ADAPTIVE ROBUST FUZZY FIN STABILIZER DESIGN FOR SHIP ROLL NONLINEAR SYSTEMS

Yang Yansheng *,1

* *Navigation College of Dalian Maritime University, Dalian, 116026, P.R. of China*

Abstract: This paper addresses the problem of designing fin control for the ship roll stabilization. A novel adaptive robust fuzzy control (ARFC) algorithm is presented for ship roll nonlinear system with unstructured uncertainties. In the algorithm, the Takagi-Sugeno type fuzzy logic systems are employed to approximate uncertain functions in the systems, and a systematic procedure is developed for the synthesis of adaptive robust fuzzy control whose adaptive mechanism has minimal learning parameterizations by use of Lyapunov theorem. Application example illustrating the method described is included for ship roll stabilization, which is shown that the derived closed-loop system can be made uniformly ultimately bounded.

Keywords: Ship roll stabilization, adaptive robust fuzzy control, uncertain nonlinear system

1. INTRODUCTION

Ship excessive roll motion induced by wave disturbances would make the crew feel uncomfortable and may also cause damage to the cargoes and equipment on board, such that the stabilization of ship roll motion has been a goal that people always strive to achieve. The fin stabilizer, which is a hull stability equipment for reduction of ship rolling by using the generating lift of the fins extended to the both sides of a ship, was invented 60 years ago and began to be equipped on the ship and showed good performance (Ohgushi, 1971). As we all know, a fin stabilizer is a kind of active stabilization system, the performance of which is effected greatly by its control methodology. To achieve better performance, its advanced control scheme has received considerable attention. From 1970s, some advanced control schemes are put into practices, such as optimal control (Whyte, 1978), fuzzy logic control (Sutton *et al.*, 1989), self-organizing fuzzy control (Fowler, 1989), adaptive LQ control (Fortuna and Muscato, 1996), H_∞ control (Hickey *et al.*, 1995), internal model control (Tzeng and Wu, 2000) and etc. However, there exist nonlinearities, parametric uncertainties and environmental disturbances in the ship roll nonlinear system from the changing sea conditions. To handle those problems, the author has ever proposed a robust adaptive fuzzy control scheme (Yang *et al.*, 2000), (Yang *et al.*, 2002). Therefore, developing the control scheme with large robustness is of much interest in the research field of fin roll stabilization systems.

In order to design an advanced fin stabilizer for ship roll nonlinear stabilization, a method of control design for uncertain nonlinear system is inves-

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tigated first in this paper. There exists a powerful methodology for designing feedback controller. Different control algorithms have been developed for nonlinear systems under various uncertainties. In the uncertain nonlinear systems, they may be subjected to following two types of uncertainties: structured uncertainties, which are referred to as parametric uncertainties, and unstructured uncertainties, which are coming from modeling errors and external disturbances. In this paper, a novel systematic procedure is developed for the synthesis of stable adaptive robust fuzzy controller for a class of nonlinear systems with unstructured uncertainties, and Takagi-Sugeno type fuzzy logic systems (Takagi and Sugeno, 1985) are used to approximate unknown functions in the systems and the adaptive mechanism with minimal learning parameterizations can be achieved . The main feature of the algorithm proposed in the paper is that no matter how many states in the system are investigated and how many rules in the fuzzy system are used, only one parameter needs to be adapted on-line, so the computation load of the algorithm can be reduced and it is a convenience to realize this algorithm for engineering. We conduct a simulation to verify it using ship roll stabilization.

This paper is organized as follows. Section 2 contains problem formulation. In section 3, a systematic procedure for the synthesis of adaptive robust fuzzy controller (ARFC) is developed. In section 4, we demonstrate how the adaptive robust fuzzy control scheme can be applied to the controller design for ship roll stabilization and a container ship is used as an example for simulation. The simulation results are described and compared. The final section contains conclusions.

