Research Article

Adaptive Fuzzy Output-Feedback Method Applied to Fin Control for Time-Delay Ship Roll Stabilization

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The ship roll stabilization by fin control system is considered in this paper. Assuming that angular velocity in roll cannot be measured, an adaptive fuzzy output-feedback control is investigated. The fuzzy logic system is used to approximate the uncertain term of the controlled system, and a fuzzy state observer is designed to estimate the unmeasured states. By utilizing the fuzzy state observer and combining the adaptive backstepping technique with adaptive fuzzy control design, an observer-based adaptive fuzzy output-feedback control approach is developed. It is proved that the proposed control approach can guarantee that all the signals in the closed-loop system are semiglobally uniformly ultimately bounded (SGUUB), and the control strategy is effective to decrease the roll motion. Simulation results are included to illustrate the effectiveness of the proposed approach.

1. Introduction

Stabilization of ship roll motion induced by wave disturbances has received considerable attention. This is because excessive roll motion would make the crew feel uncomfortable and may also cause damage to the cargoes and equipment on board. Various types of antirolling devices are introduced to reduce undesirable wave-induced roll motion [1]. Stabilizing fins are the most effective and popular antirolling devices in use. Stabilizing fins have been used extensively for high speed vessels, particularly on war ships and cruise ships. Lift forces are generated by the fins and a couple is produced to counteract the wave-induced roll moment. Since the lift force depends on the relative inflow speed, the stabilizing fins are effective only when the ships are sailing at relatively high speed. Some methods have been introduced. A multivariable control approach to the design of antirolling fins for a war ship has been proposed, where the rudder and the fins are considered simultaneously to reduce the wave-induced roll motion without sacrificing the yaw control performance [2]. Fuzzy control method basing on empirical if-then rules has also been introduced to the design of the fin stabilization system [3]. Application of the adaptive LQ method to

the stabilization for a monohull ship is reported in [4], and an H_∞ control design method has been employed in the design of a robust stabilizing fin controller [5]. A novel ship stabilizing fin controller based on the internal model control (IMC) method was proposed in [6].

Adaptive backstepping technique is an important control method in the last twenty years. The backstepping design provides a systematic framework for the design of tracking and regulation strategies, suitable for a large class of nonlinear systems [7–11]. Some fin control methods based on backstepping technique have been proposed [12, 13]. A nonlinear robust controller was designed by using backstepping and closed-loop gain shaping algorithms to improve the robustness of fin stabilizer controller. A novel sliding backstepping controller was designed to decrease the roll motion of fin stabilizer control system for the system with nonlinear disturbance observer. However, the control methods in [12, 13] are all based on the assumption that angular velocity in roll is measured. As what authors stated in [14–16], in practice, the state variables are often unmeasured for many nonlinear systems. Therefore, the existing approaches in [12, 13] cannot be implemented for the fin control system, in which the angular velocity is not measured.

Motivated by the above observation, this paper investigates the adaptive fuzzy output-feedback control problem of the time-delay ship roll stabilization. The fuzzy logic system can be used to approximate the unmodeled plant [17–19]. In this paper, assuming that angular velocity in roll cannot be measured, an adaptive fuzzy output-feedback control design problem is investigated, and a fuzzy state observer is designed to estimate the unmeasured states. By utilizing the fuzzy state observer and combining the adaptive backstepping technique with adaptive fuzzy control design, an observer-based adaptive fuzzy output-feedback control approach is developed. It is proved that the proposed control approach can guarantee that all the signals in the closed-loop system are SGUUB.

The main contribution of this paper is the innovation and application value of the proposed controller for the ship roll motion. Compared with other control strategies, the unmeasured angular velocity is considered during the design process of the controller, and the control strategy is effective to decrease the roll motion.

