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Adaptive Backstepping-Based Nonlinear Disturbance Observer for Fin Stabilizer System

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***Abstract*—In this paper, an adaptive backstepping controller based on nonlinear disturbance observer (DOB) is proposed for the nonlinear fin stabilizer system. DOB is responsible for disturbance rejection and uncertainty compensation, while the adaptive backstepping scheme is proposed for dealing with uncertain parameters of the fin stabilizer model. The designed controller guarantees uniform ultimate boundedness of all the signals in the closed-loop system and the tracking errors converge to a small neighborhood of the origin. The advantages of the proposed control scheme comprise that the DOB shorten the response time and observes the whole disturbances of the fin stabilizer system. Simulation example is presented to show the preciseness and robustness of the stabilization control realized by the proposed method.**

Keywords*— *Fin Stabilizer; Nonlinear Disturbance Observer; Adaptive Control; Backstepping

I. INTRODUCTION[α]

Due to the influences of wind, wave and flow, ship sailing on the open sea will produce strong roll resulting in the decreases of voyage comfort and safety. In order to weaken the rolling motion, various devices, such as bilge keels, antiroll tanks and fin stabilizer etc., have been equipped on ships. However, fin stabilizer is the most widely used and the most effective device which is influenced greatly by its control method [1].

With the progress of control techniques, many control techniques have already been studied for fin stabilizer system. In [2-4], the most popular PID control was employed to decrease the ship rolling motion, which had the advantages of simplicity and reliability. But the PID controller decreased robustness and adaptability. Moreover, based on the linear model, it was difficult to control the ship's rolling motion caused by nonlinear dynamics in rough sea. For the purpose of solving nonlinear dynamics and parameters perturbation, which caused by heavy sea[1], many robust algorithms, such as sliding-mode variable structure control [5-6], model predictive control [7], and Lyapunov's direct method [8], were proposed by a number of researchers engaged in the development of fin stabilizer system. However, in consideration of the parameters uncertainty of the ship model, adaptive backstepping method provided a good solution of robust control for the low order fin stabilizer system [1]. As we know, adaptive control technique was used to compensate the parameters uncertainty caused by the model perturbation, i.e., the unknown parameters were replaced by the update laws, and backstepping method, which was a recursive design procedure based on Lyapunov theory, solved the mismatch problem of the nonlinear system [1]. Its basic idea was to choose the appropriate state variety as its virtual control input, then each backstepping process would produce a control variable output based on previous process, finally when the iteration was terminated, the actual controller was gained by Lyapunov function optimization.

In recent years, researches on improving the roll reduction and high accuracy without a higher cost associated with such improvements, have received significant attention. The main challenge to achieve this goal is to overcome the difficulties caused by disturbances which mainly include two parts, namely internal disturbances and external disturbances. Unfortunately, uncertainties of fin stabilizer system caused by the unknown disturbances cannot be modeled or repeated. In order to reduce or eliminate such kind of uncertainties, various control methodologies have been proposed for fin stabilizer system such as, $H\infty$ control [9], robust control[10], sliding model control[5-6], neural network technique [11-13], auto-disturbance rejection control [14] etc.

However, more accurate and faster response is demanded in modern manufacture even under larger uncertainties and disturbances. To achieve the control goal, DOB was employed in [15-18]. The main idea of DOB is to estimate

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the equivalent disturbance by comparing the control input of the real system with the virtual control input of the nominal model. The virtual control input is derived by the output response from the inverse of the nominal model. The estimated disturbance is fed back as a cancellation signal, and then makes the whole system like a nominal system. Therefore, it has been regarded as an effective tool in achieving control system robustness with respect to disturbance. DOB has many advantages such as high performance, strong robustness, and less computational burden [19]. It is also found that, although the proposed DOB is designed for slow varying disturbance, it can estimate rapid time varying disturbances very well.