2. PROBLEM FORMULATION

The mathematical model for ship roll system (Cox and Lloyd, 1977) can be given by

$$\begin{aligned}(I_{xx}+J_{xx})\ddot{\phi}+N\dot{\phi}+W\dot{\phi}\left|\dot{\phi}\right| \\ +Dh\phi\left(1-(\phi/\phi_v)^2\right)=F_C+F_W \quad (1)\end{aligned}$$

where ϕ denotes the roll angle of ship, $(I_{xx}+J_{xx})$ is the moment of inertia and added moment of inertia, N and W denote damping parameters, D is displacement of ship, h is the transverse metacentric height, ϕ_v is a angle specified by ship type, F_W is the moment acted on ship by wave and wind, F_C is the control moment for anti-roll supplied by fin. F_C can be described by

$$F_C=-\rho V^2 A_f C_L^{\alpha}\left(\alpha_f+\frac{\dot{\phi}l_f}{V}\right)l_f \qquad (2)$$

where ρ is the density of water, V denotes ship speed, A_f is the area of the fin, C_L^{α} is the slope of lift parameter, l_f is the arm of force supplied by fin, α_f is the angle of the fin.

Without loss of generality, the mathematical model for ship roll nonlinear system (1) by fin control can be written in general model of typical 2^{nd} order dynamic system as follows

$$\ddot{\phi}=f\left(\phi,\dot{\phi}\right)+g\left(\phi,\dot{\phi}\right)\alpha_c+w \qquad (3)$$

where $f\left(\phi,\dot{\phi}\right)$ and $g\left(\phi,\dot{\phi}\right)$ are bound continuous system function and input gain function respectively. w is external disturbance by wind and wave. Let the state variable be $x_1=\phi$, $x_2=\dot{\phi}$ and control variable be $u=\alpha_c$, we can get the model for ship roll nonlinear system (3) in state space form as follows

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=f(x_1,x_2)+g(x_1,x_2)u+w\end{cases} \qquad (4)$$

In the following design, without loss of generality, suppose that the structure of $f(x_1,x_2)$ and $g(x_1,x_2)$ is unknown, then the control input u is designed such that $x_1,x_2\rightarrow 0$, which is the adaptive control.

Next, we will discuss the more general problem. Choose the system's model as n-order differential equation, i.e.

$$\begin{cases}\dot{x}_i=x_{i+1} \quad 1\le i\le n-1\\ \dot{x}_n=f_0(x)+\Delta f(x)+[g_0(x)+\Delta g(x)]u+w\end{cases} \qquad (5)$$

where $x\in R^n$ is the system state, $u\in R$ is the control input. w is the external disturbance which is unknown but bounded, e.g. $\mid w\mid\le D$, where D is an unknown constant. $f_0(x)$ and $g_0(x)$ are known functions and belong to smooth vector fields in a neighborhood of the origin $x=0$ with $f_0(0)=0$ and $g_0(x)\neq 0$. $\Delta f(x)$ is the system uncertain function and $\Delta g(x)$ is the input control uncertain function, both of which are continuous functions depending on the state x.

We have the following transformation for the control input

$$u=-g_0^{-1}(x)(f_0(x)+v) \qquad (6)$$

where v is a new control input. The design approach for v is discussed as follows.

Substituting the equation (6) into (5), we obtain

$$\dot{x}=Ax+B\{(1+E)\,v+F+w\} \qquad (7)$$

where $A=\begin{bmatrix}0&1&0&\cdots&0\\0&0&1&\cdots&0\\ \vdots&\vdots&\vdots&\vdots&\vdots\\0&0&0&\cdots&1\\0&0&0&\cdots&0\end{bmatrix}$, $B=\begin{bmatrix}0\\0\\ \vdots\\ \vdots\\1\end{bmatrix}$, $F(x)=\Delta f\left(x\right)-g_0^{-1}\left(x\right)\Delta g\left(x\right)f_0\left(x\right)$ and $E(x)=g_0^{-1}\Delta g$.

Assumption 2.1 The uncertain control gain function $E(x)$ is confined within a certain range such that

$$0 < b_{\min} \leq | 1 + E(x) | \leq b_{\max} \tag{8}$$

where $b_{\min}$ and $b_{\max}$ are the low and upper bounded parameters respectively, which true values are assumed to be unknown in this paper.

