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Fuzzy adaptive interactive algorithm design for marine dynamic positioning system under unexpected impacts of Vietnam Sea

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The factors which affect vessel motion mainly come from environmental influences. In the actual conditions, each of the oceans will exhibit different characteristics. This paper aims todevelop a fuzzy adaptive interactive (FAI) algorithm for the marine dynamic positioning system (DPs) under unexpected impacts of the Vietnam Sea. The response error ξ between the ideal model and the actual model helps to estimate more accurately the variation amplitude caused by nonlinear components. Based on the response error ξ, the control signal of actual model which is adjusted suitably to the ideal model proceeds the DPs maintain the vessel in a position under the environmental conditions of Vietnam Sea. On the other hand, the impact parameters are explored by the actual conditions to increase the reliability of the proposed solution. Simulation results of the FAI are evaluated in comparison with other methods such as fuzzy. The FAI performs the desired response of DPs better than other in two case studies, that proved the effective for the proposed controller.

[**Keywords**: Dynamic positioning, Environment, Fuzzy adaptive interactive, Model, Supply vessel, Wave impact]

Introduction

The goal of the DPs is designed to keep a vessel in position automatically and adjust position errors by applying forces of the vessel thrusters as demanded by the control system without dropping the anchors. The extraction of offshore resources is growing and expanding continuously, especially in deep water, so the DPs plays an important role to keep the vessel in position. As the Vietnam Sea exhibits complex climatic features with considerable variability by tropical monsoons, the environmental factors are changing constantly. The vessel moves under various conditions of the Vietnam Sea, makes the object highly nonlinear and difficult to maintain balance for the vessel motion. The first generation DPs often uses traditional linear controller like Proportional – Integral – Derivative (PID) algorithm, which had an advantages of simple structural and stable output. However, these are surveyed in limited activities without considering environmental impact[1]. In subsequent years, many proposed modern theories which aimed at reducing the errors and improving the quality of controller were applied to DPs[2]. Saelid *et al.*[3] presented the Kalman filter solution for the DPs to estimate the object erroneous when operating in actual conditions, hence, optimizing the actuator parameters. The obtained results verified the advantages of the proposed solution, but the restriction of study only explore the factors that cause oscillations is the wave, without the other influences such as current and wind. In Gu *et al.*[4] applied neural-network (NN) to measure the wave amplitude and estimate the external force, which had an effect on the vessel. The NN results express that this approach is able to meet the feasible solutions. More importantly, it needs to perform in practical test cases like wind and current conditions for verifying the advantage of the NN solution. For enhancing the DPs control quality in the actual environment, Xia *et al.*[5] developed the Cerebellar Model Articulation Controller (CMAC) based on the PID algorithm to approximate the nonlinear components. The responses indicated that the controller is able to adapt to the external forces. But the vessel operates at the high-frequency domain and, it is able to maintain position and heading. Fang *et al.*[6] tried to put a Neural-Fuzzy controller (NFC) into practice condition to discover the best state model for the vessel propulsion system. Thereby, the environmental disturbance is measured and eliminated by the NFC structure. The unexpected impacts make the DPs structure to be complicated and uncertain. Many other studies deal with DPs' problems and achieve good results. But these controllers need to be verified in terms of the different environmental conditions such as the complexity and vulnerability of deep water. Besides this, the time-delay of the control signal is also a matter of concern for vessel autopilot.

The FAI solution allows for controlling nonlinear systems effectively. The parameters that are uncertain due to environmental impacts are approximated by the fuzzy function[7]. This paper suggests the FAI solution for the DPs control under unexpected impacts of the actual conditions from the Binh Thuan province to Ca Mau province. Subsequently, the response error ξ helps to estimate the nonlinear parameters more accurately. Moreover, the FAI adjustment performs directly to the control signal of the actual model. So the DPs controller can decrease the time-delay for the whole system. Thereby improving the quality of the control signal that helps the DPs fast-forward to a stability domain.

