Journal of Current Science and Technology, January-April 2021
JCST Vol. 11 No.1, pp. 114-126

ISSN 2630-0656 (Online)

Cite this article: Dang, X. K., & Ho, L. A. H. (2021, January). Joint fuzzy controller and fuzzy disturbance compensator in ship autopilot system: investigate stability in environmental conditions. *Journal of Current Science and Technology*, *11*(1), 114-126. DOI:

Journal of Current Science and Technology

Journal homepage: https://jcst.rsu.ac.th

Joint fuzzy controller and fuzzy disturbance compensator in ship autopilot system: investigate stability in environmental conditions

Xuan-Kien Dang[1*] and Le Anh-Hoang Ho[2]

[1]Ho Chi Minh City University of Transport, Ho Chi Minh City, Vietnam
[2]Van Hien University, Ho Chi Minh City, Vietnam

*Corresponding author; Email: dangxuankien@hcmutrans.edu.vn

Received 13 July 2020; Revised 31 October 2020; Accepted 17 November 2020; Published online 30 January 2021

Abstract

The autopilot system is a nonlinear and complex control process that results primarily from changes due to the influence of the operating environment. Separate oceans have different characteristics. In this paper, we proposed a joint fuzzy controller and fuzzy disturbance compensator (FC-FDC) in the ship autopilot system under the impact of the nonlinear error caused by feedback states errors, random delays, uncertain models, and environmental disturbances. In the process of controlling, the designed structure of FC-FDC not only performs ship tracking control but also reduces the effect disturbance while increasing the robustness of the system. As exemplified by selecting types of ships for simulating the FC-FDC ship autopilot system in MATLAB, the simulation results proved the efficiency and advantages of the proposed method.

Keywords: *disturbance compensator; fuzzy controller; nonlinear system; ship autopilot; tracking control.*

Nomenclature

Symbol	Description
ψ	Yaw angle
M, N	Inertia matrix, damping matrix
δ	Rudder angle
τ_e	The moment force of the environmental factors including wave, wind, and current effects
τ_n	The high-frequency spectral components of the wave
T_1, T_2, T_3	Time constant
K	Rudder gain
δ_r	The command rudder angle
δ_{max}	Maximum rudder angle
$\Delta\omega, \Delta\psi$	Harmonic wave amplitude
$\psi_{r,}\omega_q, \phi_{qr}, S$	Direction, frequency, phase angle, wave spectrum
θ_{Wind}	The angle between the X-axis and the direction of the wind
$\theta_{current}$	The angle between the X-axis and the direction of the wind
ρ_{air}, ρ_{water}	The density of air, the density of water
λ, ω_0, K_w	Damping coefficient, wave frequency, gain constant

1. Introduction

Over the past decades, there have been many challenges in the design of ship motion control, and it is difficult to achieve target control because the ship is always running or maneuvering under the effect of the uncertain environmental disturbances. Almost all of the studies related to ship motion control focused on ship dynamic positioning, tracking control, course control, way-point tracking control, underactuated control, and navigation (Fossen, 2000).

In the process of ship trajectory tracking, the basic algorithms used PID (Fang, Zhuo, & Lee, 2010) and backstepping control (Zhang et al., 2017). Recently, Ta, Dang, Dong, and Do (2018) have designed the H∞ robust recurrent cerebellar model articulation controller that efficiently vanishes the effects of external disturbances such as wave, wind, and current acting on the ship to achieve the robustness of the system. The simulation showed valuable results, and the parameters of the control system were consistent with the concept of Lyapunov theory. The robustness of the system was proven to satisfy the H^{∞} robust criterion. Moreover, Sheng et al. (2006) applied H infinite control to ship steering system with uncertain parameters and the robust control law was designed based on H^{∞} μ-synthesis. Their simulation results showed that the designed control system has excellent control effect and robustness. Das and Talole (2016) used a robust design for steering autopilot under the effect of uncertainties and disturbances which was estimated using ESO. The estimate was used to augment an input-output linearization based on controller designed for the nominal system to achieve robustness. Besides, the combination of PID and other algorithms can also achieve better optimization results. For example, the combination of fuzzy control and PID algorithm (Yang, Wang, & Wu, 2014) can avoid full whirling motion in tracking control. A design method for optimal control aimed to achieve the high quality of systems, genetic algorithm (McGookin et al., 2000), and Ant Colony Optimization algorithm applied to Ship steering control (Deng, Xu, & Zhao, 2019; Tomera, 2014). The idea of prediction suggested, and the optimal values of the PID parameters were calculated by using the predictive control algorithms and applied to the ship autopilot (Moradi, & Katebi, 2001). Even though each method has its advantages, autopilot systems based intelligent control theories, such as fuzzy logic control (FLC), neural network control (NNC), cerebellar model articulation control (CMAC), adaptive neural-fuzzy control (ANFIS), have many more operation possibilities that were not feasible before. To be specific, it is easy for the ships to change positions and to keep heading using autopilot. Thanks to its excellent quality.

In recent years, FLC has developed greatly and a multitude of important results to deal with problems of the nonlinearity of autopilot systems in performing a course-keeping task (Ishaque et al., 2011), and fuzzy control for ship roll stabilization (Sutton, Roberts, & Dearden, 1989). Concerning improving the accuracy of fuzzy algorithms, the adaptive fuzzy algorithms were presented by Hu, Du, and Shi (2015) for the DP system under the unexpected impacts from the environment. The unexpected disturbances are considered as the nonlinear parameters and are approximated by the adaptive fuzzy structure even without certain information of dynamic model and time-varying of system. To improve the quality of system response which is impacted by the structure of the model, the authors (Dang et al., 2018) used the fuzzy control method to approximate the nonlinear component. The simulation results achieved good adaptability of the control system under the influence of waves. In the above studies, many problems that affect the autopilot system have been generalized, but control objectives need to be verified in the context of specific marine activities.

