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Application of Fuzzy Logic Controller to Enhance The Semi-SWATH Performance in Following Seas

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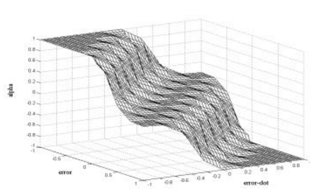
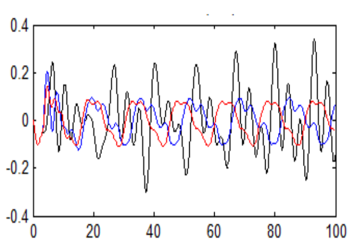
Graphical abstract





Abstract

Semi-SWATH ship has a different characteristics compared to the common ship hull. The ship has a tendency to suffer bow-dive due to low restoring force at bow when running in following seas. In some conditions, the foredeck found to be immersed under the rear of wave. Acceleration motion to the trough increases the momentum force that pushing the ship to dive. The condition may cause the ship has a loss of control even the crew can feel thrown forward. In this research, fin stabilizer was applied to reduce the effect of those conditions with application of fuzzy logic controller. The controller calculates the angle for the fin stabilizer based on the pitch angle. The fin at both ends of the ship's hull increase the lift force, reduce the trim angle, and restrain the ship from dynamic high acceleration. A numeric time-domain program developed to analyze the ship seakeeping in following sea. The results showed the controller ofthe fin stabilizer has a significant effect in preventing the ship from the unsafe condition.

Keywords: Semi-SWATH; fuzzy logic

1.0 INTRODUCTION

Comfort with a low ship motion in sailing is a basic requirement for the passenger ship, becomes a goal for the ship designer. Interaction between the ship and the water environment resulted in motion aspect that influences the passenger or crew whether they having comfort or discomfort. This becomes important for the ship designer to be considered for the passenger ship, ferry which is increase year by the years. Papanikolaou has presented the systematically data for the high-speed ship operating in worldwide since 2005, showed Catamaran was used widely in the world; she has 34.1% whilst SWATH ship has 1.2% and semi-SWATH ship has 1.4% of 653 ships[1].

Semi-SWATH, as a ship combination design of SWATH and Catamaran has the advantages in seakeeping which is proved that the demand of the ship increase and still increase in the future. The ship applied for passenger, ferry, and even for navy. However, the ship has a disadvantage running in the following high wave. Where, the bow-dive is one of the nonlinear conditions that confirmed experimentally. It happened when amidships just passing the wave crest and accelerating to the wave's trough [2, 3]. The disadvantage comes from the low restoring force at bow.

Some solutions were developed to improve the seakeeping quality of the ship. One of the solutions was implementing the active and passive fin stabilizer. The fin stabilizers resulted in lift force and moment, restrains the vertical motion velocity which is depended on the ratio of fin area, waterline area, fluid velocity, and angle of attack. In 2005, Frohlich *et al.* studied on relation of the hull design and seakeeping response of SWATH. Four modification hulls which are passive fins at the stern, additional profiles attached at the wet deck, displacement body attached at the wet deck, and additional displacement by increasing the bow flare. They investigated the attaching profiles and displacement structure were intended to provide a high additional stiffness force in high wave, while fin stabilizer provides a damping motion effect in high speed. From investigation of these variations found the pitch and heave motion of SWATH ship using aft fin stabilizer has a best performance in waves [4].

Application of fin stabilizer in improving seakeeping quality such as to reduce the effect of rolling motion and increase the ship stability in rough sea condition showed a significant effect [5, 6, 7, 8, 9]. However, the effectiveness of fin stabilizers in a normal to high sea states can severely deteriorate due to nonlinear effects arising from unsteady hydrodynamic characteristics such as dynamic stall. The nonlinear effect takes the form of a hysteresis when the effective angle of attack exceeds a certain threshold angle [10, 11, 12, 13].

In earlier, Abkowitz (1959) and Vughts (1967) have analyzed the effectiveness of the fin stabilizer installed at bow for reducing pitch motion. The results showed one-third amplitude reduction, whilst heave motion was not reduced significantly [14]. Djatmiko researched SWATH ship using a fixed fins stabilizer at bow and stern with different forward speeds showed an insignificant fin effect at a low speed but at a higher speed the heave and pitch motions are reduced significantly [15]. Investigation of pitch and heaves characteristics of Catamaran with fore passive fin stabilizer provides an increase of the seakeeping performance up to 30% in regular and irregular seas [16, 17]. Application of fin stabilizer with fuzzy logic control compared to proportional integral derivative controller showed fuzzy has high performance in long wave as well on the seakeeping performance of the SWATH ship [18, 19]. Furthermore, investigation of fins stabilizer for roll motion subjected to the wave disturbance and constraints of fins stall angle [20]. Analysis of a resonance free SWATH equipped fins at fore and aft with PD control resulted the pitch lower compared to the monohull, trimaran, and conventional SWATH design [21].

Few algorithms have been developing such as fuzzy logic, neural network, and hybrid method where the hybrid method is a combination of two or more methods such as PID and neural network, PID and fuzzy logic, fuzzy logic and neural network, etc. The methods are developing rapidly with the increase of computer processing capacity. In complex problem, calculation process required a high computer performance. One of the algorithms is the fuzzy logic algorithm that has been developing since proposed in 1965 by Zadeh. It works based on the human skill knowledge, interprets the human linguistic qualitative value in degrade of probability to control a plan system such as for ship maneuvering [23].