Materials and Methods

Dynamic Positioning System (DPs)

The DPs is defined as three degrees-of-freedom[8] (surge motion, sway motion and yaw motion). Two coordinate systems expressed in Figure 1 include the body-fixed frame i.e. *O-XYZ* and the earth-fixed frame is *O-$X_0Y_0Z_0$*. Position *(x, y)* and heading (ψ) of the absolute coordinate system $X_0Y_0Z_0$ are expressed as a vector form $\eta = (x, y, \psi)^T$. The vector $v = (u, v, r)^T$ expresses the vessel velocity of surge motion *u*, the sway motion *v* and the yaw motion *r* in the vessel-fixed frame. The vertical center of the vessel coordinate system *XYZ* is established at the roll axis, the length which is measured to the vessel center of mass from the *O* point is represented by x_G. The mathematical representation of the DPs with three degrees-of-freedom and environmental force acting is described in Eqs. (1, 2) as:

$$\dot{\eta} = J(\eta)v \qquad \dots (1)$$

$$M\dot{v} + Dv = \tau + \tau_{envi} + \tau_h \qquad \dots (2)$$

The rotation matrix $J(\psi)$, the inertia matrix *M* and the damping matrix $D^{(\text{ref. 9})}$ are as follows:

$$J(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \dots (3)$$

$$M = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_G - Y_{\dot{r}} \\ 0 & mx_G - N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix} \qquad \dots (4)$$

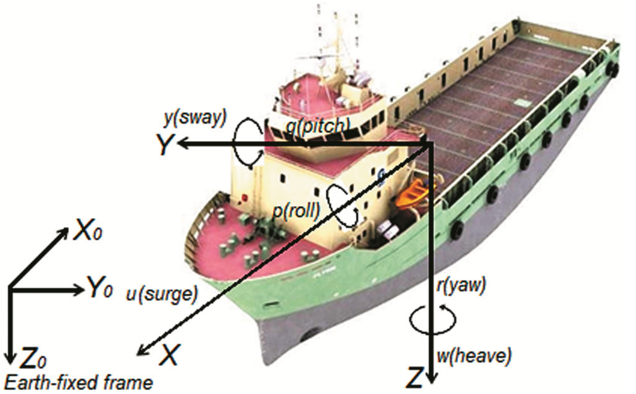

Fig. 1 — Two coordinate system of vessel: the $X_0Y_0Z_0$ earth-fixed frame and the *XYZ* vessel-fixed frame

$$D = \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & mu_0 - Y_r \\ 0 & -N_v & mx_G u_0 - N_r \end{bmatrix} \qquad \dots (5)$$

Where, *m* is ship-mass, I_Z gives expression to the inertia moment for the vessel-fixed Z-axis, x_G expresses the position of *G* in *X*-axis motion, and u_0 describes a velocity component which located at mid-vessel. The inertia quantities are increased by the acceleration of the roll, pitch, and heave direction of rotation as expressed in Eq. (6) as follows:

$$X_{\dot{u}} \triangleq \frac{\partial X}{\partial \dot{u}}, Y_{\dot{v}} \triangleq \frac{\partial Y}{\partial \dot{v}}, N_{\dot{r}} \triangleq \frac{\partial N}{\partial \dot{r}}, Y_{\dot{r}} \triangleq \frac{\partial Y}{\partial \dot{r}}, N_{\dot{v}} \triangleq \frac{\partial N}{\partial \dot{v}} \qquad \dots (6)$$

At the moment, the inertia component along the surge axis is separated from the inertia which affects along the sway and yaw axes. Because of the small velocities and starboard-port side symmetries, the increased mass in sway created by the angular acceleration in yaw motion is equal to the increased mass in yaw created by sway acceleration. As in most DPs applications, *D* expresses the damping matrix, and *M* represents the inertia matrix consisting of increased mass effects, which is symmetric and positive definite. Nevertheless, for the low speed in a practical case where the values of the damping matrix are decreased, it can be assumed that $N_v = Y_r$. The damping components along with the surge, sway, and yaw axes are established by Eq. (7):

$$X_u \triangleq \frac{\partial X}{\partial u}, Y_v \triangleq \frac{\partial Y}{\partial v}, N_{\dot{r}} \triangleq \frac{\partial N}{\partial r}, Y_{\dot{r}} \triangleq \frac{\partial Y}{\partial r}, N_{\dot{v}} \triangleq \frac{\partial N}{\partial v} \qquad \dots (7)$$