2. Nonlinear Model Descriptions of Fin Control System

In this paper, we consider the following nonlinear systems [12, 13]:

$$\begin{aligned}
 (I_{xx} + J_{xx}) \ddot{\varphi} + \delta_N \dot{\varphi} + \delta_W \dot{\varphi} |\dot{\varphi}| + Dh\varphi \left[1 - \left(\frac{\varphi}{\varphi_v} \right)^2 \right] \\
 = M_C + M_W, \\
 I_{xx} + J_{xx} = \frac{DB^2}{g} \left(0.3085 + \frac{0.0227B}{d} - \frac{0.00043L}{100} \right)^2, \\
 \delta_N = \frac{2n_1 \sqrt{Dh(I_{xx} + J_{xx})}}{\pi}, \\
 \delta_W = \frac{3n_2 (I_{xx} + J_{xx})}{4}, \\
 M_C = -\rho v^2 A_f l_f C_L^a \left(a_f + \dot{h} + \frac{\dot{\varphi} l_f}{v} \right), \\
 M_W = -Dh a_e,
 \end{aligned} \tag{1}$$

where φ is rolling angle of ship; I_{xx} and J_{xx} are inertias moments and the added inertia moments of the own ship; δ_N and δ_W are damping factors; D is the tonnage of ship; h is initial metacentric height; φ_v is flooding angle; M_C is control moment of the fin stabilizer; M_W is the moment of sea wave act on ship; g is gravitational acceleration; B is width of ship; L is length between tow-column of ship; d is draught; n_1 and n_2 are test coefficients; ρ is fluid density; v is ship's speed; A_f is the area of fin; l_f is the acting force arm of the stabilizer fin; C_L^a is the slope of lift coefficient; a_f is the rotation angle of the stabilizer fin; a_e is significant wave angle. $\dot{h} = \varphi(t - \tau(t))$ is a time-delay term, and $\tau(t)$ is an unknown bounded time delay

satisfying $|\tau(t)| \leq \bar{\tau}$ and $\dot{\tau}(t) \leq \tau^* \leq 1$, where $\bar{\tau}$ and τ^* are known constants.

From (1), we have

$$\ddot{\varphi} = a_1 \varphi + a_2 \varphi^3 + a_3 \dot{\varphi} + a_4 \dot{\varphi} |\dot{\varphi}| + b a_f + b \dot{h} + c a_e, \tag{2}$$

where $a_1 = -Dh/(I_{xx} + J_{xx})$, $a_2 = Dh/\varphi_v^2(I_{xx} + J_{xx})$, $a_3 = -\delta_N/(I_{xx} + J_{xx}) - \rho v^2 A_f l_f^2 C_L^a/(I_{xx} + J_{xx})v$, $a_4 = -\delta_W/(I_{xx} + J_{xx})$, $b = -\rho v^2 A_f l_f C_L^a/(I_{xx} + J_{xx})$ and $c = -Dh/(I_{xx} + J_{xx})$.

Define $x = [x_1, x_2]^T = [\varphi, \dot{\varphi}]^T$, $y = \varphi = x_1$, and $u = a_f$; (2) can be rewritten as

$$\begin{aligned}
 \dot{x}_1 &= x_2, \\
 \dot{x}_2 &= bu + f(x_1, x_2) + b\dot{h} + \Delta, \\
 y &= x_1,
 \end{aligned} \tag{3}$$

where $f(x_1, x_2) = a_1 x_1 + a_2 x_1^3 + a_3 x_2 + a_4 x_2 |x_2|$ and $\Delta = c a_e$.

3. Fuzzy Logic Systems

We introduce the fuzzy logic systems. A fuzzy logic system (FLS) consists of four parts: the knowledge base, the fuzzifier, the fuzzy inference engine working on fuzzy rules, and the defuzzifier. The knowledge base for FLS comprises a collection of fuzzy if-then rules of the following form:

$$R^l: \text{ If } x_1 \text{ is } F_1^l \text{ and } x_2 \text{ is } F_2^l \text{ and } \dots \text{ and } x_n \text{ is } F_n^l, \tag{4}$$

Then y is G^l , $l = 1, 2, \dots, N$,

where $x = [x_1, \dots, x_n]^T$ and y are the fuzzy logic system input and output, respectively. Fuzzy sets F_i^l and G^l are associated with the fuzzy functions $\mu_{F_i^l}(x_i)$ and $\mu_{G^l}(y)$, respectively. N is the rules number.