Considering the decrease in the effect of the environment in the autopilot system by using fuzzy logic (FL), three methods are direct fuzzy control, control based on disturbance observer, and disturbance compensator. From the above mentioned, the researchers have applied the direct neural-fuzzy algorithm (Dang, Nguyen, & Nguyen, 2015) to resolve the problem of the waves, wind, and sea currents directly interacted with the ship. In the same way, another research (Do et al., 2019) presented a genetic algorithm to optimize the multi-cascade fuzzy model for enhancing the quality of the offshore vessel dynamic positioning system. The algorithms provided effective control of nonlinear systems with uncertain environment dynamic parameters caused by effects that are approximated by the Fuzzy function. Meanwhile, a nonlinear disturbance observer (NDO) was proposed for course keeping maneuvers and speed keeping in vessel steering and showed robust performance (Liu, Lu, & Gao, 2019; Ejaz, & Chen, 2017). Disturbance compensation proposed by Li and Sun is based on model predictive control to satisfy the state constraints in the presence of environmental disturbances (Li, & Sun, 2012).

Based on the aforementioned discussion, the motivation of this paper is to design the ship autopilot system based on FLC to solve the problems of nonlinearity, uncertain ship model, and disturbance. Hence, the proposed approach combines two fuzzy controllers in the control model for the reasons as follows: 1) the fuzzy controller (FC) directly connects to the ship dynamic model aiming to approximate a nonlinear error caused by feedback states errors and random delays, and 2) the fuzzy disturbance compensator (FDC) deals with the problem of uncertain models and environmental disturbances that cause the deviation between the actual model and the ideal model. The output of FDC helps FLC not only perform ship tracking control but also helps to reduce disturbances to increase system sustainability.

The rest of this paper is organized as follows. In Section 2, we introduce the dynamic motion of the ship with some assumptions and remarks. To join the fuzzy controller and fuzzy disturbance compensator (FC-FDC) in the ship autopilot control model is presented in Section 3. Section 4 is dedicated to showing the simulation results, analysis, and evaluation of the proposed FC-FDC model. Finally, we conclude the paper in Section 5.

2. Problem formulation

2.1 The ship dynamic motion

The model of a maritime vehicle was presented by Fossen (2000) and described in a six-degree coordinate system. Due to the dynamic motion of the ship in a horizontal plane, the 6 degrees of freedom model is simplified and reduced to 3 degrees of freedom including surge, sway, and yaw. The two coordinate systems illustrated in Figure 1 include the body-fixed frame shown as $O - XYZ$ and the earth-fixed frame presented as $o - xyz$. The position (x, y) and heading ψ of the ship in the absolute coordinate system xyz are expressed in the vector form $\eta = (x, y, \psi)^T$. The linear model for the ship autopilot system (Fossen, 2000) with 3 degrees of freedom, namely, surge, sway, yaw, and the external force acting can be written as:

$$M\dot{v} + N(u)v = b\delta + \tau_e + \tau_n \tag{1}$$

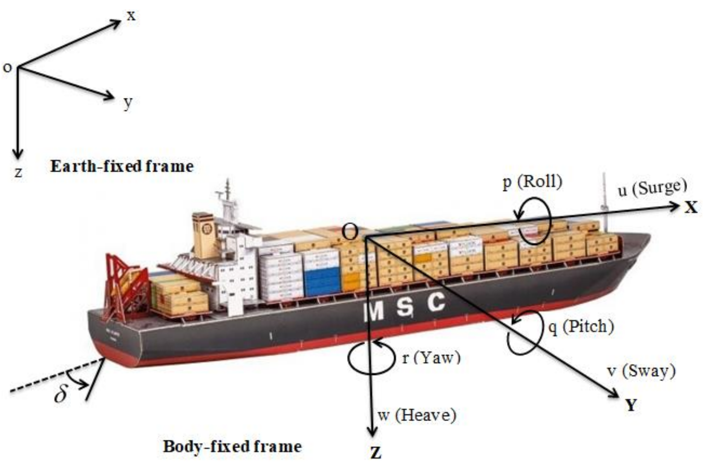


Figure 1 Body and earth-fixed reference frames

When M is the inertia matrix, N is the damping matrix of the system, and δ is the angle of the rudder. Equation (1) shows the rudder and yaw angle described as follows (Fossen, 2000):

$$\begin{bmatrix} m - Y_{\dot{v}} & mx_G - Y_{\dot{r}} \\ mx_G - N_{\dot{v}} & I_Z - N_{\dot{r}} \end{bmatrix} \begin{bmatrix} \dot{V} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} -Y_v & m - Y_{\dot{v}} & u - Y_r \\ -N_v & mx_G - Y_{\dot{r}} & u - N_r \end{bmatrix} \begin{bmatrix} V \\ r \end{bmatrix} = -\begin{bmatrix} Y_\delta \\ N_\delta \end{bmatrix} \delta \tag{2}$$

From equation (2), application of the Laplace transformation yields (Fossen, 2000):

$$\frac{r(s)}{\delta(s)} = \frac{K(1+T_3 s)}{(1+T_1 s)K(1+T_2 s)} \qquad (3)$$

Equation (3) is referred to as the second-order Nomoto model. K represents a static yaw rate, T_1, T_2 and T_3 represent time constant and $\dot{\psi} = r$ represents the heading. The control input vector δ is the rudder of the ship supplied by the actuator. Vector τ_e denotes the moment force of the environmental factors including wave, wind, and current effects. Vector τ_n is the high-frequency spectral components of the wave which affect the ship. τ_e and τ_n are defined as:

$$\tau_e = \tau_{wind} + \tau_{current} + \tau_{wave}$$
$$\tau_n = h(s) \qquad (4)$$

The rudder actuating mechanism has some saturation limits in terms of the maximum rudder angle and the slew rate. For most ships, the saturation limits on the rudder angle are 35°. The saturation limits implement in the form of the block diagram in Figure 2, where the command rudder angle δ_r from the controller modifies as the actual rudder angle δ (Fossen, 2000).