The problem of adaptive robust fuzzy control design for $v(t)$ has recently received attention with renewed interest (Wang, 1997), (Yang *et al.*, 2000). If using fuzzy systems to approximate $F(x)$ and $E(x)$, then an "integral" control law is necessary, i.e., a dynamic feedback controller

$$\begin{aligned}\dot{\chi} &= \varpi(\chi, \xi(x), x), \quad \varpi(0,0,0) = 0\\ v(t) &= \alpha_r(\chi, \xi(x), x), \quad \alpha_r(0,0,0) = 0\end{aligned}$$

where $\xi(e)$ is a known fuzzy base function vector. And $\chi \in R^{n_\chi}$, $\varpi(\cdot)$, $\alpha_r(\cdot)$ are smooth functions on $R^{n_\chi} \times R^K \times R^n$. An important quality of the control law is of course the property that the dimension n_χ of χ should be as small as possible, and in particular not dependent on the dimension of the state. However, most of the previous adaptive fuzzy-based control laws available in the literature have the property that the dimension n_χ of χ is equal to the number of parameters to describe the fuzzy systems which are used to approximate the unknown uncertain functions in the designed systems. In such a way, the learning times of them will tend to become unacceptable large for systems of higher order. For the conventional adaptive fuzzy-based control laws, there is another of main difficulties which comes from uncertainty $E(x)$, which is usually approximated by fuzzy system $\hat{E}(x,\theta)$. Consequently, the estimate $1 + \hat{E}(x,\theta)$ must be away from zero for avoiding a possible singularity problem. In this paper, we will develop a new stable adaptive robust fuzzy controller which does not require to estimate the unknown function $E(x)$, and therefore avoids the possible controller singularity problem usually met in the traditional adaptive fuzzy control laws.

3. DESIGN OF ADAPTIVE ROBUST FUZZY CONTROLLER

3.1 T-S fuzzy system

Consider a T-S fuzzy system to uniformly approximate a continuous multi-dimensional function $y = f(x)$ that has a complicated formulation, and x is an input vector with n independent $x = [x_1, x_2, \cdots, x_n]^T$. The domain of x_i is $\theta_i = [a_i, b_i]$. It follows that the domain of x is

$$\Theta = \theta_1 \times \theta_2 \times \cdots \times \theta_r = [a_1, b_1] \times [a_2, b_2] \times \cdots \times [a_n, b_n]$$

In order to construct a fuzzy system, the interval $[a_i, b_i]$ is divided into N_i subintervals

$$a_i = C_0^i < C_1^i < \cdots < C_{N_n}^i = b_i, \quad 1 \leq i \leq n$$

On each interval $\theta_i\,(1 \leq i \leq n)$, $N_i + 1 (N_i > 0)$ continuous input fuzzy sets, denoted by A_j^i, are defined to fuzzify x_i. The membership function of A_j^i is denoted by $\mu_j^i(x_i)$, and $\mu_j^i(x_i)$ can be represented by triangular, trapezoid, generalized bell or Gaussion type and so on.

Generally, the fuzzy system can be constructed by the following $K (K > 1)$ fuzzy rules

$$\begin{aligned}R_i:\ & \text{IF } x_1 \text{ is } A_{h_1}^i \text{ AND } x_2 \text{ is } A_{h_2}^i \text{ AND}\\ & \ldots\ldots \text{AND } x_n \text{ is } A_{h_n}^i \text{ THEN } y \text{ is}\\ & a_{i0} + a_{i1}x_1 + \cdots + a_{in}x_n, i = 1, 2, \cdots, K\end{aligned}$$

where $a_{ij}, i = 1, 2, \cdots, K, j = 0, 1, 2, \cdots, n$ is the constant. The product fuzzy inference is employed to evaluate the ANDs in the fuzzy rules. After being defuzzyfied by a typical center average defuzzifier, the output of the fuzzy system is

$$y = F(x) = \sum_{i=1}^{K} y_i \xi_i(x) = \xi(x) A_x \bar{x} \tag{9}$$

where $y_i = a_{i0} + a_{i1}x_1 + \cdots + a_{in}x_n$ and $\xi_i(x) = \prod_{j=1}^{n} \mu_{h_j}^i(x_j) \Big/ \sum_{i=1}^{K} \left[\prod_{j=1}^{n} \mu_{h_j}^i(x_j) \right]$. $\xi_i(x)$ is called a fuzzy base function. When the membership function $\mu_j^i(x_i)$ in the $\xi_i(x)$ is denoted by some types of membership function, $\xi_i(x)$ is a known continuous function. And $A_x = \begin{bmatrix} a_{10} & a_{11} & \cdots & a_{1n} \\ a_{20} & a_{21} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{K0} & a_{K1} & \cdots & a_{Kn} \end{bmatrix}$, $\xi(x) = [\xi_1(x), \xi_2(x), \cdots, \xi_K(x)]$, $\bar{x} = [1, x]^T$.