Through singleton function, center average defuzzification, and product inference [20], the fuzzy logic system can be expressed as

$$y(x) = \frac{\sum_{l=1}^N \bar{y}_l \prod_{i=1}^n \mu_{F_i^l}(x_i)}{\sum_{l=1}^N \left[\prod_{i=1}^n \mu_{F_i^l}(x_i) \right]}, \tag{5}$$

where $\bar{y}_l = \max_{y \in R} \mu_{G^l}(y)$.

Define the fuzzy basis functions as

$$\bar{\phi}_l = \frac{\prod_{i=1}^n \mu_{F_i^l}(x_i)}{\sum_{l=1}^N \left(\prod_{i=1}^n \mu_{F_i^l}(x_i) \right)}. \tag{6}$$

Denote $\theta = [\bar{y}_1, \bar{y}_2, \dots, \bar{y}_N]^T = [\theta_1, \theta_2, \dots, \theta_N]^T$ and $\phi^T(x) = [\bar{\phi}_1(x), \dots, \bar{\phi}_N(x)]$; then, fuzzy logic system (5) can be rewritten as

$$y(x) = \theta^T \phi(x). \tag{7}$$

Lemma 1 (see [20]). *Let $f(x)$ be a continuous function defined on a compact set Ω . Then, for any constant $\varepsilon > 0$, there exists an FLS (5) such as*

$$\sup_{x \in \Omega} |f(x) - \theta^T \phi(x)| \leq \varepsilon. \tag{8}$$

The optimal parameter vector θ_i^* is defined as

$$\theta^* := \arg \min_{\theta \in \mathbb{R}^l} \left\{ \sup_{x \in D} |f(x) - \theta^T \phi(x)| \right\}. \quad (9)$$

4. Fuzzy State Observer Design

The state $x_2 = \dot{\varphi}$ in system (3) is not available for feedback. Therefore, a state observer should be established to estimate the states

$$\begin{aligned} \dot{\hat{x}}_1 &= \hat{x}_2 + k_1 (y - \hat{x}_1), \\ \dot{\hat{x}}_2 &= k_2 (y - \hat{x}_1) + \hat{f}(x_1, \hat{x}_2) + bu, \\ \hat{y} &= \hat{x}_1, \end{aligned} \quad (10)$$

where $\hat{f}(x_1, \hat{x}_2) = \theta^T \phi(x_1, \hat{x}_2)$ is the fuzzy logic system and is used to approximate the nonlinear term $f(x_1, \hat{x}_2)$ in (11). System (10) can be rewritten as

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + Ky + E_2\hat{f} + E_2bu + E_2b\hat{h}, \\ \hat{y} &= E_1^T \hat{x}, \end{aligned} \quad (11)$$

where $\hat{x} = [\hat{x}_1, \hat{x}_2]^T$, $A = \begin{bmatrix} -k_1 & 1 \\ -k_2 & 0 \end{bmatrix}$, $K = [k_1, k_2]^T$, $E_1^T = [1 \ 0]$, and $E_2 = [0 \ 1]^T$.