This paper presents the effectiveness of the fin stabilizer application using fuzzy logic controller on the seakeeping of semi-SWATH in following high sea to decrease the dynamic motion.

2.0 MATHEMATICAL MODEL

2.1 Ship Motion Model

Numerical simulation program can express the ship behavior in the art of mathematics. The ship modeled in the second order of differential equation. The model was developed in 3DOF of surge, heave, and pitch motion. The axis motion follows the right hand axis rule. The ship motion axis generally was translated in two spaces of coordinate, fixed and moving coordinate. Fixed coordinate refers to earth (OXYZ) and another refers to the ship (*OXsYsZs)*. The fixed coordinate system located at a calm water surface with Z axis pointing upwards. The moving coordinate system is located at the centre of gravity.

The numerical model consists of longitudinal and vertical motion. The longitudinal motion consists of surge motion and vertical motion consist heave and pitch. The longitudinal and vertical motions can be arranged in uncouple equation. The surge motion has a negligible cross effect to the vertical motion and can be ignored in modeling [24], whilst the vertical motions of heave and pitch has a significant cross effect that cannot be ignored [25].

Surge motion is a longitudinal motion which superimposed on the propeller thrust, hull resistance, and harmonic incident wave force of Froude-Krylov, [26, 27]. Ship's weight as an internal force was integrated in the model that has influence to push the ship forward or backward during the ship being in relative angle to the wave. The internal force and moment exist along with the external wave force and cause the ship having nonlinear response. It causes the encounter wave frequency will changes each time there a surge motion displacement relative to the wave. Thus, the equation of the ship model must be developed using a time-varying model. The model can express the nonlinear response and express the ship behavior.

Hydrodynamic coefficients of the model consist of mass, added mass, damping, and stiff expressed with *m*, *a*, *b*, *c* respectively. Index *1,3,5* indicate surge, heave and pitch respectively and *F* is force or moment of wave as shown in following form;

$$\begin{aligned}
&(a_{11}+m)\ddot{x}_1+[R(u)-T(u,n)]=F_1^W-mg\,\mathbf{sin}\,\theta \\
&(a_{33}+m)\ddot{x}_3+b_{33}\dot{x}_3+c_{33}x_3+a_{35}\ddot{x}_5+b_{35}\dot{x}_5+c_{33}x_5\cdots \\
&=F_3+mg\,\mathbf{cos}\,\theta \\
&a_{53}\ddot{x}_3+b_{53}\dot{x}_3+c_{53}x_3+(a_{55}+I_{55})\ddot{x}_5+b_{55}\dot{x}_5+c_{55}x_5\cdots \\
&=F_5-x_S mg\,\mathbf{cos}\,\theta
\end{aligned} \tag{1}$$

The fin stabilizer coefficients are integrated in the ship motion. The added mass, damping and stiff coefficients were integrated in the model equation as well as the resistance and propeller thrust. Superscript of *w*, *f*, *p* indicate wave, fin and propeller respectively. The model equation derived and expressed in as follows;

$$\begin{aligned}
&(a_{11}+m)\ddot{x}_1+\left\{[3r_3c^2+2(r_2-\tau_2)c+r_1]-\tau_1 n\right\}\dot{x}_1\cdots \\
&+\left[3r_3c+(r_2-\tau_2)\right]\dot{x}_1^{\,2}+r_3\dot{x}_1^{\,3}=(\tau_2c^2+\tau_1cn+\tau_0n^2)\cdots \\
&-(r_1c+r_2c^2+r_3c^3)-f\sin(kx_1)-mg\sin x_5+F_1^f
\end{aligned} \tag{2.a}$$

$$\begin{aligned}
&(a_{33}+m+a_{33}^f+m_f)\ddot{x}_3+(b_{33}+b_f)\dot{x}_3+c_{33}x_3\cdots \\
&+(a_{35}-l(m_f+a_{33}^f)\ddot{x}_5+(b_{35}-b_f)\dot{x}_5+(c_{35}+c_{35}^f)x_5\cdots \\
&=F_3^w+F_3^f+mg\cos x_5
\end{aligned} \tag{2.b}$$

$$\begin{aligned}
&(a_{53}-l(m_f+a_{33}^f)\ddot{x}_3+(b_{53}-b_f)\dot{x}_3+c_{53}x_3+(a_{55}+I_{55}\cdots \\
&+l^2(m_f+a_{33}^f))\ddot{x}_5+(b_{55}+b_f)\dot{x}_5+(c_{55}-c_{55}^f)x_5\cdots \\
&\quad=F_5^w+F_5^f-x_{S(G)}mg\cos x_5
\end{aligned} \tag{2.c}$$

$$\begin{aligned}
&R(u)=r_1u+r_2u^2+r_3u^3 \\
&T(u,n)=(1-t_p)\rho n^2D_P^4K_T(u;n)
\end{aligned} \tag{3}$$

$$\begin{aligned}
&K_T(u;n)=K_0+K_1J(u;n)+K_2J^2(u;n) \\
&J(u;n)=\frac{u(1-w_P)}{nD_P} \\
&T(u;n)=\tau_0n^2+\tau_1un+\tau_2u^2
\end{aligned} \tag{4}$$

$$\begin{aligned}
&\tau_0=\kappa_0(1-t_P)\rho D_P^4 \qquad \tau_1=\kappa_1(1-t_P)(1-w_P)\rho D_P^3 \\
&\tau_2=\kappa_2(1-t_P)(1-w_P)^2\rho D_P^2
\end{aligned} \tag{5}$$