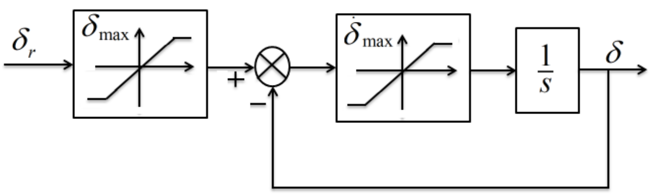


Figure 2 Saturation model of the rudder mechanism

***Assumption 1*:** If the vessel operates in a practical case under environmental impacts, the parameter object will be highly nonlinear underlying physical processes.

Modern solutions are highly effective, which allows users to make decisions based on their experience. Besides, the structure parameters set up with a fixed status, the nonlinear autopilot system does not give high precision, and as such, Assumption 1 is reasonable and more practical.

***Assumption 2*:** The rudder actuating mechanism has saturation limits in terms of the maximum rudder angle is ±35°.

2.2 Disturbances model

A ship will be exposed to waves, wind, and currents. These environmental disturbances with various effects on the ship have been analyzed. The impacts of the environmental conditions from Binh Thuan province to Ca Mau province sea area, which are nonlinear and has the strongest impact on the safety of the operating ship, are illustrated in Figure 3 (Dang et al., 2018). Besides, the high-frequency wave components are also considered to improve the quality of the purpose controller.

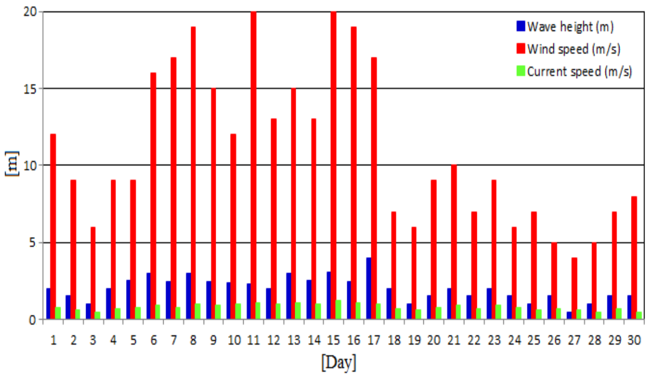


Figure 3 Wave, wind and current speed, July 2017, Vietnam sea states

2.2.1 Wave model

The process of wave generation due to wind starts with small wavelets appearing on the water surface increased the drag force, which in turn allows short waves to grow. These short waves continue to grow until they finally break, and their energy dissipates. The mathematical wave model (Fossen, 2000; Dang, Ho, & Do, 2018) uses for modeling the wave surface construction and determining the wave height. The wave factor affected the ship autopilot system as in equation (5).

$$\tau_{wave} = \zeta(x,y,t) = \sum_{q=1}^{N}\sum_{r=1}^{M}\sqrt{2S(\omega_q,\psi_r)\Delta\omega\Delta\psi}\, sin\left(\omega_q t + \phi_{qr} - k_q(xcos\psi_r + ysin\psi_r)\right) \quad (5)$$

2.2.2 Wind model

The wind is defined as the movement of air relative to the surface of the Earth. The wind forces and moments are used in ship autopilot systems to improve the performance and robustness of the system in extreme conditions. They are illustrated according to wind forces regulations in Vietnam and written as (Fossen, 2000; Dang, Ho, & Do, 2018):

$$\begin{aligned} u_{wind} &= V_{wind} cos(\theta_{Wind} - \psi) - u \\ v_{wind} &= V_{wind} sin(\theta_{Wind} - \psi) - v \\ X_{wind} &= \frac{1}{2} R_{wx}\rho_{air}A_T(u_{wind})^2 \\ Y_{wind} &= \frac{1}{2} R_{wy}\rho_{air}A_L(v_{wind})^2 \end{aligned} \quad (6)$$

2.2.3 Current model

Ocean currents are horizontal and vertical circulation systems of ocean waters produced by gravity, wind friction, and water density variation in different parts of the ocean. The current velocity was given by (Fossen, 2000; Dang et al., 2018):

$$\begin{aligned} u_{current} &= V_{current} cos(\theta_{current} - \psi) - u \\ v_{current} &= V_{current} sin(\theta_{current} - \psi) - v \\ X_{current} &= \frac{1}{2} R_{wx}\rho_{water}A_T(u_{water})^2 \\ Y_{current} &= \frac{1}{2} R_{wy}\rho_{water}A_L(v_{water})^2 \end{aligned} \quad (7)$$

2.2.4 The high-frequency wave model

The linear approximation equation of high-frequency spectra is usually preferred by ship autopilot systems engineers, owing to its simplicity and applicability and is written as (Fossen, 2000):

$$\tau_n = h(s) = \frac{K_w s}{s^2 + 2\lambda\omega_0 s + \omega_0^2} \quad (8)$$

3. Joint fuzzy controller and fuzzy disturbance compensator (FC-FDC) in the ship autopilot system

3.1 Ship autopilot design using FC

To reduce the nonlinear characteristics of the ship autopilot system caused by unwanted effects from the waters, we used the weather in the sea from Binh Thuan to Ca Mau province in Vietnam. We consider the Fuzzy controller to keep the ship heading illustrated as in Figure 4 (Dang, Ho, & Do, 2018; Do, & Dang, 2019). The Fuzzy controller has two inputs: $e(t)$, $de(t)/dt$, and the output $\tau(t)$ used the Takagi-Sugeno Fuzzy reference method. The purpose of the fuzzy algorithm is based on the practical experience of the ship heading and has established a measurable Fuzzy table.