The coefficients k_1 and k_2 are chosen such that the polynomial $p(s) = s^2 + k_1s + k_2$ is a Hurwitz. Thus, given a $Q^T = Q > 0$, there exists a positive definite matrix $P^T = P > 0$ such that

$$A^T P + PA = -Q. \quad (12)$$

Let $e = x - \hat{x}$ be observer error. Then, from (3) and (11), we have the observer errors equation

$$\dot{e} = Ae + E_2\Delta + E_2\tilde{f} + E_2b\hat{h}, \quad (13)$$

where $\tilde{f} = f(x_1, x_2) - \hat{f}(x_1, \hat{x}_2)$. Consider the following Lyapunov candidate V_0 for (13) as

$$V_0 = e^T P e. \quad (14)$$

The time derivative of V_0 along the solutions of (13) is

$$\dot{V}_0 = -e^T Q e + 2e^T P (E_2\Delta + E_2\tilde{f} + E_2b\hat{h}). \quad (15)$$

Since $f(x_1, x_2) = a_1x_1 + a_2x_1^3 + a_3x_2 + a_4x_2|x_2|$ satisfies lipschitz condition, we have

$$|f(x_1, x_2) - f(x_1, \hat{x}_2)| \leq L_f |x_2 - \hat{x}_2|, \quad (16)$$

where L_f is a constant. By using Young's inequality and $\phi^T(x_1, \hat{x}_2)\phi(x_1, \hat{x}_2) \leq 1$, we have

$$\begin{aligned} 2e^T P E_2 (\Delta + \tilde{f} + b\hat{h}) &\leq \bar{L} \|e\|^2 + \bar{D} + \|P\|^2 \bar{\theta}^T \bar{\theta} \\ &+ x_1^2 (t - \tau(t)), \end{aligned} \quad (17)$$

where $\bar{L} = 3 + 2\|P\|L_f + \|P\|^2$, $\bar{\theta} = \theta^* - \theta$, $\bar{D} = \|P\|^2 \Delta^2 + \|P\|^2 \varepsilon^{*2}$, and ε is the fuzzy minimum approximation error, which satisfies $|\varepsilon| \leq \varepsilon^*$, and ε^* is an unknown constant. Substituting (17) into (15) yields

$$\dot{V}_0 \leq -e^T Q e + \bar{L} \|e\|^2 + \bar{D} + \|P\|^2 \bar{\theta}^T \bar{\theta}. \quad (18)$$

5. Adaptive Fuzzy Backstepping Control Design and Stability Analysis

Define the following change of coordinates:

$$\begin{aligned} \chi_1 &= y, \\ \chi_2 &= \hat{x}_2 - \alpha_1, \end{aligned} \quad (19)$$

where α_1 is an intermediate control function which will be designed in the following.

Step 1. The time derivative of χ_1 is

$$\dot{\chi}_1 = x_2 = \hat{x}_2 + e_2 = \chi_2 + \alpha_1 + e_2. \quad (20)$$

Consider the following Lyapunov function candidate V_1 :

$$V_1 = V_0 + \chi_1^2. \quad (21)$$

The time derivative of V_1 is

$$\begin{aligned} \dot{V}_1 &\leq -e^T Q e + (\bar{L} + 1) \|e\|^2 + \bar{D} + \|P\|^2 \bar{\theta}^T \bar{\theta} + x_1^2 (t - \tau(t)) \\ &+ 2\chi_1 \left(\chi_2 + \alpha_1 + \frac{1}{2}\chi_1 \right). \end{aligned} \quad (22)$$

Choose the intermediate control function α_1 :

$$\alpha_1 = -\frac{1}{2}\chi_1 - c_1\chi_1 - \frac{e^{r\bar{\tau}}}{1 - \tau^*} \chi_1. \quad (23)$$

By substituting (23) into (22), we have

$$\begin{aligned} \dot{V}_1 &\leq -e^T Q e + (\bar{L} + 1) \|e\|^2 + \bar{D} + \|P\|^2 \bar{\theta}^T \bar{\theta} \\ &+ x_1^2 (t - \tau(t)) + 2\chi_1\chi_2 - 2c_1\chi_1^2 - \frac{e^{r\bar{\tau}}}{1 - \tau^*} \chi_1^2. \end{aligned} \quad (24)$$