The control vector τ produced by the vessel's propellers and thruster systems. Vector τ_{envi} expresses the dynamic disturbances from environment, consisting of wave force τ_{wave}, wind force τ_{wind} and current force $\tau_{current}$. Vector T_{au_h} is the high-frequency spectral components of wave that affect to the vessel in Eq. (8) as follows:

$$\tau = \left[\tau_x, \tau_y, \tau_\psi\right]^T \qquad \dots (8)$$
$$\tau_{envi} = \tau_{wave} + \tau_{wind} + \tau_{current}$$
$$\tau_h = h(s)$$

The unexpected effects of Vietnam Sea

Many unexpected elements are affecting the vessel motion where the wave, wind, and current effects are the major factors[8]. Vietnam Sea has complex climatic features with considerable variability by the tropical monsoon, so each year many storms affect to the environment of the Vietnam Sea. In this study, the research group has analyzed the impacts of the Vietnam Sea from Binh Thuan province to Ca Mau province. Hence, wave, wind, and current elements are the nonlinear components that have the strongest impact on the safe operation of the ships.

Vietnam Sea is directly influenced by the trade wind of two major monsoons: the northeast monsoon and the southwest monsoon. Southwest monsoons occur from June through September where winds blow from west to the southwest. And the northeast monsoons occur from September through April next year, and during this period the wind blows from east to the northeast. The wave, wind, and current parameters are built according to the Vietnam environmental conditions that are changeable by the monsoon climate. Based on Vietnam Building Code Natural Physical and Climatic Data for Construction to find out wind speed and wave height affecting to the vessel into the actual operating case[10], are shown in Figures 2, 3, 4 and 5. Besides, the high-frequency wave components are also considered to improve the quality of the proposed controller.

Wave impact model

This study is carried out the wave model suggested by Fossen[1]. So the wave impact model can be rewritten as Eq. (9):

$$\tau_{wave} = \zeta(x, y, t) = \sum_{q=1}^{N} \sum_{r=1}^{M} \sqrt{2S(\omega_q, \psi_r)\Delta\omega\Delta\psi}\, \sin\left(\omega_q t + \phi_{qr} - k_q(x\cos\psi_r + y\sin\psi_r\right) \qquad \dots (9)$$

Where, the wave amplitude ζ_{aqr} is given as:

$$\zeta_{aqr} = \sqrt{2S(\omega_q, \psi_r)\Delta\omega\Delta\psi} \qquad \dots (10)$$

Where, $\Delta\omega$ and $\Delta\psi$ represent the harmonic wave amplitude, $\psi_r, \omega_q, \phi_{qr}$ and S represents the direction, frequency, phase angle and wave spectrum[10]. The phase angle of all wave components is between *0* and 2π. In the coordinate system relative to the earth-fixed frame, the surface in the coordinate *(x, y)* is given by Eq. (11):

$$\zeta_{qr}(x, y, t) = \zeta_{aqr} \sin\left(\omega_q t + \phi_{qr} - k_q(x\cos\psi_r + y\sin\psi r\right. \qquad \dots (11)$$

Where, $k_q = 2\pi/\lambda_q$ is the wave number, λ_q is the wave-length, the dispersion relation $\omega_q = \sqrt{kg}$ (with g is the gravity acceleration).