In this paper, an adaptive controller has been presented for uncertain nonlinear fin stabilizer system with disturbances by combining the adaptive backstepping method with the DOB technique. And the proposed scheme guarantees all the signals in the closed-loop are stable. Meanwhile, this method overcomes the parameters uncertainty of system, the whole disturbances of the system can be estimated. Most importantly, the response time is greatly decreased. The proposed scheme will obtain better anti-rolling effectiveness and robustness.

The rest of this paper is organized as follows. In section Ⅱ, the nonlinear model of the fin stabilizer will be characterized. The controller design and stability analysis are presented in section Ⅲ. In section Ⅳ, simulation results are used to illustrate our approach. Section Ⅴ concludes this paper.

II. PROCEDURE FOR PAPER SUBMISSION

A. Fin stabilize model

We use the nonlinear mathematical model of the fin stabilizer to reflect the roll movement [20-21]

$$(I_{xx}+J_{xx})\ddot{\varphi}+\delta_N\dot{\varphi}+\delta_W\dot{\varphi}|\dot{\varphi}|+Wh\varphi\left[1-(\varphi/\varphi_v)^2\right]$$
$$=M_c+M_W$$
(1)

where φ is rolling angle of ship, I_{xx} and J_{xx} are the inertia moments and the added inertia moments of the own ship, δ_N, δ_w are the damping factors, W is the displacement 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 act on ship of sea wave. I_{xx}, J_{xx}, δ_N, δ_W and M_c can be denoted

$$\delta_N=\frac{2c_1\sqrt{Wh(I_{xx}+J_{xx})}}{\pi},\ \delta_W=\frac{3c_2(I_{xx}+J_{xx})}{4},$$

$$M_c=-\rho v^2A_fl_fC_L^{\alpha}(\alpha_f+\frac{\dot{\varphi}l_f}{v}),$$

$$I_{xx}+J_{xx}=\frac{WB^2}{g}(0.3085+\frac{0.0227B}{d}-\frac{0.0043L}{100})^2$$

where g is acceleration of gravity, B is the breadth of ship, L is length between perpendiculars, d is draft, c_1, c_2 are test coefficients, ρ is the fluid density, v is the ship speed, A_f is the area of fin, l_f is the acting force arm of fin stabilizer, C_L^{α} is the lift coefficient of fin stabilizer, α_f is the rotation angle of fin stabilizer. Tidy the equation, we can get

$$\ddot{\varphi}=a_1\varphi+a_2\varphi^3+a_3\dot{\varphi}+a_4\dot{\varphi}|\dot{\varphi}|+b\alpha_f+f_W \tag{2}$$

where a_1, a_2, a_3, a_4, b are coefficients, f_W is the disturbance of sea wave.

B. The state space model of fin stabilizer

By choosing $x=[x_1,x_2]^T=[\varphi,\dot{\varphi}]^T$ as the state variable, $y=\varphi=x_1$ as the output variable, $u=\alpha_f$ as the input. It is considered that the uncertainties of the fin system, formula (2) can be transformed into the state space model as follows:

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=\theta^T\psi(x)+bu+f\\ y=x_1\end{cases} \tag{3}$$

Where $\theta^T=[\theta_1\ \theta_2\ \theta_3\ \theta_4]$ are the unknown parameters. $\psi(x)=[\psi_1(x)\ \psi_2(x)\ \psi_3(x)\ \psi_4(x)]$, Where b, $\tilde{f}$, $k_2\geq 0$, $\psi_4(x)=x_2\cdot|x_2|$ are smooth and continuity, b is the known gain of the control and a nonzero constant, f is the disturbances (which contains internal disturbance and external disturbance). The ideal output is $y_r=0$.

For the development of the control laws, the following assumption is made. [22]

Assumption. The disturbance f has an upper bound, that is, there has an unknown constant $\bar{\varpi}>0$ which satisfies $|f|<\bar{\varpi}$.

