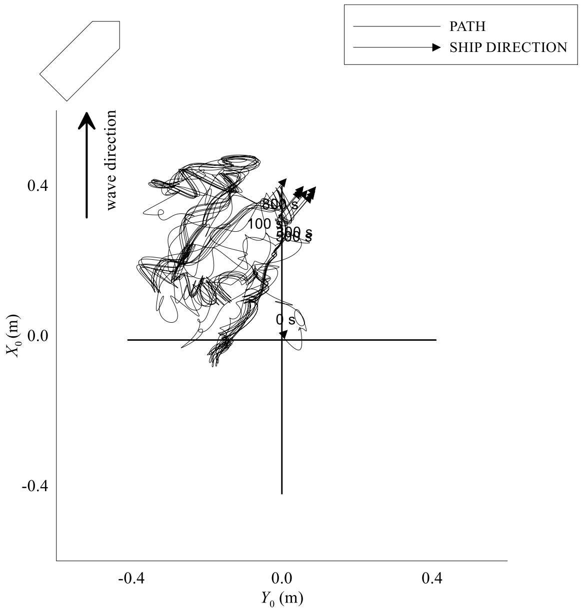
(a) Wave heading ψ = 180°



(b) Wave heading ψ = 0°



(c) Wave heading ψ = 135°



(d) Wave heading ψ = 45°

Fig. 7 Ship DP trajectories under DP system, which the R.P.M. of thrusters determined by the present fuzzy algorithm

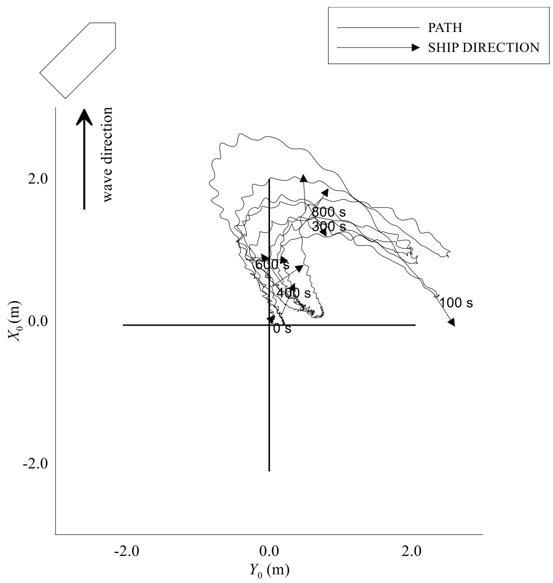


Fig. 8 Ship DP trajectory in ψ = 45^o under DP system, which the control gains of PD control determined by the traditional trial and error method

5. Conclusions

In the paper, the dynamic motion simulations for a ship with DP system have been carried out and the results show to be practically reasonable. Three outboard thrusters are applied in the present DP system to control the barge. From the above numerical simulations, we can conclude that the portable DP system designed in the paper (i.e., two stern thrusters and one bow thruster with the present fuzzy controller) can work well in random waves. In a word, the R.P.M. control of the propellers determined by the present fuzzy algorithm generally indeed improve the DP system performance and may be served as a useful and practical tool for DP purpose, especially for the ships originally without a DP system in waves.

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