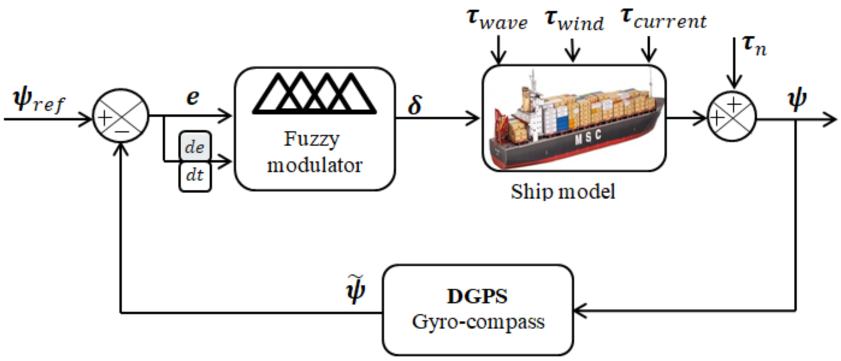


Figure 4 Ship autopilot using fuzzy controller

The inputs and output of the FC for the ship autopilot system are defined as follows:

$e(t) = \{ NE \quad ZE \quad PO \}$

$de(t)/dt = \{ NE \quad ZE \quad PO \}$

$\tau(t) = \{ NB \quad NS \quad ZE \quad PS \quad PB \}$

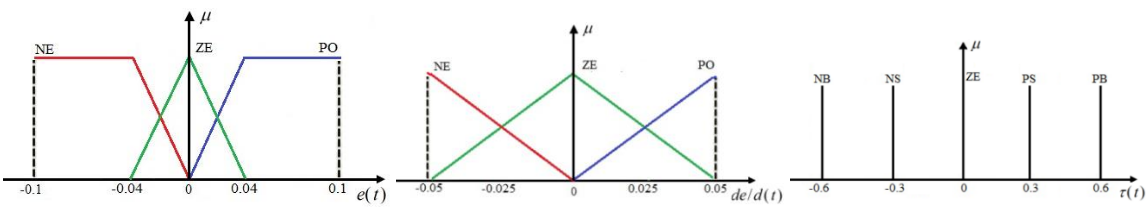
And based on the practical issues of the ship autopilot system, we use fuzzy control rules for the selected ship autopilot system shown in Table 1 (Narwane et al., 2020).

Table 1 Fuzzy rule inference for the ship autopilot system with FC

$\tau(t)$		$e(t)$ NE	ZE	PO
$de(t)/d(t)$	NE	NB	NS	ZE
	ZE	NS	ZE	PS
	PO	ZE	PS	PB

The impact of environmental noise often causes the ship control signal to become distorted. The reason is the change in the dynamic characteristic of the object.

The automatic control concepts of the fuzzy algorithm are implemented corresponding to the input errors. Controls error is reduced as well as the control target maintained. Membership functions described the input and out characteristics in Figure 5.



(a) (b) (c)

Figure 5 Membership functions: (a) error $e(t)$, (b) velocity of error $de(t)/dt$, and (c) force $\tau(t)$

3.2 Proposed FC-FDC structure for the ship autopilot system

The structure of FC-FDC is shown in Figure 6 (Hu, Du, & Shi, 2015). In case the FC directly controls the ship, the results are very satisfactory under ideal conditions or a low impact level. The characteristics of Vietnamese waters are causes of the structural dynamics of the Ships, along with the long duration of continuous motion ship imbalance.

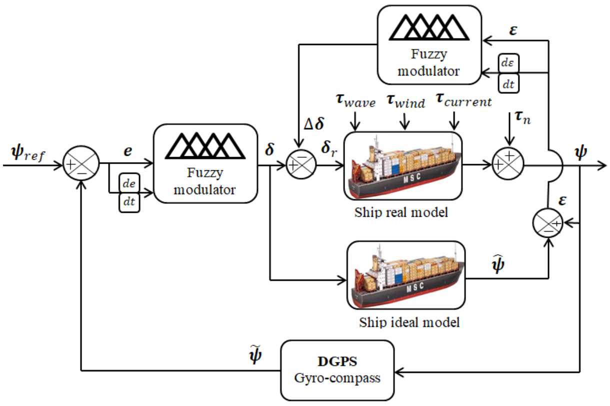


Figure 6 FC-FDC structure for ship autopilot

The main idea of the FC-FDC structure based on the output response error ε within the real model and the ideal model, thereby compensating for an additional amount of $\Delta\delta$ (appropriately adjusted by the fuzzy algorithm based on the parameter ε) on the real model control signal to satisfy the output of the reduced-deviation object and remain in the control domain. The error between the real model and the ideal model which shows below:

$$\varepsilon = \Psi - \widehat{\Psi} = P_t(s).U_t(s) - P(s).U(s) \quad (9)$$

The control signal of the real model can be presented by

$$\delta_r = \delta - \Delta\delta \quad (10)$$

To determine the quantity $\Delta\delta$ for the surge, sway, and yaw motion control signals, we consider the fuzzy modulator which has double-inputs: the error $\varepsilon(t)$ and the velocity error $d\varepsilon(t)/d(t)$ between setting values and real values for fuzzy sets shown in Table 2. The membership function describes these input/output in Figures 7 (a), (b), and (c) and collections set as below:

$\varepsilon(t) = \{VPS \quad PS \quad PM \quad PB \quad VPB\}$

$d\varepsilon(t)/dt = \{PS \quad PM \quad PB\}$

$\Delta\delta = \{VPS \quad PSS \quad PS \quad PM \quad PB \quad PBB \quad VPB\}$

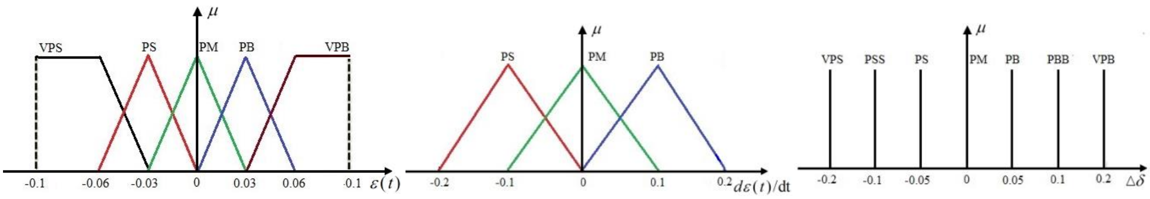
Table 2 The rules for adjusting $\Delta\delta$ coefficient