Lemma. If $V(t,x)$ is positive definite function and $\dot{V}\leq -k_1V+k_2$, where $k_1\geq 0$ and $k_2\geq 0$ are constant. Then

$$V(t,x)\leq\frac{k_2}{k_1}+\left(V(0)-\frac{k_2}{k_1}\right)e^{-k_1t} \tag{4}$$

C. The nonlinear DOB

The structure of a practical control system with nonlinear disturbance observer is shown in Fig.1, which indicates the principle of disturbance observer design

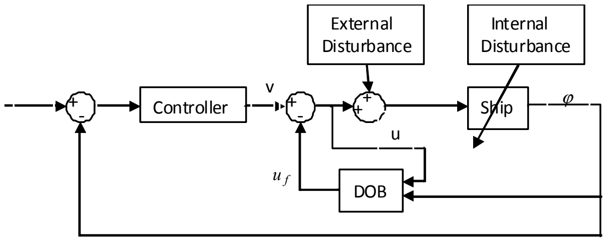

Fig. 1. The structure of DOB

A basic idea in the design of observers is to modify the estimation by the difference between the estimated disturbance and the actual disturbance. Where u_f is the compensation signal, v is the actual output of controller, u is the actual input of the system.

III. CONTROLLER DESIGN AND STABILITY ANALYSIS

The nonlinear DOB is designed in the following:

By combining the internal disturbance and external disturbance, the second function of the system (3) can be written as

$$f = \dot{x}_2 - \theta^T \psi(x) - bu \tag{5}$$

And the disturbance observer can be proposed as follow in [23].

$$\dot{\hat{f}} = -L(x_1, x_2)\hat{f} + L(x_1, x_2)(\dot{x}_2 - \theta^T \psi(x) - bu) \tag{6}$$

where $L(x_1, x_2) = a$, $a > 0$ is the design parameter. Since, there is no prior information about the derivative of the disturbance f , it is assumed that disturbance in Eq.(5) varies slowly[24]:

$$\dot{f} = 0 \tag{7}$$

But in Section □, it will be illustrated by simulation that the proposed observer estimates also fast time-varying disturbances.

Define the observer error as a difference between actual disturbance and estimated disturbance

$$\tilde{f} = f - \hat{f} \tag{8}$$

which can be expressed as below

$$\dot{\tilde{f}} = -L(x_1, x_2)\tilde{f} \tag{9}$$

It can be seen from Eq.(6), acceleration signal $\dot{x}_2$, which is hard to obtain, is required to realize the DOB. The problem is circumvented by defining an auxiliary variable $s = \hat{f} - p(x_2)$. By defining

$$\dot{p}(x_2) = L(x_1, x_2)\dot{x}_2 \tag{10}$$

Then

$$\dot{s} = -L(x_1, x_2)s + L(x_1, x_2)(-\theta^T \psi(x) - bu - p(x_2)) \tag{11}$$

and the estimated disturbance can be obtained by

$$\hat{f} = s + p(x_2) \tag{12}$$

It is known from the system (3) that

$$\dot{x}_2 = \theta^T \psi(x) + b(u + f / b) \tag{13}$$

Therefore, we design

$$u_f = \hat{f} / b \tag{14}$$

The second function of the system (3) can be written as

$$\dot{x}_2 = \theta^T \psi(x) + b(v - u_f) + f = \theta^T \psi(x) + bv + \tilde{f}$$
(15)

where $\tilde{f} = f - \hat{f}$, $u = v - u_f$ and the system is transformed into the following

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \theta^T \psi(x) + bv + \tilde{f} \\ y = x_1 \end{cases} \tag{16}$$

In the following, a novel design procedure for the system (16) is developed by employing the adaptive backstepping technique.

Sep1. At this step the first equation of the fin stabilizer system (16) is considered, define the error variable , and choose the intermediate stabilizing function as a virtual control law for the first subsystem. At the same time, define error variable , the time derivative of is

$$\dot{z}_1 = z_2 + \alpha_2 \tag{17}$$

The virtual control law is chosen as

$$\alpha_2 = -c_1 z_1 \tag{18}$$

where $c_1 > 0$ is the design parameter, substituting(18) into (17)

$$\dot{z}_1 = -c_1 z_1 + z_2 \tag{19}$$

Consider the Lyapunov function candidate $V_1 = \frac{1}{2} z_1^2$

and the time derivative of V_1 is

$$\dot{V}_1 = -c_1 z_1^2 + z_1 z_2 \tag{20}$$

The first term on the left-hand side is negative, and the second term will be considered in the next step.