When the fuzzy system is used to approximate the continuous function, two questions of interest may be asked: whether there exists a fuzzy system to approximate any nonlinear function to an arbitrary accuracy? how to determine the parameters in the fuzzy system if such a fuzzy system does exist. The following lemma (Wang, 1997) gives a positive answer to the first question.

Lemma 3.1 Suppose that the input universe of discourse U is a compact set in R^r. For any given real continuous function $f(x)$ on U and arbitrary $\forall \varepsilon > 0$, then there exists a fuzzy system in the form of equation (9) such that

$$\sup_{x \in U} |f(x) - \xi(x) A_x \bar{x}| \leq \varepsilon \tag{10}$$

We close this section by giving a useful technical lemma whose proof is straightforward.

Lemma 3.2 For any x and y in R^n, and for any positive real number ϵ, we have

$$x^T y \leq \frac{1}{4\epsilon^2} x^T x + \epsilon^2 y^T y \tag{11}$$

3.2 Control Design

In order to make the stabilization of uncertain nonlinear system (7), owing to (A, B) is controllable, it ensures the existence of the solution of the algebraic Riccati equation in the following

$$A^T P + PA - \rho PBB^T P + Q = 0 \tag{12}$$

where $\rho > 0$ and $Q > 0$ are specified by the designer, such that the solution is $P = P^T > 0$.

For the system (7), the uncertainties $F(x)$ and $E(x)$ are the bounded functions in the control engineering. Hence there exists low bound for $E(x)$ as Assumption 2.1. If $\Delta f(x)$ and $\Delta g(x)$ are the complicated formulation system functions that can be considered to be continuous, the uncertain function $F(x)$ is also a continuous function, according to Lemma 3.1 T-S fuzzy system can be used to approximate $F(x)$ as follows

$$F(x) = \xi(x) A_x x + \varepsilon(x) \tag{13}$$

where $\varepsilon(x)$ is a bounded function approximation error, i.e. $|\varepsilon(x)| < \delta$, where δ is an unknown constant.

Assume that $c_\theta = \|A_x\| = \lambda_{\max}^{1/2}(A_x^T A_x)$ exists such that $A_x = c_\theta A_x^m$ and $\|A_x^m\| \leq 1$. Substituting the equations (13) into (7), it follows that Eq. (7) reduces to

$$\begin{aligned}\dot{x} =&(A - \frac{\rho}{2} BB^T P)x + B[(1+E)v + \frac{\rho}{2} B^T Px \\ &+ \varepsilon(x) + w] + c_\theta B \xi(x) A_x^m x\end{aligned} \tag{14}$$

We propose an adaptive robust fuzzy controller (ARFC) shown in the following

$$v = -\hat{\lambda}\vartheta(x) B^T P x \tag{15}$$

where $\vartheta(x) = \{\frac{\rho}{2} + \frac{1}{4}\xi(x)\xi^T(x) + \frac{1}{4\varrho^2}\}$. Let $\hat{\lambda}$ be the estimate of $\lambda = \kappa^{-1}\max(c_\theta^2, (D+\delta)^2, 1)$ and $\kappa = (1 + b_{\min})$. The adaptive law for $\hat{\lambda}$ is now chosen as

$$\dot{\hat{\lambda}} = \Gamma\left[\frac{1}{4}\vartheta(x) x^T PBB^T Px - \sigma(\hat{\lambda} - \lambda_0)\right] \tag{16}$$

where $\Gamma > 0$ can be considered as the updating rate, σ and λ_0 are design constants, which are chosen by designer respectively.

Theorem 3.1 Consider the system (14), suppose that $F(x)$ can be approximated by T-S fuzzy system as shown in equation (13). If picking $\lambda_{\min}(Q) > 2$, then control scheme (15) with adaptive law (16) is one of the adaptive robust fuzzy controller (ARFC) which can make all the solutions $(x(t), \hat{\lambda})$ of the derived closed loop system uniformly ultimately bounded. Furthermore, given any $\mu > 0$, we can tune our controller parameters such that closed-loop system satisfies $\lim_{t\to\infty} | x_1(t) | \leq \mu$.