The resistance equation obtained from experimental data while the trust propeller equation obtained from the empirical data. Both equations derived in polynomial equation with ship's speed *u* as variable. The propeller design isa Wageningen B-series propeller

[28]. Parameters of thrust calculation were water velocity to propeller's discus, number of revolution n, diameter D_P, and advanced coefficients J [26]. The surge speed x_1, is the relative of ship velocity u and the wave celerity c written as $x_1=u-c$. Furthermore, the water velocity at propeller obtained by integrating the water perturbation as follows [27].

$$u \approx u_0 + u_{(P)}$$

$$u \approx u_0 + \frac{1}{D_P}\int_{D_P} k\zeta_a V_w e^{-kz} \cos k(x - V_w t)dz$$

The model in Equation (2) can be simplified in state space form as shown below;

$$\begin{aligned}
&\boldsymbol{M}(t)\,\dot{\boldsymbol{x}}(t) = \boldsymbol{A}(t)\,\boldsymbol{x}(t) + \boldsymbol{B}(t)\,\boldsymbol{u}(t)\\
&\dot{\boldsymbol{x}}(t) = \boldsymbol{M}^{-1}(t)\boldsymbol{A}(t)\,\boldsymbol{x}(t) + \boldsymbol{M}^{-1}(t)\,\boldsymbol{B}(t)\,\boldsymbol{u}(t)\\
&\dot{\boldsymbol{x}}(t) = \boldsymbol{A}_t(t)\,\boldsymbol{x}(t) + \boldsymbol{B}_t(t)\,\boldsymbol{u}(t)\\
&\boldsymbol{y}(t) = \boldsymbol{C}(t)\,\boldsymbol{x}(t)
\end{aligned} \tag{6}$$

$\boldsymbol{M}$ is the added mass matrix, $\boldsymbol{A}$ is a variable state matrix consists of damping and stiff coefficients, $\boldsymbol{B}$ is a matrix of input coefficients, u is a vector of input system consists of external force and moment, x is a vector of state variable, and y is vector of output variable. Solution of the state space form (6) can be obtained as follows;

$$\boldsymbol{x}(t) = e^{A_t(t-t_0)}\,\boldsymbol{x}(t_0) + \int_{t_0}^{t} \boldsymbol{e}^{A_t(t-\tau)}\boldsymbol{B}_t(t)\,\boldsymbol{u}(\tau)d\tau \tag{7}$$

The equation above is solved using a discrete integration as follows;

$$\begin{aligned}
\boldsymbol{x}[(k+1)T] = \boldsymbol{\varphi}[(k+1)T, kT]\boldsymbol{x}(kT)\cdots\\
+\int_{kT}^{(k+1)T} \boldsymbol{\varphi}[(k+1)T, \tau]\boldsymbol{B}_t(\tau)\,\boldsymbol{u}(\tau)\,d\tau
\end{aligned} \tag{8}$$

The integration equation simply calculated using a simple discrete integral as follow [29];

$$\begin{aligned}
&\phi[(k+1)T, kT] = e^{\int_{kT}^{(kT+1)T} A(\beta)d\beta}\\
&\mathrm{x}[(k+1)T] = \varphi[(k+1)T, kT]\,\mathrm{x}(kT) + \frac{T}{2}\mathrm{B}_t[(k+1)T]\,\mathrm{u}[(k+1)T]\cdots\\
&\qquad + \frac{T}{2}\varphi[(k+1)T, kT]\,\mathrm{B}_t(kT)\,\mathrm{u}[(k+1)T]
\end{aligned} \tag{9}$$

2.2 Fin Stabilizer Model

The mathematical model of a servo control of fin stabilizer is based on first order equation in Laplace function [30, 31]. The model of the steering rudder machine with settling time τ_r, desired fin angle δ_d, and fin angle δ written as follows;

$$\frac{\delta(s)}{\delta_d(s)} = \frac{1}{1+\tau_r s} \tag{10}$$

$$\delta(t) = \int_0^{\infty} e^{-\tau_r t} e^{-st}\delta_d(t)dt \tag{11}$$

The settling time calculated from the fin servo system. The time captured from the simple test of the system as shown in the Figure 1.

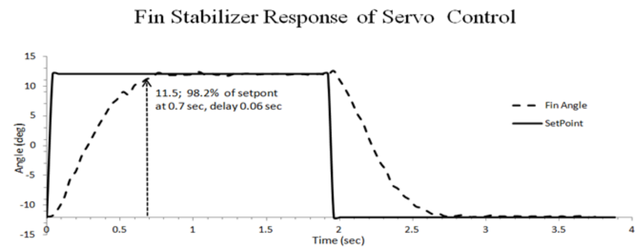


Figure 1 Response of a fin servo system applied for the Semi-SWATH under test with input step 22 deg from 0s to 1.9s

2.3 Fin Force and Moment

The force and moment of fin stabilizer calculation using the wing model equation, influenced by the angle of attack and the losses of effective lift of fin (E). The losses of lift of fin consist of; losses by the submergence of fin, interaction of fore and aft fin and hull boundary layer. The losses of lift coefficient is obtained using empirical data of a fin combination that found in research of Lloyd [25, 33].