Step2. Define $z_2 = x_2 - \alpha_2$, and differentiate z_2 with respect to time yields

$$\dot{z}_2 = \dot{x}_2 - \dot{\alpha}_2 \tag{21}$$

where $\dot{x}_2 = \theta^T \psi(x) + bv + \tilde{f}$ $\dot{\alpha}_2 = -c_1 x_2$. And design the control law as

$$v = (-c_2 z_2 - z_1 + \dot{\alpha}_2 - \hat{\theta} \psi(x)) / b \tag{22}$$

where $c_2 > 0$ is the design parameter.

Choose the Lyapunov function

$$V_2 = V_1 + \frac{1}{2} z_2^2 + \frac{1}{2} \tilde{\theta}^T \Gamma^{-1} \tilde{\theta} + \frac{1}{2} \tilde{f}^2 \tag{23}$$

Its derivative is given by

$$\dot{V}_2 = -c_1 z_1^2 + z_1 z_2 + z_2 (\theta^T \psi(x) + bv + \tilde{f} - \dot{\alpha}_2) - \tilde{\theta}^T \Gamma^{-1} \dot{\hat{\theta}} - \tilde{f} \cdot \dot{\hat{f}} \tag{24}$$

Submit (9) (22) into (24), then

$$\dot{V}_2 = -c_1 z_1^2 - c_2 z_2^2 + z_2 \tilde{f} - \tilde{\theta}^T \Gamma^{-1}(\dot{\hat{\theta}} - \Gamma \psi(x) z_2) - L(x_1, x_2)\tilde{f}^2 \tag{25}$$

Choose the update law

$$\dot{\hat{\theta}} = \Gamma(\psi(x) z_2 + \sigma\hat{\theta}) \tag{26}$$

The second term on the right-hand side is “leaking term” which is used to avoid parameter excursion in the adaptation law. σ is a small positive design parameter[25].

Then

$$\dot{V}_2 = -c_1 z_1^2 - c_2 z_2^2 + z_2 \tilde{f} - \sigma\tilde{\theta}^T\hat{\theta} - L(x_1, x_2)\tilde{f}^2 \tag{27}$$

According to the assumption, and using the fact that $z_2 \tilde{f} \le \frac{1}{2} z_2^2 + \frac{1}{2}\tilde{f}^2$, $2\tilde{\theta}^T\hat{\theta} \ge \|\tilde{\theta}\|^2 - \|\theta^*\|^2$ and submit $L(x_1, x_2) = a$ into (27), then

$$\begin{aligned} \dot{V}_2 &\le -c_1 z_1^2 - (c_2 - \frac{1}{2}) z_2^2 - \frac{\sigma}{2}(\|\tilde{\theta}\|^2 - \|\theta^*\|^2) - (a - \frac{1}{2})\tilde{f}^2 \\ &\le -c_1 z_1^2 - (c_2 - \frac{1}{2}) z_2^2 - \frac{\sigma}{2\lambda_{\max}(\Gamma^{-1})}\tilde{\theta}^T\Gamma^{-1}\tilde{\theta} + \frac{\sigma}{2}\|\theta^*\|^2 \\ &\quad - (a - \frac{1}{2})\tilde{f}^2 \end{aligned} \tag{28}$$

Define $D = \frac{\sigma}{2}\|\theta^*\|^2$ and

$$C = \min[c_1, (c_2 - \frac{1}{2}), \frac{\sigma}{2\lambda_{\max}(\Gamma^{-1})}, (a - \frac{1}{2})]$$

It is easy followed from (28) that

$$\dot{V}_2 \le -C V_2 + D \tag{29}$$

Obviously, the equation (29) means that $V_2(t)$ is boundedness (please refer to [22] for details) according to the assumption and lemma.