$\Delta\delta$		$\varepsilon(t)$				
		VPS	PS	PM	PB	VPB
$d\varepsilon(t)/dt$	PS	VPS	PSS	PS	PM	PB
	PM	PSS	PS	PM	PB	PBB
	PB	PS	PM	PB	PBB	VPB

The fuzzy logic is used as a solution to reduce the effect of model error because, as is well known, a fuzzy system can approximate to arbitrary closeness a wide class of real nonlinear functions. The error ε helps to estimate the value and the level of relative environmental impacts. The objective of the proposed method is to remove the unexpected value ε by modulating the real model control signal with $\Delta\delta$ to satisfy the adaptive output according to the ideal model signal. It means $\varepsilon \to 0$ when $t \to \infty$ equivalent

$$P_t(s).U_t(s) = P(s).U(s) \quad (11)$$

Another problem that harms the autopilot system is timing. Errors make the object structure change continuously when operating in the actual situation, so there is a delay in adjusting the control signal, which is not appropriate. In contrast, they gain bias and the risk of imbalance. With the FC-FDC structure, the direct adjustment is basing on the actual model control signal, and the optimization is time-tuning. The result is improving the quality of control.



(a) (b) (c)

Figure 7 Membership functions: (a) error $\varepsilon(t)$, (b) velocity of error $d\varepsilon(t)/dt$, and (c) force $\Delta\delta$

4. Simulation and discussion

4.1 Simulation parameters

Table 3 The parameters for the ship

Ship Parameters	
Length overall	171.80 m
Length between perpendiculars	160.93 m
Maximum beam	23.17 m
Design draught	8.23 m
Design displacement	18541 m^3
Design speed	15 knots
Max rudder derivative	5 (rad/s)
Max rudder angle	35 (rad)
Controller Parameters	
Rudder contant K	0.185s^{-1}
T_1	25 s
T_2	7.8 s
T_3	18.5s

In this section, we consider numerical simulation (with Assumption 1 and Assumption 2) to show the effectiveness of the proposed FC-FDC. Using parameters in Table 3, we simulate the results by using Matlab software with detailed parameters for each of the components are chosen (Fossen, 2000; Dang, Ho, & Do, 2018). For example,

Wave model: $H_s = 0.8\ m,\ \omega_p = 0\ rad/s,\ \psi_0 = -30^0,\ s = 2,\ N = 20,\ M = 10,\ \xi = 3, k = 0.005$;

Wind model: $A_L = 2.4, A_T = 9.34, V_\omega = 10\ m/s$, and $\beta_\omega = 20^0$;

Current model: $V_C = 2\ m/s$, and $\beta_C = 30^0$;

High-frequency wave model: $w_0 = 0.8976\ rad/s, \lambda = 0.1$, and $\sigma = \sqrt{2}$.