Proof: Choose the Lyapunov function as

$$V = \frac{1}{2} x^T P x + \frac{1}{2}\kappa\Gamma^{-1}\widetilde{\lambda}^2 \tag{17}$$

where $\widetilde{\lambda} = (\lambda - \hat{\lambda})$.

The time derivative of V along the system trajectory (14) is

$$\begin{aligned}\dot{V} =&\frac{1}{2} x^T \left(A^T P + PA\right) x - \kappa\Gamma^{-1}\widetilde{\lambda}\dot{\hat{\lambda}} \\ &+ x^T PB\Big[(1+E(x))v + \frac{\rho}{2} B^T Px + \varepsilon(x) + w\Big] \\ &+ x^T PB c_\theta \xi(x) A_x^m x\end{aligned} \tag{18}$$

We deal with relative items in Eq. (18), substitute Eq. (15) into the relative items above, and obtain

$$\begin{aligned}x^T PB(1+E)v =& -\hat{\lambda}(1+E)\vartheta(x) x^T PBB^T Px \\ \leq& -\kappa\hat{\lambda}\vartheta(x) x^T PBB^T Px\end{aligned} \tag{19}$$

and by use of Lemma 3.2, we can get

$$\begin{aligned}&x^T PB c_\theta \xi(x) A_x^m x \\ &\leq \frac{c_\theta^2}{4} x^T PB\xi\xi^T B^T Px + x^T A_x^{mT} A_x^m x \\ &\leq \frac{c_\theta^2}{4} x^T PB\xi\xi^T B^T Px + x^T x\end{aligned} \tag{20}$$

and by means of Lemma 3.2, there exists a non-negative constant ϱ, it yields

$$\begin{aligned}&x^T PB(\varepsilon(x) + w) \\ &\leq\| x^T PB \| (D+\delta) \\ &\leq \frac{(D+\delta)^2}{4\varrho^2} x^T PBB^T P + \varrho^2\end{aligned} \tag{21}$$

We can get

$$\begin{aligned}&x^T PB c_\theta \xi(x) A_x^m x + x^T PB(\varepsilon(x) + w) \\ &\quad + \frac{\rho}{2} x^T PBB^T Px \\ &\leq \frac{c_\theta^2}{4} x^T PB\xi\xi^T B^T Px + x^T x + \frac{\rho}{2} x^T PBB^T Px \\ &\quad + \frac{(D+\delta)^2}{4\varrho^2} x^T PBB^T Px + \varrho^2 \\ &\leq \kappa\lambda\vartheta(x) x^T PBB^T Px + x^T x + \varrho^2 \\ &\leq \kappa\hat{\lambda}\vartheta(x) x^T PBB^T Px \\ &\quad + \kappa\widetilde{\lambda}\vartheta(x) x^T PBB^T Px + x^T x + \varrho^2\end{aligned} \tag{22}$$

Substituting Eq. (22) into (18) such that

$$\begin{aligned}\dot{V} \leq& -\frac{1}{2} x^T (Q - 2I_{n\times n}) x + \kappa\Gamma^{-1}\widetilde{\lambda} \\ &\times \left(\Gamma\vartheta(x) x^T PBB^T Px - \dot{\hat{\lambda}}\right) + \varrho^2\end{aligned} \tag{23}$$

Substituting Eq. (15) into (23), we get

$$\begin{aligned}\dot{V} \leq& -\frac{1}{2} x^T (Q - 2I_{n\times n}) x + \sigma\kappa\widetilde{\lambda}(\hat{\lambda} - \lambda_0) + \varrho^2 \\ \leq& -\frac{1}{2} x^T (Q - 2I_{n\times n}) x - \frac{1}{2}\sigma\kappa\widetilde{\lambda}^2 + d_1 \\ \leq& -c_1 V + d_1\end{aligned} \tag{24}$$

where $d_1 = \frac{1}{2}\kappa\sigma(\lambda - \lambda_0)^2 + \varrho^2$ and $c_1 = \min\{(\lambda_{\min}(Q) - 2)/\lambda_{\max}(P), \sigma\Gamma\}$. From Eq. (24), we get