IV. SIMULATION RESEARCH

The simulation is based on a container ship, the parameters of the ship, such as, the length between perpendicular 175m, the breadth of ship 25.4m, draft 8.5m, displacement 21120t, the area of fin 20.2m2, the acting force arm of fin stabilizer 14.88m, flooding angle 43° , initial metacentric height 1m, designed speed 7.71m/s. the lift coefficient of fin stabilizer 3.39.

In simulation, the control system parameters were selected: $c_1 = 0.1$, $c_2 = 2$, $a = 15$, $\sigma = 0.1$, $\Gamma = diag\{0.001\}$, and the disturbance is chosen as sinusoidal signal , square-wave signal and step signal respect. The initial condition of the states $x(0) = [0.35, 0.01]^T$ and parameters $\theta(0) = [0.2117, -0.2938, 0.7438, 0.113]^T$, Simulation results in Fig.2-10 illustrate the control performance of the proposed scheme.

The disturbance signal is chosen as sinusoidal signal $d = 0.35\sin(0.8t)$

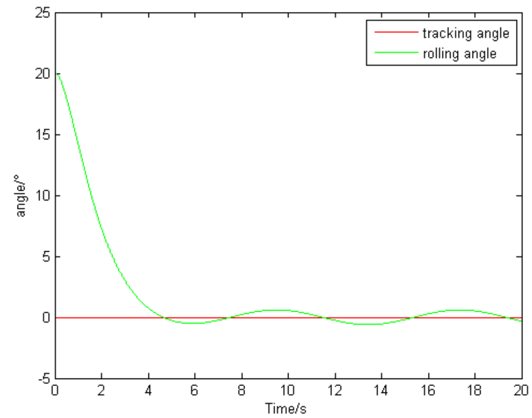

Fig. 2 Ship rolling angle and the tracking.