Step 2. The time derivative of χ_2 is

$$\begin{aligned} \dot{\chi}_2 &= \hat{x}_2 - \dot{\alpha}_1 \\ &= bu + \theta^T \varphi(x_1, \hat{x}_2) + \bar{\theta}^T \varphi(x_1, \hat{x}_2) - \bar{\theta}^T \varphi(x_1, \hat{x}_2) \\ &+ k_2 (y - \hat{x}_1) - \frac{\partial \alpha_1}{\partial x_1} e_2 - \frac{\partial \alpha_1}{\partial x_1} \hat{x}_2. \end{aligned} \quad (25)$$

Consider the following Lyapunov-Krasovskii functional

$$V = V_1 + \chi_2^2 + \bar{V} + \frac{1}{2\gamma} \bar{\theta}^T \bar{\theta}, \quad (26)$$

where γ is a positive design constant and $\bar{V} = (e^{r(\bar{\tau}-t)})/(1 - \tau^*) \int_{t-\tau(t)}^t e^{rs} x_1^2(s) ds$ with r being a positive constant.

The time derivative of V is

$$\begin{aligned}\dot{V} = \dot{V}_1 + 2\chi_2 \left(bu + \theta^T \phi(x_1, \hat{x}_2) + k_2(y - \hat{x}_1) \right. \\ \left. + \tilde{\theta}^T \phi(x_1, \hat{x}_2) - \tilde{\theta}^T \phi(x_1, \hat{x}_2) \right. \\ \left. - \frac{\partial \alpha_1}{\partial x_1} e_2 - \frac{\partial \alpha_1}{\partial x_1} \hat{x}_2 \right) + \frac{1}{\gamma} \tilde{\theta}^T \dot{\tilde{\theta}} - r \bar{V} \\ + \frac{e^{r\bar{\tau}}}{1 - \tau^*} x_1^2 - x_1^2(t - \tau(t)).\end{aligned}\quad (27)$$

By using Young's inequality, we have

$$\begin{aligned}-2\chi_2 \frac{\partial \alpha_1}{\partial x_1} e_2 &\leq \left(\chi_2 \frac{\partial \alpha_1}{\partial x_1} \right)^2 + \|e\|^2, \\ -2\chi_2 \tilde{\theta}^T \phi(x_1, \hat{x}_2) &\leq \chi_2^2 + \tilde{\theta}^T \tilde{\theta}.\end{aligned}\quad (28)$$

Substituting (28) into (27) yields

$$\begin{aligned}\dot{V} \leq -e^T Q e + (\bar{L} + 2) \|e\|^2 - r \bar{V} + \bar{D} + (\|P\|^2 + 1) \tilde{\theta}^T \tilde{\theta} \\ - 2c_1 \chi_1^2 + 2\chi_2 \left(\chi_1 + \frac{1}{2} \chi_2 + bu + \theta^T \phi(x_1, \hat{x}_2) \right. \\ \left. + k_2(y - \hat{x}_1) + \frac{1}{2} \chi_2 \left(\frac{\partial \alpha_1}{\partial x_1} \right)^2 - \frac{\partial \alpha_1}{\partial x_1} \hat{x}_2 \right) \\ + \tilde{\theta}^T (2\chi_2 \phi(x_1, \hat{x}_2)) - \frac{1}{\gamma} \dot{\tilde{\theta}}.\end{aligned}\quad (29)$$