$$V(t) \leq \frac{d_1}{c_1} + (V(t_0) - \frac{d_1}{c_1})e^{-c_1(t-t_0)}$$

It results that the solutions of composite closed-loop system are uniformly ultimately bounded, and implies that, for any $\mu_1 > (d_1/c_1)^{1/2}$, there exists a constant $T > 0$ such that $\mid x_1(t) \mid \leq \mu$ for all $t \geq t_0 + T$. The last statement follows readily since $(d_1/c_1)^{1/2}$ can be made arbitrarily small if the design parameters $\lambda_0, \sigma, \varrho$ are chosen appropriately.

4. ADAPTIVE ROBUST FUZZY STABILIZATION FOR SHIP ROLL NONLINEAR SYSTEM

To illustrate the applicability of the ARFC scheme proposed in this paper, we conduct a simulation on the ship roll stabilization.

We use the system (5) for design the ARFC scheme. And setting

$$\begin{cases} f_0(x) = 0 \\ g_0(x) = 1 \\ \Delta f(x, w) = f(x_1, x_2) \\ \Delta g(x, w) = g(x_1, x_2) - 1 \end{cases} \tag{25}$$

Owing to the system function $f(x_1, x_2)$ is unknown with a continuous complicated formulation system function, T-S fuzzy system can be constructed to approximate the function $f(x_1, x_2)$ by he following four fuzzy IF-THEN rules

IF x_1 is positive AND x_2 is positive THEN y_1 is $a_{11}x_1 + a_{12}x_2$

IF x_1 is positive AND x_2 is negative THEN y_2 is $a_{21}x_1 + a_{22}x_2$

IF x_1 is negative AND x_2 is positive THEN y_3 is $a_{31}x_1 + a_{32}x_2$

IF x_1 is negative AND x_2 is negative THEN y_4 is $a_{41}x_1 + a_{42}x_2$

where the fuzzy sets "positive" and "negative" are characterized by the following membership functions

$$\mu_{\text{positive}}(x) = \frac{1}{1 + \exp(-ax)}$$
$$\mu_{\text{negative}}(x) = \frac{1}{1 + \exp(ax)}$$

where a is the parameter correlated to the ship type and the state.

Using the center average defuzzifier and the product inference engine, the output of the above fuzzy system can be written as

$$F(x) = \xi(x) A_x x + \varepsilon$$

where

$$\xi_1(x) = \frac{1}{1 + \exp(-ax_1)} \frac{1}{1 + \exp(-ax_2)} \Big/ \beta,$$
$$\xi_2(x) = \frac{1}{1 + \exp(-ax_1)} \frac{1}{1 + \exp(ax_2)} \Big/ \beta,$$
$$\xi_3(x) = \frac{1}{1 + \exp(ax_1)} \frac{1}{1 + \exp(-ax_2)} \Big/ \beta,$$
$$\xi_4(x) = \frac{1}{1 + \exp(ax_1)} \frac{1}{1 + \exp(ax_2)} \Big/ \beta$$

$$\begin{aligned}\beta = &\frac{1}{1 + \exp(-ax_1)} \frac{1}{1 + \exp(-ax_2)} \\ &+ \frac{1}{1 + \exp(-ax_1)} \frac{1}{1 + \exp(ax_2)} \\ &+ \frac{1}{1 + \exp(ax_1)} \frac{1}{1 + \exp(-ax_2)} \\ &+ \frac{1}{1 + \exp(ax_1)} \frac{1}{1 + \exp(ax_2)}\end{aligned}$$

In this simulation, we are intended to relax Assumption 2.1 to check the robustness of the proposed controller. And moreover we get $\rho = 1, Q = \text{diag}\{3, 3\}$, then the solution of the algebraic Riccati equation (12) is obtained by $P = \begin{bmatrix} 4.4037 & 1.7321 \\ 1.7321 & 2.5425 \end{bmatrix}$. If the gain is $\varrho = 0.5$, the following fuzzy adaptive robust control scheme can be derived for ship roll stabilization.

$$\begin{aligned} u = &- \hat{\lambda} \left[1.5 + 0.25 \sum_{i=1}^{4} \xi_i^2(x) \right] \\ &\times (1.7321x_1 + 2.5425x_2) \end{aligned} \tag{26}$$

$$\begin{aligned} \dot{\lambda} = 100 &\left[\left(1.5 + 0.25 \sum_{i=1}^{4} \xi_i^2(x) \right) \right. \\ &\left. \times (1.7321x_1 + 2.5425x_2)^2 - 0.5(\hat{\lambda} - 0.1) \right] \end{aligned} \tag{27}$$

where $\lambda(0) = 0$ and the parameter a in membership functions is 30.