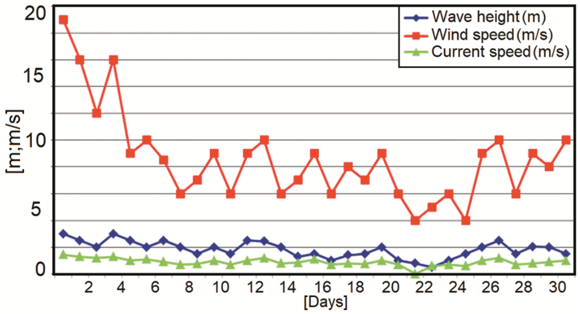

Fig. 2 — Environmental effects in July

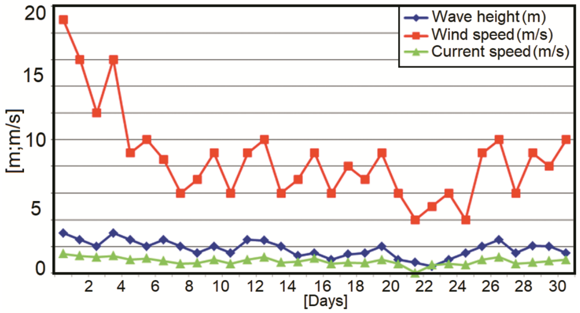

Fig. 3 — Environmental effects in August

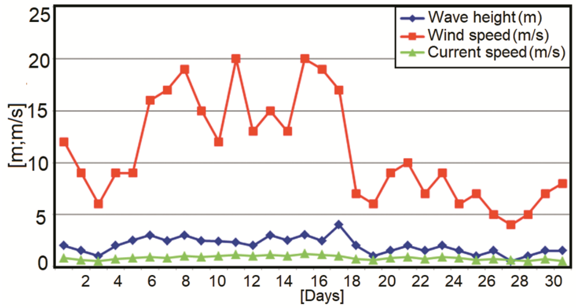

Fig. 4 — Environmental effects in September

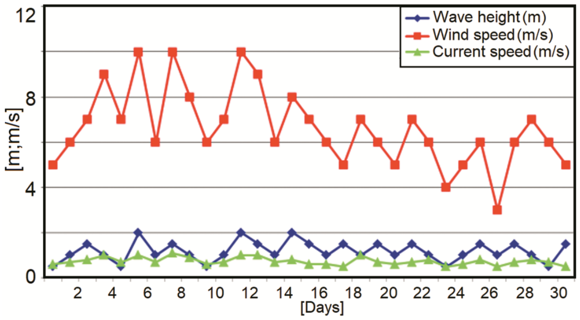

Fig. 5 — Environmental effects in October

Low-frequency wind model

The wind speed which affects the vessel is defined as V_w and the wind direction β_w is modeled as the slow variable quantities[8]. The wind force of surge, sway, and yaw motions are determined by the regulations of Vietnam wind speed and described in the following Eq. (12):

$$\tau_{wind} = [X_{wind}, Y_{wind}, N_{wind}]^T \qquad \dots (12)$$

Where, X_{wind}, Y_{wind} and N_{wind} are the wind forces acting on the vessel can be expressed as Eq. (13):

$$\begin{aligned} X_{wind} &= 0.5C_X g_R \rho_w V_R^2 A_T \\ Y_{wind} &= 0.5C_Y g_R \rho_w V_R^2 A_T \qquad \dots (13) \\ N_{wind} &= 0.5C_N g_R \rho_w V_R^2 A_L L \end{aligned}$$

Where, C_X and C_Y are the traction[11], C_N is the coefficient of blast force acting on the body-vessel, ρ_w represents the air density of the operating environment, A_T and A_L are areas of the ichnography, L is the overall length of the vessel, V_R and g_R express the speed and direction of wind that affect to the vessel are defined as:

$$\begin{aligned} V_R &= V_w \\ g_R &= \beta_w - \psi_L - \psi_H \qquad \dots (14) \end{aligned}$$

Current impact model

We assumed that the current is invariable in both directions and as well as in amplitude. In such a way as to correct, the current speed V_c and the current direction β_c are modeled as the slow variable parameters in the earth axis. The current speed of vessel coordinates is introduced by Fossen[1] and is given by:

$$\begin{aligned} u_c &= V_c cos(\beta_c - \psi_L - \psi_H) \\ v_c &= V_c sin(\beta_c - \psi_L - \psi_H) \qquad \dots (15) \\ \tau_{current} &= [u_c, v_c, 0]^T \end{aligned}$$

Where, ψ_L and ψ_H are the angular components affected by the low-frequency and high-frequency quantities, u_c and v_c are components of the current speed.

High frequency wave model

A linear wave response approximation is usually preferred by the vessel control systems engineers, owing to its simplicity and applicability[8]. The linear approximation equation which defined the high-frequency spectrum is rewritten as follows:

$$\tau_h = h(s) = \frac{K_w s}{s^2 + 2\lambda\omega_0 s + \omega_0^2} \qquad \dots (16)$$

Where, K_w is related to the on-sea conditions, we have: $K_w = 2zwS_w$, S_w is the coefficient describing the wave density, z gives expression to the damping coefficient, and w shows a frequency of the wave. The z damping factor can be chosen randomly ($z < 10$), $\omega_0 = 0.88(g/V)$ is the interfering frequency with V expresses the speed of wind and λ is the damping coefficient. The high-frequency movement of the vessel is mainly maintained by the high-frequency wave and does not change the vessel position.