$$E = \frac{\textit{Efective lift of fin}}{\textit{Nominal lift of fin}}$$

The lift force and moment of fins along the projected fin area A were obtained as follows;

$$\begin{aligned}
&F_L = \tfrac{1}{2}\rho V_S^{\,2}\,A\,E\,C_L(\alpha)\\
&F_D = \tfrac{1}{2}\rho V_S^{\,2}\,A\,E\,C_D(\alpha)\\
&M = F_L\, l_f
\end{aligned} \tag{12}$$

$$\alpha = x_5 + \delta + \frac{-\dot{x}_3 - \dot{x}_5\, l_f + \upsilon}{V_s} \tag{13}$$

$$\upsilon = \zeta_a V_w k e^{-kz} \sin k(x - V_w t) \tag{14}$$

Fin angle α_f to a normal axis of motion obtained by pitch angle θ, fin angle δ, and attack angle α by incoming flow to axis of fin. The ship speed $V_s = u$ and the vertical water velocity υ. Parameters of fin stabilizer angle and its position installed were shown in Figure 2 and the fin position was shown in Figure 3.

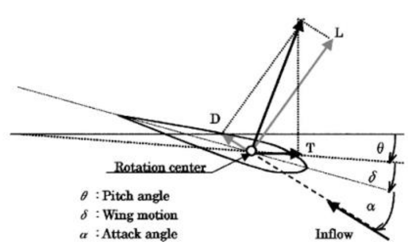


Figure 2 Angle of attack of fin stabilizer

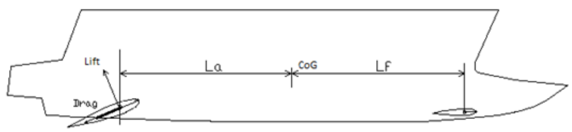


Figure 3 Longitudinal position of fin stabilizer

The fin stabilizer has a symmetrically streamlined section. At a small angle of attack, the lift coefficient increases linearly to the incidence angle. The lift curve slope of rectangular plan forms as a function of an aspect ratio written as follows [33].

$$\frac{dC_L}{d\alpha} = \frac{1.8\,\pi\, a_F}{1.8 + \sqrt{a_F^2 + 4}} \qquad rad^{-1} \tag{15}$$

Lift and drag coefficients C_L and C_D were calculated as follows;

$$C_L(\alpha) = \frac{dC_L}{d\alpha}\ \alpha\ C_D(\alpha) = C_{D0} + \frac{C_L^2(\alpha)}{0.9\,\pi\, a} \tag{16}$$

C_{D0} is the minimum section drag. In this research the minimum section drag coefficient is C_{D0}=0.0065 [34].

3.0 CONTROL SYSTEM

Control system consists of controller, actuator, and sensors. Fuzzy logic controller is one of nonlinear controller that mimics the human knowledge. The controller was applied in stabilizing the seakeeping of the ship. Controller calculates the variable control based on the ship state of pitch angle measured by a sensor, then fed a control command to the fin stabilizer or actuator. The system consists of an inner loop and outer loop controller. The inner loop controller regulates the angle of the fins stabilizer using a servo system with Proportional-Derivative (PD) controller and the signal come from outer loop controller. The outer loop controller calculates the control signal proportionally to pitch angle using fuzzy logic controller. Its concept is based on interpretation of human skill in regulating the ship motions like controlling the inverted pendulum being at its stable position. The controller developed using Fuzzy-Mamdani method [23]. The control system concept was shown in the following Figure 4.

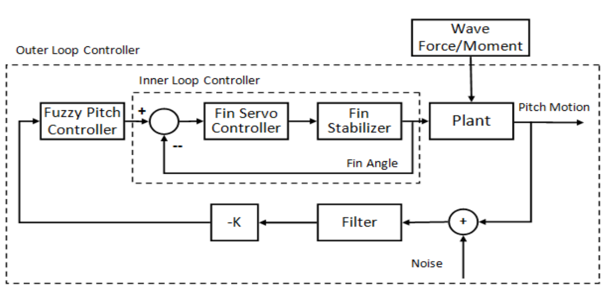


Figure 4 Control system

3.1 Fuzzy Logic

The structure of a fuzzy logic controller consists of input stage of fuzzification, processing stage with interference rules, and output stage as defuzzification as shown in Figure 5**Error! Reference source not found.**. The input stage maps the input variables from sensors to the relevant membership functions, afterwards the fuzzy set value mapped into the rules that translate the appropriate knowledge to regulate the motion of the ship in the stage of inference rule processing and then combines the results of the rules. Finally, the output stage converts the combined result back into a specific control output value as shown in Figure 5.

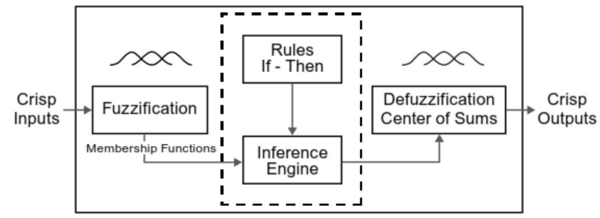


Figure 5 Fuzzy logic control system

3.2 Fuzzification Process

The fuzzification is a conversion process of the crisp input value to a linguistic value in the class of intervals using membership function (antecedent).

The crisp value inputs were error and derivative of the error. Error is defined as a difference between the set point value and the current value. The inputs classified in certain membership functions.