Choose control input u and the adaptive function θ as

$$\begin{aligned}u = \frac{1}{b} \left[-c_2 \chi_2 - \chi_1 - \frac{1}{2} \chi_2 - \theta^T \phi(x_1, \hat{x}_2) - k_2(y - \hat{x}_1) \right. \\ \left. - \frac{1}{2} \chi_2 \left(\frac{\partial \alpha_1}{\partial x_1} \right)^2 + \frac{\partial \alpha_1}{\partial x_1} \hat{x}_2 \right], \\ \dot{\theta} = \gamma [2\chi_2 \phi(x_1, \hat{x}_2) - \sigma \theta],\end{aligned}\quad (30)$$

where c_2 and σ are positive design constants. Substituting (30) into (29) yields

$$\begin{aligned}\dot{V} \leq -e^T Q e + (\bar{L} + 2) \|e\|^2 + \bar{D} - r \bar{V} - 2c_1 \chi_1^2 - 2c_2 \chi_2^2 \\ + \sigma \tilde{\theta}^T \tilde{\theta} + (\|P\|^2 + 1) \tilde{\theta}^T \tilde{\theta}.\end{aligned}\quad (31)$$

By using Young's inequality, the following inequality can be obtained:

$$\sigma \tilde{\theta}^T \tilde{\theta} = \sigma \tilde{\theta}^T (\theta^* - \tilde{\theta}) \leq -\frac{\sigma}{2} \tilde{\theta}^T \tilde{\theta} + \frac{\sigma}{2} \theta^{*T} \theta^*. \quad (32)$$

Therefore, we have

$$\begin{aligned}\dot{V} \leq -[\lambda_{\min}(Q) - \bar{L} - 2] \|e\|^2 + \bar{D} - 2c_1 \chi_1^2 - 2c_2 \chi_2^2 \\ - \left(\frac{\sigma}{2} - (\|P\|^2 + 1) \right) \tilde{\theta}^T \tilde{\theta} + \frac{\sigma}{2} \theta^{*T} \theta^*,\end{aligned}\quad (33)$$

where $\lambda_{\min}(Q)$ is the smallest eigenvalue of Q . Choose $\rho = \lambda_{\min}(Q) - \bar{L} - 2 > 0$ and $q = (\sigma/2) - (\|P\|^2 + 1) > 0$. Let $\beta = \min\{\rho/\lambda_{\max}(P), c_1/2, c_2/2, \gamma q, r\}$, $\bar{\pi} = \bar{D} + (\sigma/2) \theta^{*T} \theta^*$, and (33) can be expressed as

$$\dot{V} \leq -\beta V + \bar{\pi}. \quad (34)$$

Equation (34) can be rewritten as

$$V(t) \leq V(0) e^{-\beta t} + \frac{\bar{\pi}}{\beta}. \quad (35)$$

According to (35), it can be shown for the signals that x , e , χ_2 , θ_2 , $\bar{w}$, and u are SGUUB. $|y(t)| \leq \sqrt{V(0)} e^{-\beta t} + \sqrt{\pi/\beta}$ and $\|e(t)\| \leq (\sqrt{V(0)} e^{-\beta t} + \sqrt{\pi/\beta})/\sqrt{\lambda_{\max}(P)}$. It is worth noting that $t \rightarrow \infty$, $e^{-\beta t} \rightarrow 0$, $\lim_{t \rightarrow \infty} |y(t) - y_r(t)| = \sqrt{\pi/\beta}$, and $\lim_{t \rightarrow \infty} \|e(t)\| = \sqrt{\pi/\beta}/\sqrt{\lambda_{\max}(P)}$.

6. Simulation Study

The parameters of a certain war ship are as follows: the length between perpendiculars is 98 m, the width of ship is 10.2 m, draught is 3.1 m, tonnage is 1458 t, the area of fin is 5.22 m², the acting force arm of fin stabilizer is 3.46 m, the lift coefficient of fin stabilizer is 3.39, flooding angle is 43°, initial metacentric height is 1.15 m, designed speed is 18 kt, test coefficients are $n_1 = 0.031$ and $n_2 = 0.051$, and $\tau = 0.5(1 + \sin(t))$.