4.2 Simulation results and discussion

4.2.1 Simulated conditions like those in Vietnam's waters

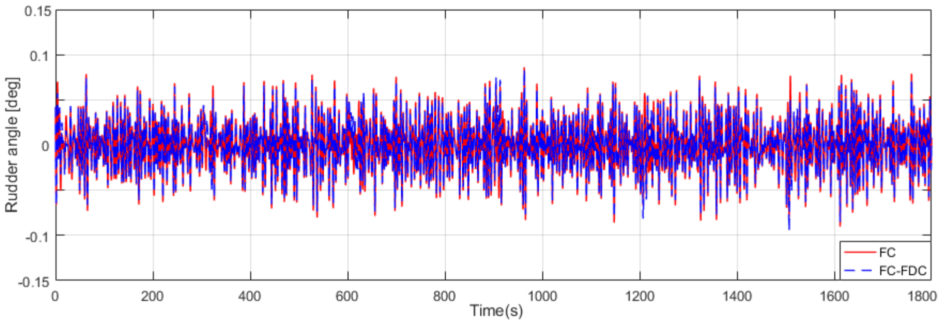


Figure 8 Simulation results of ship autopilot rudder angles - level 3

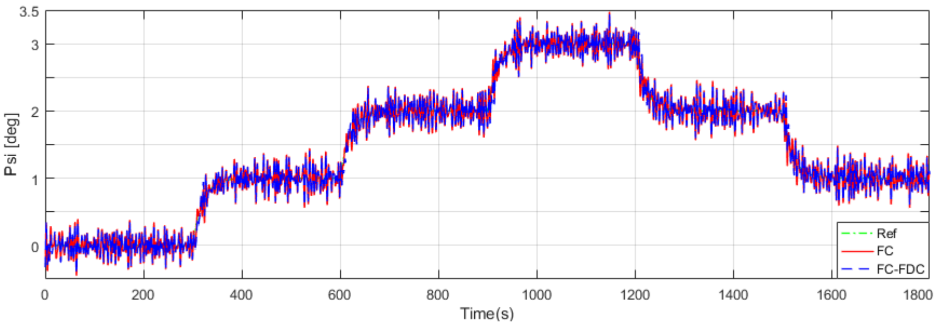


Figure 9 Simulation results of ship autopilot heading – level 3

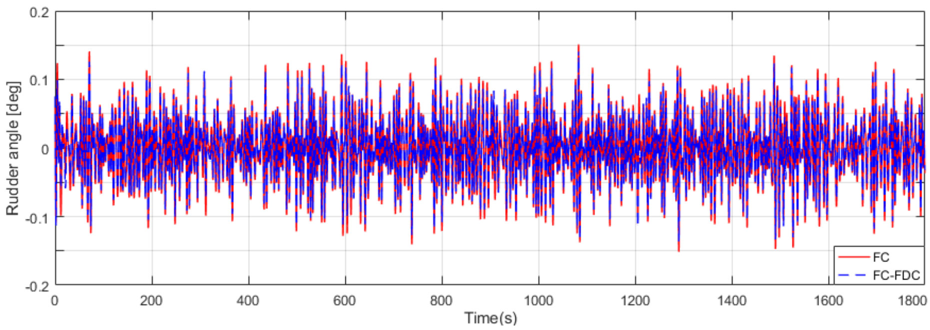


Figure 10 Simulation results of ship autopilot rudder angles – level 5

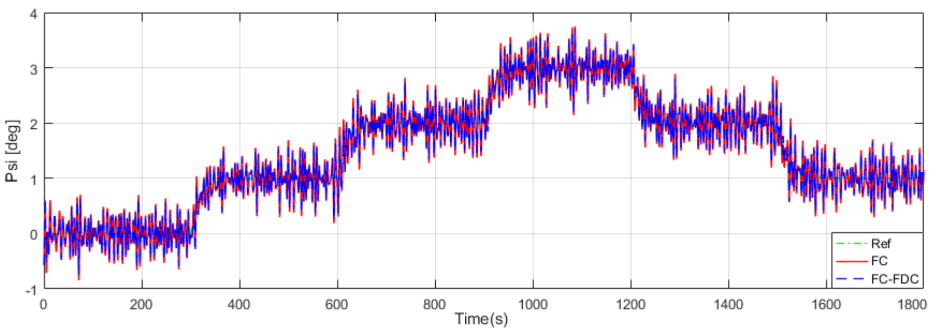


Figure 11 Simulation results of ship autopilot heading – level 5

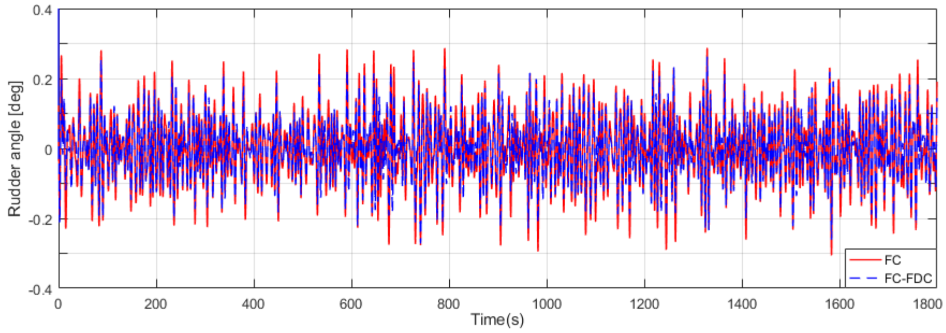


Figure 12 Simulation results of ship autopilot rudder angles – level 6

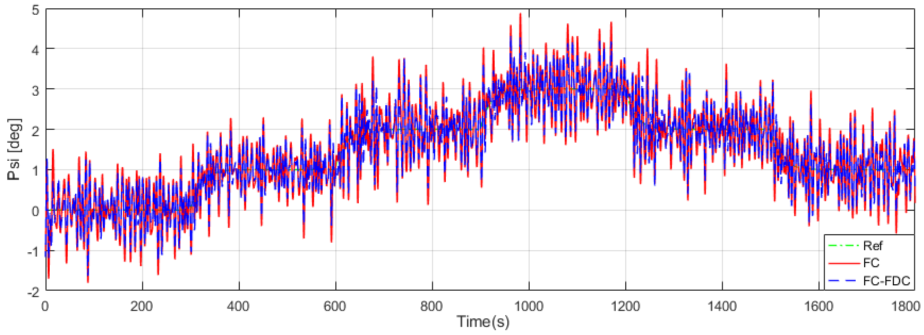


Figure 13 Simulation results of ship autopilot heading – level 6

The simulation is similar to the conditions in Vietnam's waters (Dang, Ho, & Do, 2018). We compared the FC and the FC-FDC (Dang et al., 2018) in the case of sea level from 3 to 6, and the results are shown in Figures 8-13. The above results show that both systems do not eliminate the impact of the environment, while the responses of the heading and rudder angle toward the stable domain of the ship autopilot system using FC-FDC are faster than that using the FC.