3.3 Inference Process

Inference process is linguistic translating from fuzzification to defuzzification process using rules of antecedent-consequence. The process uses Mamdani method with min-max interference. Minimum inference defined as an intersection of inference inputs (fuzzification) and maximum inference defined as union of inference results (defuzzification). The rules were arranged as like as controlling an inverted pendulum in which the concept has been applied in control of a ship in maneuver and roll motion [23, 35, and 36].

The rule has arrangement in the form “IF-THEN” statements where “IF” part is called “antecedent” and “THEN” part is called “consequent". The fuzzy inputs and output were classified in interval membership function with linguistic labels as; NB (negative big), NM (negative medium), NS (negative small), NVS (negative very small), ZR (zero), PVS (positive very small), PS (positive small), PM (positive medium), PB (positive big). The input was error pitch angle and error rate of pitch angle, and the output space *U* represents the desired controlled fin angle. All input and output at x-axis value were normalized in the range -1 to +1, while the y-axis from 0 to +1 as it indicates probability value of membership function. The input and output were arranged using triangle membership function as shown in Figure 6:

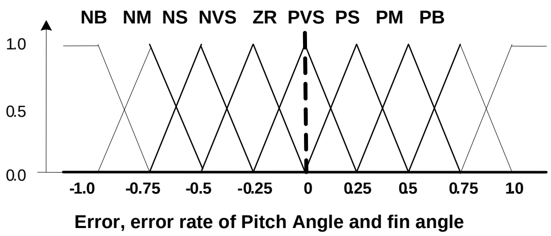


Figure 6 Membership function of input and output

Table 1 Rule arrangement

		Error (pitch angle)								
		NB	***NM***	***NS***	***NVS***	***ZR***	***PVS***	***PS***	***PM***	***PB***
Error Rate (Pitch rate)	***NB***	*NB*	*NB*	*NB*	*NM*	*NM*	*NS*	*NS*	*NVS*	*ZR*
	NM	*NB*	*NB*	*NM*	*NM*	*NS*	*NS*	*NVS*	*ZR*	*PVS*
	NS	*NB*	*NM*	*NM*	*NS*	*NS*	*NVS*	*ZR*	*PVS*	*PS*
	NVS	*NM*	*NM*	*NS*	*NS*	*NVS*	*ZR*	*PVS*	*PS*	*PS*
	ZR	*NM*	*NS*	*NS*	*NVS*	*ZR*	*PVS*	*PS*	*PS*	*PM*
	PVS	*NS*	*NS*	*NVS*	*ZR*	*PVS*	*PS*	*PS*	*PM*	*PM*
	PS	*NS*	*NVS*	*ZR*	*PVS*	*PS*	*PS*	*PM*	*PM*	*PB*
	PM	*NVS*	*ZR*	*PVS*	*PS*	*PS*	*PM*	*PM*	*PB*	*PB*
	PB	*ZR*	*PVS*	*PS*	*PS*	*PM*	*PM*	*PB*	*PB*	*PB*

The rules arranged in the Table 1 as relation of two inputs; *error* and *error rate* to output (consequence). The contour of relation input-output was displayed in the Figure 7. The contour showed nonlinear changes of input-output relation. The fin angle being at maximum when the ship's pitch angle is far from the set point and the rate change is in opposite direction to the set point or the rate change is too slow. The fin will affect the ship to have fast response to the set point. The fin angle being at minimum when the ship pitch angle is far from the set point but has high rate change to the set point direction or the fin angle is near the set point with almost zero rate angles. The contour between the maximum and minimum fin angle command showed that controller will take a restraining action when the pitch angle near the set point with rate change in pitch angle is still high.

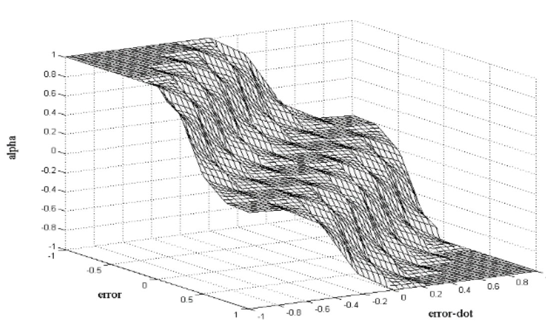


Figure 7 Contour relation of input and output of fuzzy logic control

3.4 Defuzzification Process

Defuzzification is a process of conversion of the linguistic value to the crisp value using center of area of the output membership function. The output value of the membership function is a degree of value of the output (consequent) where the value is in between -1 and +1. The value was a normalized fin angle for -20 to +20 degree.

4.0 SIMULATION AND RESULTS

The time-domain simulation program was developed using Matlab-Simulink, it has advantages by combining text programming and graphical programming. The numerical program applied was a strip theory method, which has a fast calculation and has a good result. The results have been validated with experimental results [37]. The ship and fin stabilizer particulars used for the simulation as shown in Table 2.