To demonstrate the feasibility of the proposed scheme, consider a container ship with the length 175 m and displacement 25,000 tons as an example for simulation.

In the simulation the external disturbance is assumed as a sinusoidal wave with wave height 7 m and wave direction 50^o. Simulation results based on the Matlab Simulink package are given as follows.

Fig. 1 illiterates the time response of the ship roll angle without the fin control. Fig. 2 shows the time response of the ship roll angle with ARFC scheme (26) and Fig. 3 shows the time response of fin control angle by ARFC scheme when ship speed is 7.71 m/sec. Fig. 4 shows the history of parameter λ. As comparing Fig. 1 with Fig. 2, the excellent performance and robustness of ARFC are exhibited.

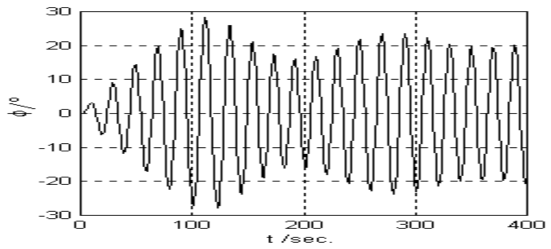

Fig. 1. *Time response of roll angle without fin control.*

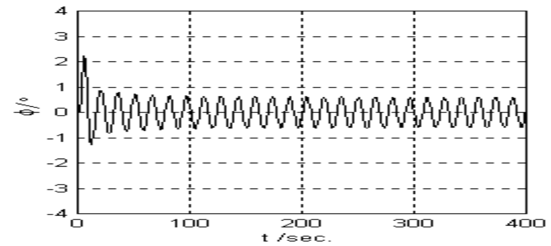

Fig. 2. *Time response of roll angle with fin control.*

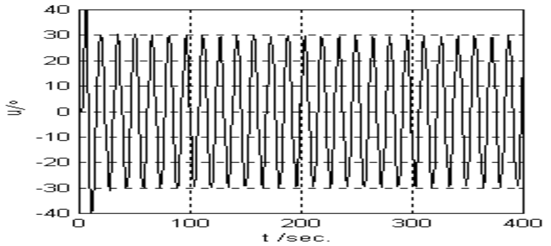

Fig. 3. *Time response of fin control angle.*

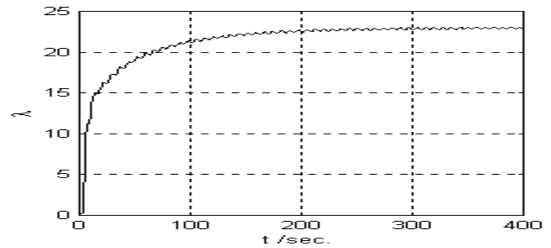

Fig. 4. *Adaptation of the parameter λ.*

5. CONCLUSIONS

In this paper, we propose a novel adaptive robust fuzzy control (ARFC) scheme, which can be used to control a class of uncertain nonlinear systems, for the problem of ship roll stabilization. In the scheme, Takagi-Sugeno type fuzzy logic systems are used to approximate unknown functions in the systems and adaptive robust fuzzy control (ARFC) algorithm, which makes the closed-loop be uniformly ultimately bounded around $x(t) = 0$, can be achieved by use of Lyapunov theorem. The main feature of the algorithm proposed in this paper is the adaptive mechanism with minimal learning parameterizations, e.g. no matter how many states in the system are investigated and how many rules in the fuzzy system are used, only one parameter needs to be adapted on-line, so the computation load of the algorithm can be reduced and it is a convenience to realize this algorithm for engineering. The feasibility of the proposed method is verified through a container ship simulation. Simulation results show the effectiveness of the control scheme.

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