4.2.2 Simulated conditions when the ship is affected by environmental disturbance and high-frequency wave

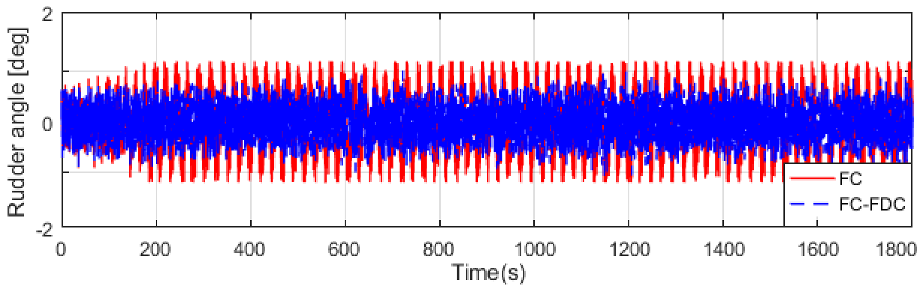


Figure 14 Simulation results of ship autopilot rudder angles – level 3

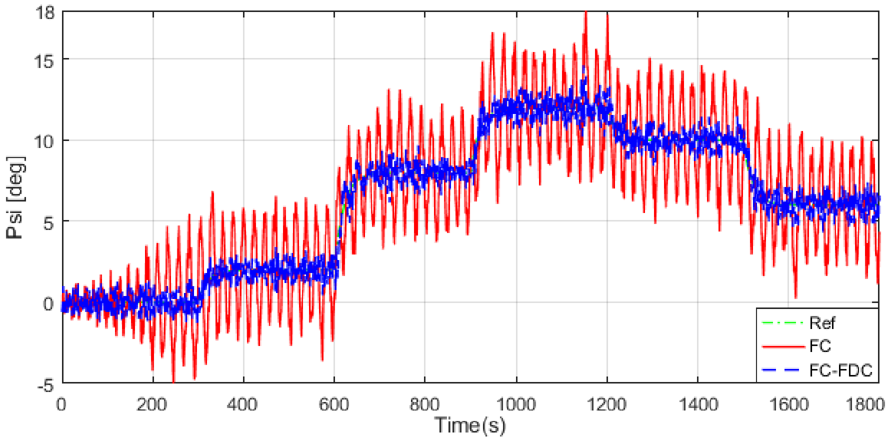


Figure 15 Simulation results of ship autopilot heading – level 3

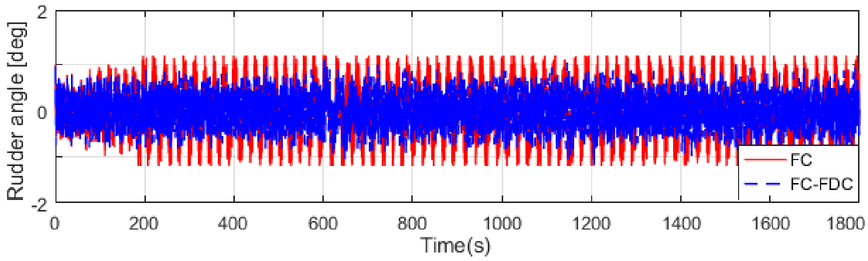


Figure 16 Simulation results of ship autopilot rudder angles – level 5

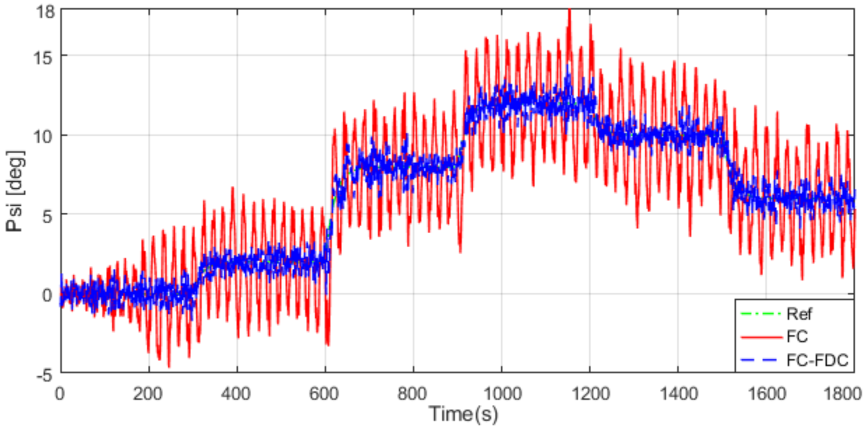


Figure 17 Simulation results of ship autopilot heading – level 5

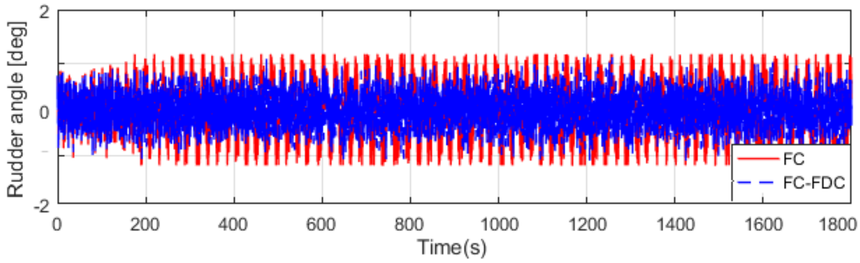


Figure 18 Simulation results of ship autopilot rudder angles – level 6

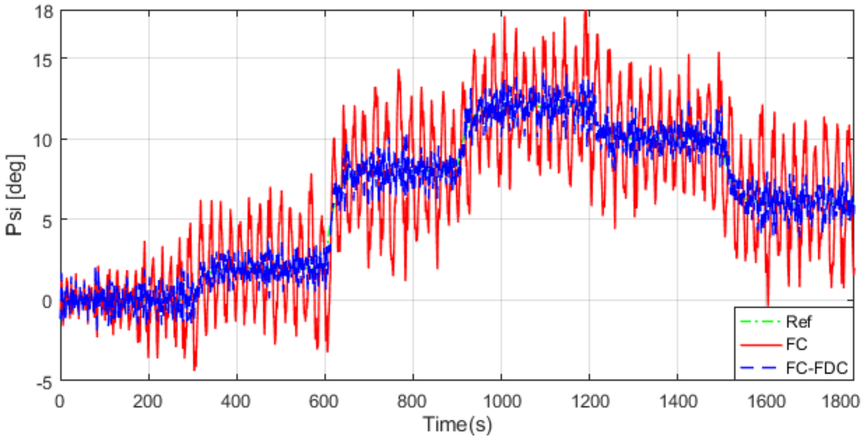


Figure 19 Simulation results of ship autopilot heading – level 6

In case of the ship is affected by environmental disturbance and high-frequency wave, the simulation results are presented in Figures 14-19. The results show that the response of the FC-FDC is better than the FC. Besides, the response of the FC-FDC is better than those from other studies using nonlinear disturbance observer controllers (Liu et al., 2019) and disturbance compensating model predictive control (Li, & Sun, 2012) when the ship is affected by many environmental impacts.

The FC-FDC enables identification of these deviations through which the correction of the control signal quality is performed. The FC-FDC improves the yaw of the low vibration ship and stable even when operating under the influence of the environment, which are unwanted components with high nonlinear characteristics such as from Binh Thuan province to the Ca Mau province sea area in Vietnam.

5. Conclusion

In this paper, we present a method for designing a ship autopilot system under unexpected impacts of the sea area in Vietnam using the FC-FDC algorithms to improve the performance of autopilot systems. The proposed structure has been estimated fairly accurately and eliminated deviation due to the adverse effects of the environment and the high-frequency wave on the ship. On the other hand, the impact parameters explored by actual sea conditions from the area from Binh Thuan province to the Ca Mau province, thereby improving the quality and reliability of the controller to help the ship retain the desired heading over time. The results of the simulation of the ship's autopilot system show that the FC-FDC structure applied to the ship's desired course tracking with better compatibility and robustness compared with the fuzzy controller. However, the proposed method needs to be explored further in a variety of maritime conditions to demonstrate the viability of the idea.