Table 2 Model particulars

Particulars	
Length	2.311 m
Breadth	0.8 m
Draft	0.2 m
Deck high	0.36 m
Hull distance	0.64 m
Fin Type	NACA 0015
Fore fins	0.146Ls (from FP),0.28T (from BL)
Aft fins	0.816Ls (from FP),0.32T (from BL)

Simulation parameters for analyzing the ship seakeeping were ratios of ship length to wave length, wave height to wave length, and ship's speed to wave celerity. They were 1.35, 0.07, and 1.27 respectively, one of the extreme condition when the ship running in following sea, according to the previous research [38]. The simulation showed the ship seakeeping performance using fixed and active fin stabilizer and showed the effectiveness of the fin stabilizer in reducing the motions of surge, heave and pitch. To analyzed the fin performance, the ship's weight that influences the surge motion was ignored. The heave and pitch motion were simulated where the ship's encounter wave frequency and the hydrodynamic coefficients were constant. While simulation with ship's weight effect may cause the ship being in surfing condition or entrapped in wave. This condition requires the ship modeled in a time-varying simulation model. The hydrodynamic coefficients were changing each time because the ship in acceleration or deceleration. This simulation was developed for both conditions.

Analysis of the ship response by comparing the maximum amplitude motions of the ship for fin modes; using all fixed fins (C1), using active fin at stern, and passive fin at bow (C2), and using active fin at stern, and at bow (C3). The results of calculation were shown in Table 3 and Table 4 in a unit of percentage. C21 is a comparison of C2 and C1, C31 is a comparison of C3 and C1, and C32 is a comparison of C3 and C2.

In Figure 8 showed the ship running in a constant speed, and the velocity and acceleration of the surge motion is zero. In heave motion, there is a small difference phase between the ship with passive and with active fin stabilizer. It showed the effect of the active fin stabilizer is more responsive than with passive fin. The amplitudes of heave motion for both passive and active fins were almost having equal amplitude (1.8% and 6.06% difference), whilst the rate of heave motion for active fin was lower than for passive fin, as well as for heave acceleration. The damping of the heave increases up to 42.52% for the ship with active aft fin and 40.52% for the ship with both active aft fin and fore fin.

Significant changes were shown in the pitching motion where the amplitude was reduced by 53.8% for the ship with active fin at aft and 69.98% for the ship with both active aft fin and fore. The fin can reduce the amplitude of pitch rate about 60.6% for active aft fin and 71.76% for both active aft and fore fin stabilizer, while acceleration reductions were 66.67% and 71.04% respectively.

Table 3 Reduction of motion amplitude without surging effect

	Heave (%)			Pitch (%)		
Comparison	**C21**	**C31**	**C32**	**C21**	**C31**	**C32**
Movement	1.87	6.06	4.59	53.80	69.98	35.02
Velocity	42.52	40.20	4.03	60.61	71.76	28.31
Acceleration	42.89	49.25	11.13	66.67	71.04	13.12

Table 4 Reduction of motion amplitude with surging effect

	Surge (%)			Heave (%)			Pitch (%)		
Comparison	**C21**	**C31**	**C32**	**C21**	**C31**	**C32**	**C21**	**C31**	**C32**
Movement	31.12	54.99	34.54	29.89	30.56	0.95	60.35	74.51	35.73
Velocity	74.67	77.39	10.71	67.41	71.83	13.55	78.03	84.91	30.46
Acceleration	61.43	71.67	22.52	73.55	76.03	9.37	82.37	85.73	19.08