Fuzzy controller

In order to reduce nonlinear properties of the DPs that isproduced by the unexpected effects from Binh Thuan province to Ca Mau province waters. The fuzzy controller for the supply vessel is presented by Do *et al.*[12,13], which has a double-input e_η, de_η/dt, and single-output τ. The inference process combines the membership functions (MFs) with applying the fuzzy logic operators and if-then rules[14]. This paper employed the Takagi-Sugeno (TS) fuzzy inference, the MFs collections are established as:

$$\begin{aligned} &e_\eta: \{NE \quad NS \quad ZEPS \quad PO\} \\ &de_\eta/dt: \{NS \quad ZE \quad PS\} \\ &\tau: \{NE \quad NSS \quad NSZE \quad PS\,PSS \quad PO\} \end{aligned}$$

For designing a TS fuzzy logic with the basic concept of consistent rule, the B_k^i rule designation format is a binary variable, which makes out the rule consequence[15] and B_k^i is defined as follows:

R_i : If $\hat{e}_1$ is A_{k1}^i… and $\hat{e}_n$ is A_{kn}^i then u_{fk} is B_k^i.

Where, $A_{k1}^i, A_{k2}^i, \dots A_{kn}^i$ and B_k^i display the fuzzy sets[16,17]. By using the singleton fuzzifier and the center average defuzzifier[18], the response of the fuzzy controller can be performed as:

$$u_{fk} = \frac{\sum_{i=1}^{h} \theta_k^{-i} [\prod_{j=1}^{n} \mu_{A_{kj}^i}(\hat{e}_j)]}{\sum_{i=1}^{h} [\prod_{j=1}^{n} \mu_{A_{kj}^i}(\hat{e}_j)]} = \theta_k^T \varphi_k(\hat{e}) \qquad \dots (17)$$

For, $\mu_{A_{kj}^i}(\hat{e}_j)$ is the MFs of fuzzy controller, h is the If-Then rules amount[19], θ_k^{-i} expresses the point at which the MFs variable is $\mu_{B_k^i}(\theta_k^{-i}) = 1$ and $\varphi_k(\hat{e}) = [\varphi_k^1, \varphi_k^2, \dots, \varphi_k^h]^T \in R^h$ is the fuzzy basis vector with the φ_k^i elements are given by:

$$\varphi_k^i(\hat{e}) = \frac{\prod_{j=1}^{n} \mu_{A_{kj}^i}(\hat{e}_j)]}{\sum_{i=1}^{h} [\prod_{j=1}^{n} \mu_{A_{kj}^i}(\hat{e}_j)]} \qquad \dots (18)$$

The environmental impacts often cause the control signal to mislead that makes out by the time-varying characteristics. If the controller does not cover the control error, the control quality is not high. Automatic tuning concepts of fuzzy controller execute corresponding to the input error, thereby reducing aswell as the control goal. The MFs describe these input/output characteristics of the vessel translation motion as details in Figure 6.

Fuzzy adaptive interactive solution

For using the fuzzy solution to decrease the control erroneous, the obtained result is highly feasible. Nevertheless, the restriction of the fuzzy controller is only to examine in the small range of input error. More actually, the characteristics of the Vietnam Sea are the reason that causes vessel structure to be uncertain along with the long duration of continuity as salinity factor, waves factor, and viscosity. The control signal of the actual model is calibrated by an amount of interactive adaptive ΔU which is defined by the fuzzy function, that is the prime theoretical point of FAI solution. The calibration is realized according to the level of output error ξ, i.e., the error between the response of the actual model and the ideal model[3,7]. It is well calibrated to decrease the error of the actual model. The response error ξ is defined as:

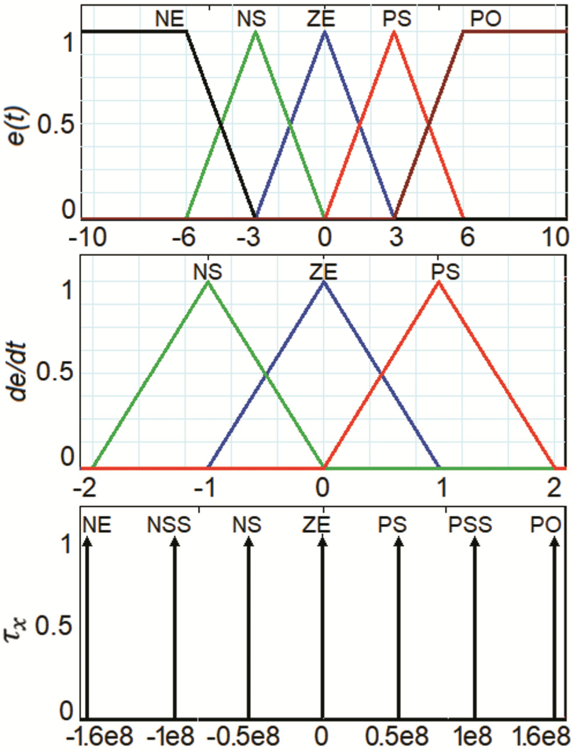

Fig. 6 — The MFs of error input e(t), velocity of error de/dt and impact force τ

$$\xi = \eta - \hat{\eta} = P_t(s).U_t(s) - P(s).U(s) \qquad \dots (19)$$

The control signal which acting on the actual model is presented as:

$$U_t = U + \Delta U \qquad \dots (20)$$

The ΔU presents the calibration control for the surge motion, sway motion, and yaw motion. This study applies the fuzzy modulator consisting of double-input: the error $\xi(t)$, and the velocity error $d\xi(t)/d(t)$. The determined fuzzy rules base with 15 rules for ΔU calibration is shown in Table 1.

The error ξ assists to identify a level of the relative environmental effects. The goal of the proposed solution is to eliminate the erroneous value ξ. The control signal of the actual model is calibrated by adjusting ΔU to adapt to the ideal model, i.e., $\xi \to 0$ when $t \to \infty$, respectively

$$P_t(s).U_t(s) = P(s).U(s) \qquad \dots (21)$$

Another problem that occurs in the DP control process is the time-delay. During the process control system and the time-varying of structure, the time-delay becomes a challenge in the system control. On the contrary, it makes the DPs more injurious and risk of imbalanced. The calibration is performed directly on the control signal of the actual model. Consequently, the goal of the FAI solution is to optimize the time-delay of the calibration process and enhance the system quality. The proposed structure of the FAI solution is described in Figure 7.

Table 1 — The rule for adjusting ΔU coefficient

$\tau_{\Delta x}/\tau_{\Delta y}/\tau_{\Delta\psi}$		$d\xi/dt$		
		Ns	Ze	Ps
$\xi(t)$	Ne	$Ne_{\Delta X}/ Ne_{\Delta Y}/Ne_{\Delta\psi}$	$Nss_{\Delta X}/ Nss_{\Delta Y}/Nss_{\Delta\psi}$	$Ns_{\Delta X}/ Ns_{\Delta Y}/Ns_{\Delta\psi}$
	Ns	$Nss_{\Delta X}/ Nss_{\Delta Y}/Nss_{\Delta\psi}$	$Ns_{\Delta X}/ Ns_{\Delta Y}/Ns_{\Delta\psi}$	$Ze_{\Delta X}/ Ze_{\Delta Y}/Ze_{\Delta\psi}$
	Ze	$Ns_{\Delta X}/ Ns_{\Delta Y}/Ns_{\Delta\psi}$	$Ze_{\Delta X}/ Ze_{\Delta Y}/Ze_{\Delta\psi}$	$Ps_{\Delta X}/ Ps_{\Delta Y}/Ps_{\Delta\psi}$
	Ps	$Ze_{\Delta X}/ Ze_{\Delta Y}/Ze_{\Delta\psi}$	$Ps_{\Delta X}/ Ps_{\Delta Y}/Ps_{\Delta\psi}$	$Pss_{\Delta X}/ Pss_{\Delta Y}/Pss_{\Delta\psi}$
	Po	$Ps_{\Delta X}/ Ps_{\Delta Y}/Ps_{\Delta\psi}$	$Pss_{\Delta X}/ Pss_{\Delta Y}/Pss_{\Delta\psi}$	$Po_{\Delta X}/ Po_{\Delta Y}/Po_{\Delta\psi}$