6. References

Dang, X. K., Ho, L. A. H., & Do, V. D. (2018). Analyzing the sea weather effects to the ship maneuvering in Vietnam's Sea from Binh Thuan province to Ca Mau province based on fuzzy control method. *TELKOMNIKA Telecommunication, Computing, Electronics and Control, 16*(2), 533-543. DOI: 10.12928/telkomnika.v16i2.7753

Dang, X. K., Nguyen, T. Q., & Nguyen, X. P. (2015). Ship autopilot system design and testing on Santana ship model based on neural-fuzzy method. In *Proc. 3rd Vietnam Conference on Control and Automation – VCCA*, 683-689. DOI: 10.15625/vap.2015.0016

Das, S., & Talole, S. E. (2016). Robust steering autopilot design for marine surface vessels. *IEEE Journal of Oceanic Engineering, 41*(4), 913-922. DOI: 10.1109/JOE.2016.2518256

Deng, W., Xu, J., & Zhao, H. (2019). An improved ant colony optimization algorithm based on hybrid strategies for scheduling problem. *IEEE Access, 7*, 20281-20292. DOI: 10.1109/ACCESS.2019.2897580

Do, V. D., & Dang, X. K. (2019). The fuzzy particle swarm optimization algorithm design for dynamic positioning system under unexpected impacts. *Journal of Mechanical Engineering and Sciences (JMES)*, *13*(3), 5407-5423. DOI: 10.15282/jmes.13.3.2019.13.0439

Do, V. D., Dang, X. K., Huynh, L. M. T., & Ho, V. C. (2019). Optimized multi-cascade fuzzy model for ship dynamic positioning system based on genetic algorithm. *International Conference on Industrial Networks and Intelligent Systems*, *293,* 165-180. DOI: 10.1007/978-3-030-30149-1_14

Ejaz, M., & Chen, M. (2017). Optimal backstepping control for a ship using firefly optimization algorithm and disturbance observer. *Transactions of the Institute of Measurement and Control, 40*(6), 1983-1998. DOI: 10.1177/0142331217695388

Fang, M. C., Zhuo, Y. Z., & Lee, Z. Y. (2010). The application of the self-tuning neural network PID controller on the ship roll reduction in random waves. *Ocean Engineering***,** *37*(7), 529-538. DOI: 10.1016/j.oceaneng.2010.02.013

Fossen, T. I. (2000). A survey on nonlinear ship control: from theory to practice. *IFAC Conference on Manoeuvring and Control of Marine Craft***,** *33*(21), 1-16. DOI: 10.1016/S1474-6670(17)37044-1

Hu, X., Du, J., & Shi, J. (2015). Adaptive fuzzy controller design for dynamic positioning system of vessels. *Applied Ocean Research*, *53,* 46-53. DOI: 10.1016/j.apor.2015.07.005

Ishaque, K., Abdullah, S. S., Ayob, S. M., & Salam, Z. (2011). A simplified approach to design fuzzy logic controller for an underwater vehicle. *Ocean Engineering, 38*(1), 271-284. DOI: 10.1016/j.oceaneng.2010.10.017

Li, Z., & Sun, J. (2012). Disturbance compensating model predictive control with application to ship heading control. *IEEE Transactions on Control Systems Technology, 20*(1), 257-265. DOI: 10.1109/TCST.2011.2106212

Liu, Z., Lu, X., & Gao, D. (2019). Ship heading control with speed keeping via a nonlinear disturbance observer. *Journal of Navigation*, *72*(4), 1035-1052. DOI: 10.1017/S0373463318001078

McGookin, E. W., Smith, D. J. M., Li, Y., & Fossen. T. I. (2000). The optimization of a tanker autopilot control system using genetic algorithms. *Transactions of the Institute of Measurement and Control***,** *22*(2), 141-178. DOI: 10.1177/014233120002200203

Moradi, M. H., & Katebi, M. R. (2001). Predictive PID control for ship autopilot design. *IFAC Proceedings, 34*(7), 375-380. DOI: 10.1016/S1474-6670(17)35111-X

Narwane, V. S., Narkhede, B. E., Bhosale, V. V., & Jain, P. (2020). Comparative analysis of PID and fuzzy logic controller: A case of furnace temperature control. *Journal of Current Science and Technology, 10*(2), 109-120. DOI: 10.14456/jcst.2020.11

Sheng, L., Ping, Y., Yan, L. Y., & Chun, D. Y. (2006). Application of H infinite control to ship steering system. *Journal of Marine Science and Application, 5*(1), 6-11. DOI: 10.1007/s11804-006-0041-8

Sutton, R., Roberts, G. N., & Dearden, S. R. (1989). Design study of a fuzzy controller for ship roll stabilization. *Electronics & Communication Engineering Journal, 1*(4), 159-166. DOI: 10.1049/ecej:19890033

Ta, V. P., Dang, X. K., Dong, V. H., & Do, V. D. (2018). Designing dynamic positioning system based on H^{∞} robust recurrent cerebellar model articulation controller. *2018 4th International Conference on Green Technology and Sustainable Development (GTSD),* 652-657. DOI: 10.1109/GTSD.2018.8595553

Tomera, M. (2014). Ant colony optimization algorithm applied to ship steering control. *Procedia Computer Science, 35,* 83-92. DOI: 10.1016/j.procs.2014.08.087

Yang, Z., Wang, J. H., & Wu, Y. P. (2014). Straight line path following of unmanned surface vessel based on Fuzzy PID. *Computer Engineering***,** *40*(10), 270-274.

Zhang, Q., Jiang, N., Hu, Y., & Pan, D. (2017). Design of course-keeping controller for a ship based on backstepping and neural networks. *International Journal of e-Navigation and Maritime Economy***,** *7,* 34-41. DOI: 10.1016/j.enavi.2017.06.00