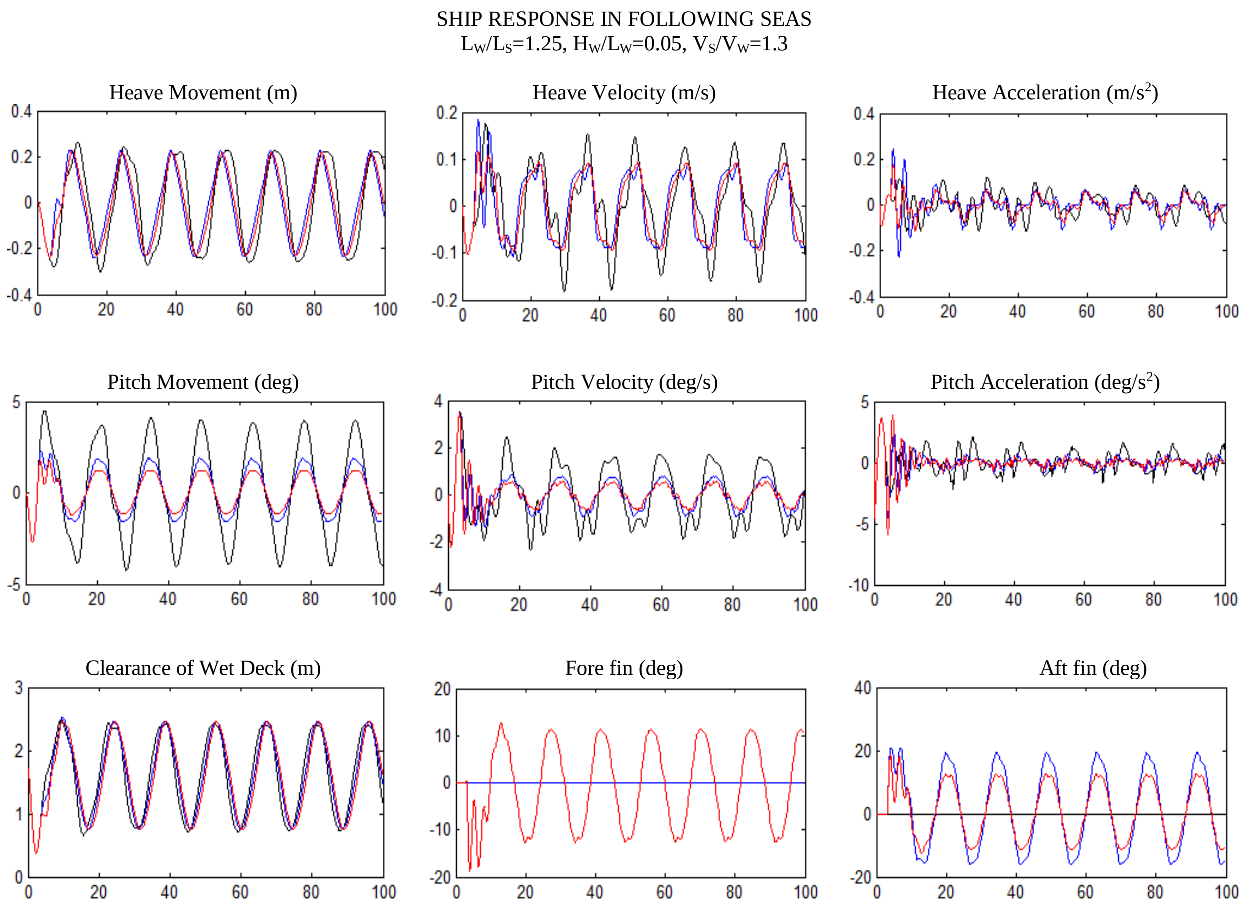


Figure 8 Ship seakeeping in following seas with all fixed fin stabilizer (black), with fixed fin stabilizer at fore and active fin stabilizer at aft (blue), all active fin stabilizer (red). The ship simulated without surge motion effect in 100 seconds

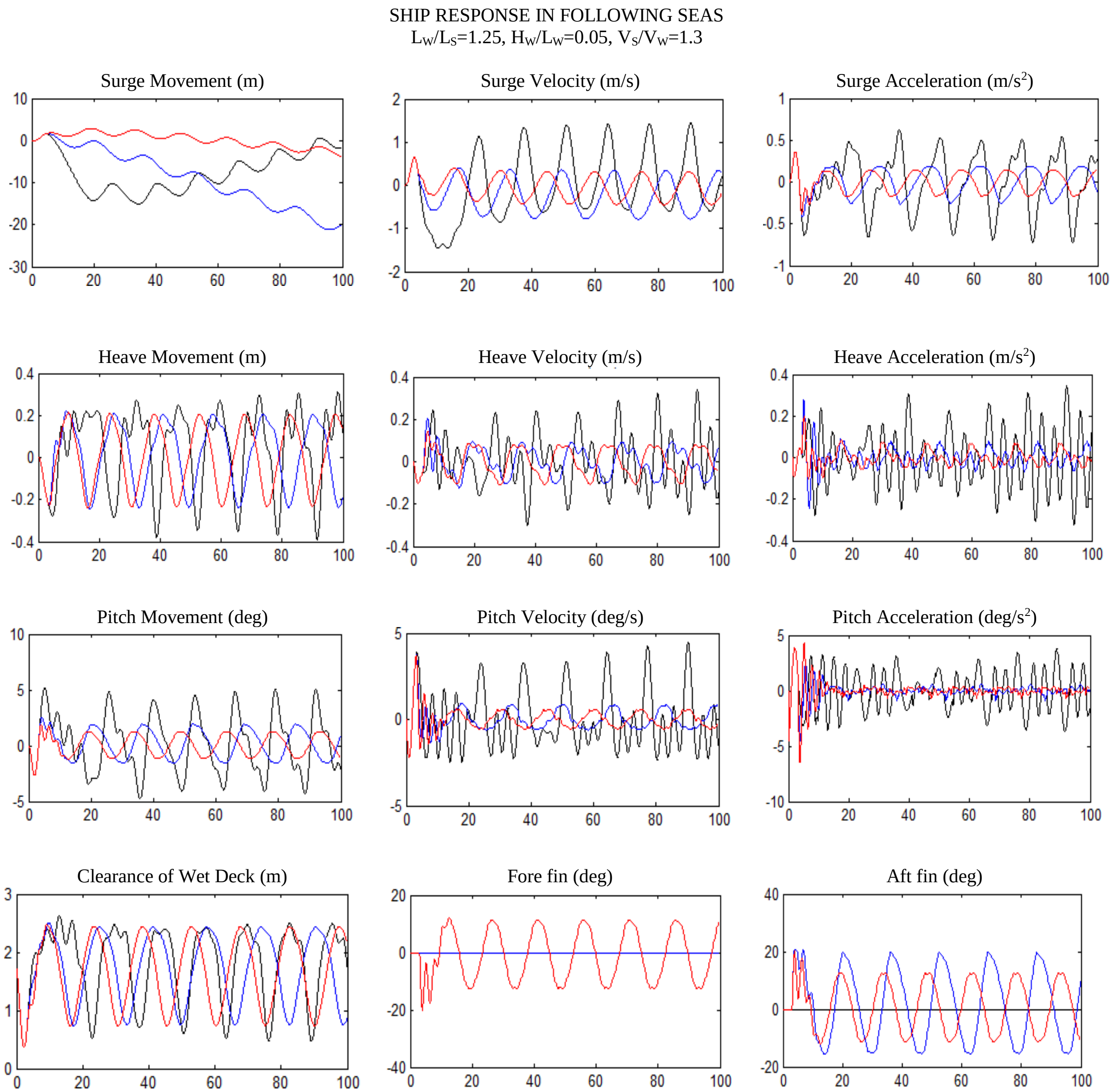


Figure 9 Ship seakeeping in following seas with all fixed fin stabilizer (black), with fixed fin stabilizer at fore and active fin stabilizer at aft (blue), all active fin stabilizer (red). The ship simulated with surge motion effect in 100 seconds