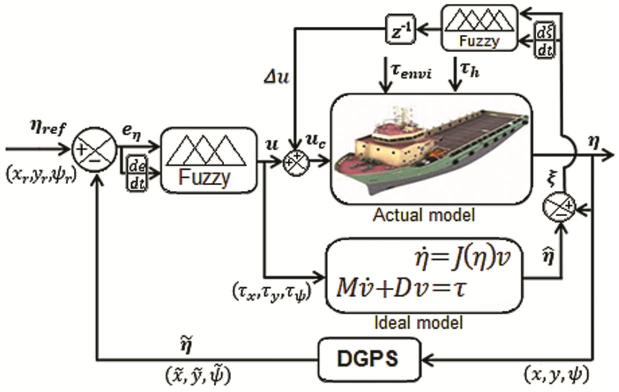

Fig. 7 — The FAI propose structure for actual model

Results and Discussion

Simulation configuration parameters

The FAI solution is examined on the Mariner Class vessel[20] with a length overall 76.2 m, a length between perpendiculars 48 m, beam 18.8 m, design draft 6.25 m, design displacement 350 m^3, and design speed 8 knots. Operation parameters of the Mariner Class vessel are supplied by:

$$M=\begin{bmatrix} 5.0242e4 & 0 & 0 \\ 0 & 2.7229e5 & -4.3933e6 \\ 0 & -4.3933e6 & 4.1894e8 \end{bmatrix}$$

$$D=\begin{bmatrix} 5.3122e6 & 0 & 0 \\ 0 & 8.2831e6 & 0 \\ 0 & 0 & 3.7454e9 \end{bmatrix}$$

The wave, wind, current, and high-frequency wave model are the most four factors in the actual environment. The kinetic model of the wave factor is expressed by Eq. (9). In the use of simulation, the wave parameters are established as follows: the wave height $H_s = 0.8m$, the wave spectrum peak frequency $\omega_p = 0rad/s$, the wave direction $\psi_0 = -30^0$, the spreading coefficient $s = 2$, the requencies number $N = 20$, the directions number $M = 10$, the cutoff coefficient of frequency $\xi = 3$, the energy limit of wave factor $k = 0.005$ and the direction limit of wave factor $\psi_{lim} = 0$. The kinetic model of wind is given by Eq. (12). The simulation parameters[8] of the wind factor is initialized as follow: $A_L = 2.4$, $A_T = 9.34$, the wind speed of Vietnam Sea $V_\omega = 2m/s$ and the impact angle of wind stream $\beta_\omega = 20^0$. Besides that, Eq. (15) presents these factors of a current kinetic model. The default simulation parameters of the current factor are established as follows: the current speed $V_C = 2m/s$, the direction of vessel's motion $\beta_C = 30^0$, the low-frequency rotation and the high-frequency rotation are by passed $\psi_L = \psi_H = 0$. The high-frequency wave model is given by Eq. (16). In this study, the high frequency coefficients are chosen as: the dominating wave frequency $w_0 = 0.8976rad/s$, the damping coefficient $\lambda = 0.1$, and the wave intensity $\sigma = \sqrt{2}$.