In the simulation studies, the if-then rules are chosen as

$$\begin{aligned}R^1: \quad &\text{If } x_1 \text{ is } F_1^1 \text{ and } \hat{x}_2 \text{ is } F_2^1, \text{ then } y \text{ is } G^1; \\ R^2: \quad &\text{If } x_1 \text{ is } F_1^2 \text{ and } \hat{x}_2 \text{ is } F_2^2, \text{ then } y \text{ is } G^2; \\ R^3: \quad &\text{If } x_1 \text{ is } F_1^3 \text{ and } \hat{x}_2 \text{ is } F_2^3, \text{ then } y \text{ is } G^3; \\ R^4: \quad &\text{If } x_1 \text{ is } F_1^4 \text{ and } \hat{x}_2 \text{ is } F_2^4, \text{ then } y \text{ is } G^4; \\ R^5: \quad &\text{If } x_1 \text{ is } F_1^5 \text{ and } \hat{x}_2 \text{ is } F_2^5, \text{ then } y \text{ is } G^5,\end{aligned}\quad (36)$$

where fuzzy sets are chosen as $F_1^1 = (\text{NL})$, $F_2^1 = (\text{NL})$, $F_1^2 = (\text{NS})$, $F_2^2 = (\text{NS})$, $F_1^3 = (\text{ZE})$, $F_2^3 = (\text{ZE})$, $F_1^4 = (\text{PS})$, $F_2^4 = (\text{PS})$, $F_1^5 = (\text{PL})$, $F_2^5 = (\text{PL})$, which are defined over the interval $[-2, 2]$ for variables x_1 and $\hat{x}_2$, respectively. NL, NS, ZO, PS, and PL denote negative large, negative small, zero, positive small, and positive large, respectively.

In this section, the fuzzy membership functions are determined by using the expertise and experimental result. Center points of these membership functions are selected as -2 , -1 , 0 , 1 , and 2 , respectively. The corresponding fuzzy membership functions are given by

$$\begin{aligned}\mu_{F_l^i}(x_1) &= \exp \left[-\frac{(x_1 - 3 + l)^2}{4} \right], \\ \mu_{F_l^i}(\hat{x}_2) &= \exp \left[-\frac{(\hat{x}_2 - 3 + l)^2}{4} \right],\end{aligned}\quad l = 1, \dots, 5. \quad (37)$$

Define fuzzy basis functions as

$$\phi(x_1, \hat{x}_2) = \frac{\mu_{F_l^1} \mu_{F_l^2}}{\sum_{k=1}^5 [\mu_{F_k^1} \mu_{F_k^2}]}, \quad l = 1, \dots, 5. \quad (38)$$

FIGURE 1: Ship roll angle φ . FIGURE 2: Fin control angle a_f .

The design parameters are chosen as $Q = \text{diag}\{30, 30\}$, $k_1 = 2$, $k_2 = 2$, $\sigma = 32$, $\gamma = 20$, $r = 1$, $\tau^* = 0.6$, $\bar{\tau} = 1.1$, $c_1 = c_2 = 4$. The initial conditions are given as $\varphi(0) = 11.26^\circ$, $\dot{\varphi}(0) = 5.63^\circ$, and the other initial values are chosen as zeros. The simulation results are shown in Figures 1 and 2.

7. Conclusions

In this paper, the time-delay ship roll stabilization by fin control system has been considered. Assuming that angular velocity in roll cannot be measured, an adaptive fuzzy output-feedback control has been investigated. The fuzzy logic system was used to approximate the uncertain term of the controlled system, and a fuzzy state observer was designed to estimate the unmeasured states. By utilizing the fuzzy state observer, an adaptive fuzzy output-feedback control approach was developed for fin control system. It is proven that the proposed control approach can guarantee that all the signals in the closed-loop system are SGUUB.

In the future research, the input constraints of the fin control system should be considered. In fact, the input variable of the fin control system is limited in a certain range. The adaptive fuzzy output-feedback controller with the input saturation will be researched in the future.

Conflict of Interests

The author of the paper has declared no conflict of interests.

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