Simulation with considering the ship's weight effect on longitudinal motion showed the ship having acceleration and deceleration. The velocity of the surge motion showed an oscillating response, exceeds up to 1.4m/s in surfing and reduced up to 0.5 m/s in climbing for the ship with passive fin stabilizer. At initial, the motion moves backward relative to the wave and then went forward with an oscillating response, whilst the ship with active fins showed the motion moves backward with an oscillating response along the simulations. The motion causes the ship's speed changes, particularly for the ship with active fins stabilizer was decreased significantly. The fin stabilizers restrain the ship surfing to the trough and reduced the pitch angle causes the ship's momentum also decreased. The velocity of the surging motion decreased about 74.67% up to 77.39% whilst the acceleration motion decreased about 61.43% up to 71.67%. Furtherm ore, the ship with all active fins compared to the ship with active aft fin can reduce the surging motion, speed, and acceleration about 34.54%, 10.71%, and 22.51% respectively.

In heave motion, the performance of active fins stabilizer showed amplitude of the heave motion decreased about 29.9% up to 30.5%, the speed of heave about 67.4% up to 71.83%, and acceleration about 76.03% up to 73.55%. Furthermore, the ship with all active fins compared with active aft fins showed amplitude of heave, rate, and acceleration were about 0.95%, 13.55%, and 9.37% respectively..

The significant motion reduction was found in pitch motion where reduction of pitch angle about 60.35% up to 74.51%, rate of pitch angle about 78.03% up to 84.91% and acceleration about

82.37% up to 85.73%. Furthermore, comparing the ship with all active fins and active aft fin showed the pitch angle, rate of angle and acceleration were about 35.73%, 30.46%, and 19.08% respectively.

The effect of the ship surfing the wave's trough can lead to a bow diving. However, in Figure 8 and Figure 9, the wet foredeck were still above the wave surface between 0.8m to 2.5m with the clearance has been almost equal to the three combinations of the fin stabilizer. The fin performance restrains the ship from the bow-dive conditions. The fin angle moves proportional to the pitch angle.

■5.0 DISCUSSION

Simulations of the ship using the active fin stabilizer showed the fin stabilizer performance can decrease the dynamic motion. The decreased rate amplitude of the motions showed a good improvement for the ship seakeeping. Amplitude of ship motion for pitch angle has also significant improvement for all fin modes using active fins.

The fin stabilizer was analyzed by ignoring the effect of surging motion. The ship response showed a linear response. The performance of the control system can overcome the nonlinear ship response without a wind up effect, decrease the motion amplitude, and increase damping effect. The amplitude of heave motion showed a not significant improvement due to the control system uses only pitch angle as the control variable. Furthermore, the vertical fin force has less force compared to the wave force. It cannot be applied to reduce the amplitude of heave displacement but useful to reduce the dynamic of vertical motion. The damping force increases significantly to reduce the vertical rate motion and acceleration. However, the ship performance in heave motion was under the coupling effect to the pitch motion, although the heave was not proportional to reduction of the pitch angle. The ship motion performance of pitch angle has a significant improvement where the controller maintains a low angle of pitch motion using the fin stabilizer.

The performance of the fin stabilizer, in effect, of ship's weight momentum was shown when the ship running down the slope of wave. The ship has acceleration and deceleration. It is different to the ship model without surging effect, where surging motion causes the ship having the change of speed or change of wave encounter. This cause the ship has a nonlinear response. The ship has oscillatory response, particularly when the ship with the fixed fin stabilizer was on the wave's crest. The dynamic motion of the ship was increased. Furthermore, the ship with active fin stabilizer showed the ship motion damped significantly. The fin stabilizer changed the angle of attack that can increase the lift force as well increase the damping force of dynamic vertical motion and the angle of the fin changed proportionally to the pitch angle.

■6.0 CONCLUSION AND SUGGESTION

According to the simulation, the fin stabilizer with active fins using the fuzzy logic controller has significant improvement in seakeeping performance. The improvement can prevent the ship from loss of control of nonlinear of vertical response during surf to the trough. The amplitudes of the ship motion compared to the fixed fin stabilizer motion were decreased significantly. The developed control system can decrease the amplitude of pitch angle even in nonlinear ship response without windup effect. The fin stabilizer increases the damping that restrains high dynamic vertical motion. However, the ship with active fin stabilizer showed the performance in heave motion displacement almost has the same amplitude compared to the fixed fin.

Ship performance simulation without surging response showed the ship motion has a linear response which is used to investigate the fin stabilizer effect of vertical motion. In simulation with surging motion effect showed the ship has a nonlinear response. The ship's speed changes during in waves by the effect of ship's weight act in the wave slop. The changes were caused by the ship's weight force to surf from the wave's crest to the trough. The ship's acceleration can be reduced then decrease the effect of surfing.

Nonlinear ship's response in following seas, particularly running in extreme conditions happens to all motions. For longwise motion, the ship has a coupled effect to transverse motion. This motion has a nonlinear response. For the comprehensive and detail analysis, the simulation will be extended including the transverse motion.

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