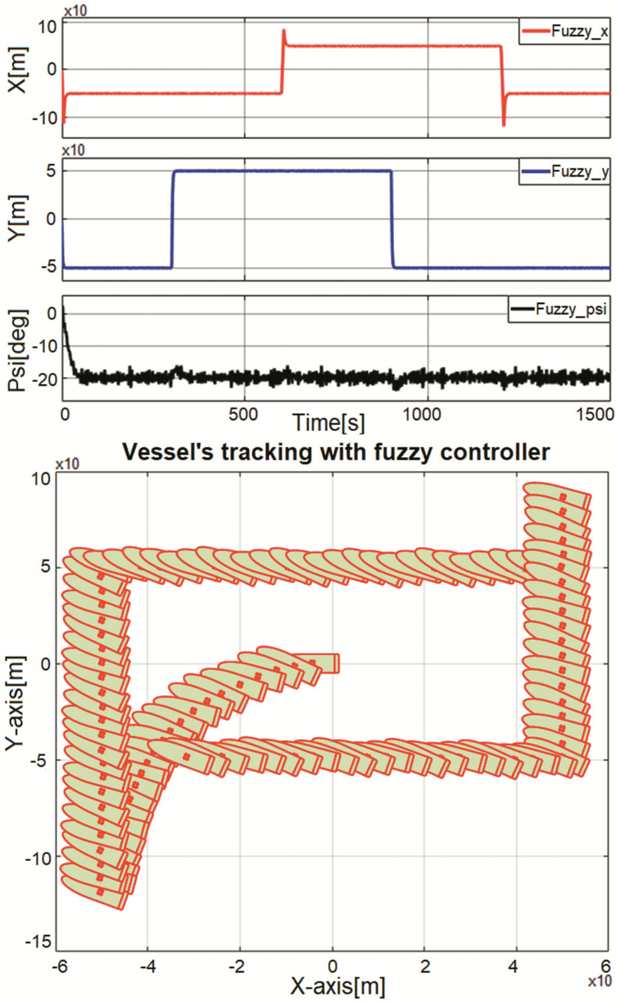

Fig. 8 — Fuzzy controller results at level 6 effects

Simulation results

In summary, the FAI controller is evaluated in comparison with simulation results using the fuzzy controller. In the case of fuzzy controller simulation, the vessel's tracking will be stable in the case of a low impact level and fluctuate in the case of a higher impact level (shown in Fig. 8). On the other hand, the vessel's heading oscillates as per the affecting level of unexpected factors. In the case of FAI controller simulation, the purpose of controller releases to estimate erroneous which caused by environmental factors. Consequently, the performance of the control signal is enhanced, which keeps the oscillation

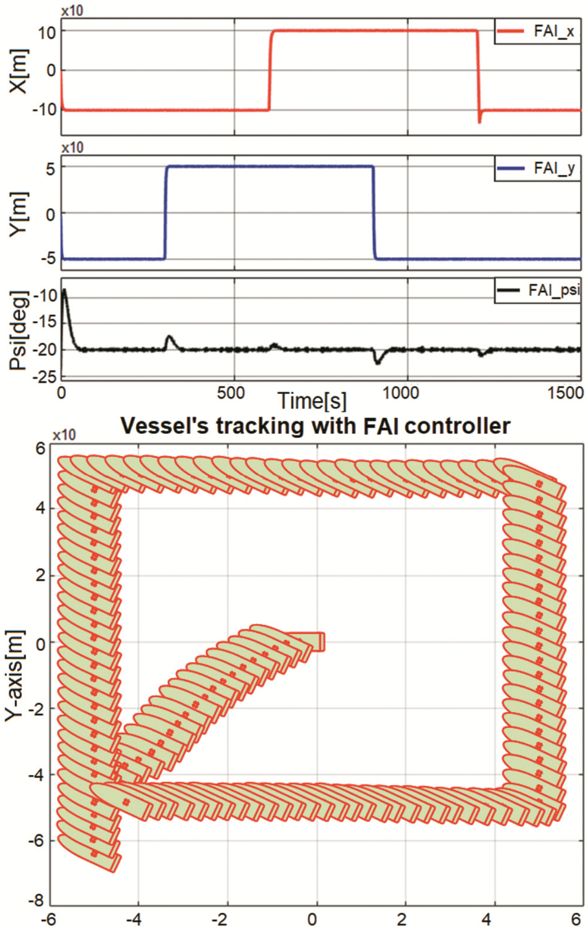

Fig. 9 — FAI controller results at level 6 effects

amplitude of surge, sway, and yaw axes within the allowed limit and maintain balance for the vessel, as seen in Figure 9. Even though operating under the environmental influences case, which is highly nonlinear characteristics from Binh Thuan province to Ca Mau Province.

Conclusion

In this paper, the FAI algorithm has estimated accurately the control erroneous of DPs which caused by the unexpected impacts. On the other hand, the environmental parameters are surveyed from the actual conditions of theVietnam Sea, there by improving the quality and reliability of the proposed controller. That helps maintain the vessel in position and desired direction. More practically, the control signal of the actual model is directly calibrated, hence optimizing the time-delay for the DPs control process. The genetic algorithm which would be considered in the future works to improve the estimation of the nonlinear parameter, instead of the FAI solution.

Conflict of Interest

The authors declare no conflicting interest involved in the research presented in this paper.

Author Contributions

Conceptualization, validation, data curation, and review and editing: VDD and XKD; methodology, software, investigation, visualization, writing–original draft preparation and project administration: VDD; and formal analysis, resources and supervision: XKD. Both the authors have read and agreed to the published version of the manuscript.

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