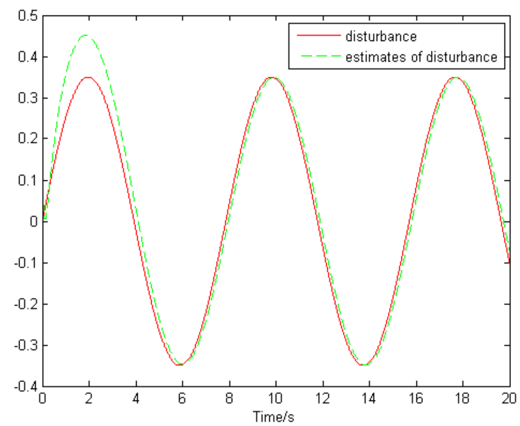

Fig. 3 . The disturbances and output of the DOB

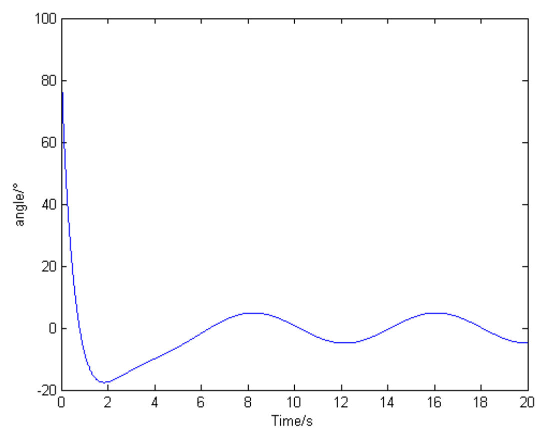

Fig. 4. The fin angle

The disturbance is chosen as square-wave $d = 0.35(sign(\sin(0.8t)))$

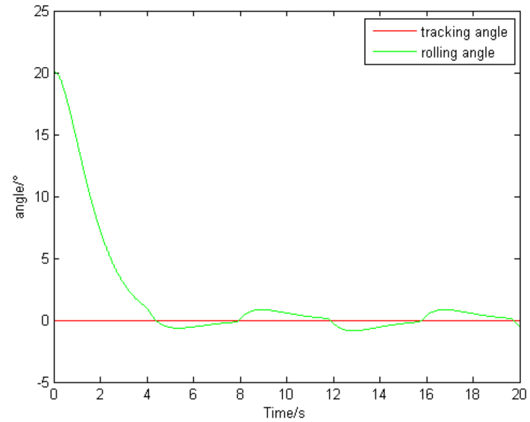

Fig. 5. Ship rolling angle and the tracking angle

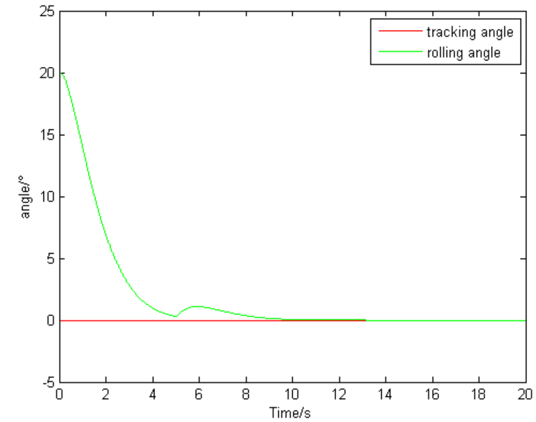

Fig. 8. Ship rolling angle and the tracking angle

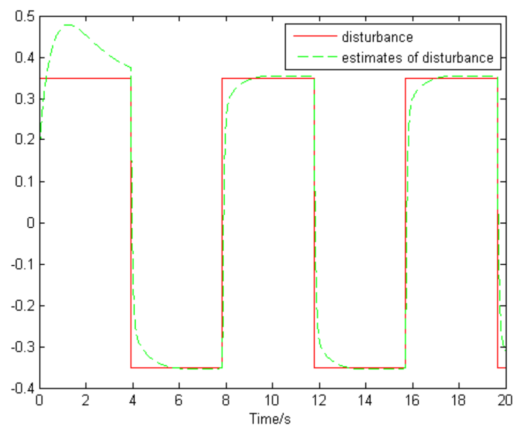

Fig. 6. The disturbances and output of the DOB

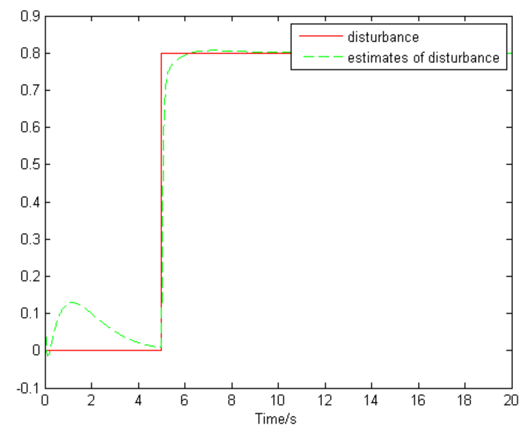

Fig. 9. The disturbances and output of the DOB

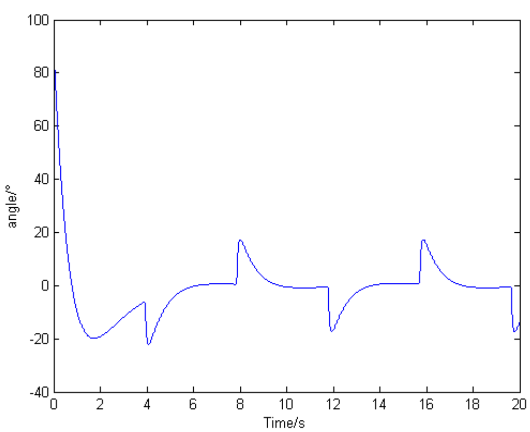

Fig. 7. The fin angle

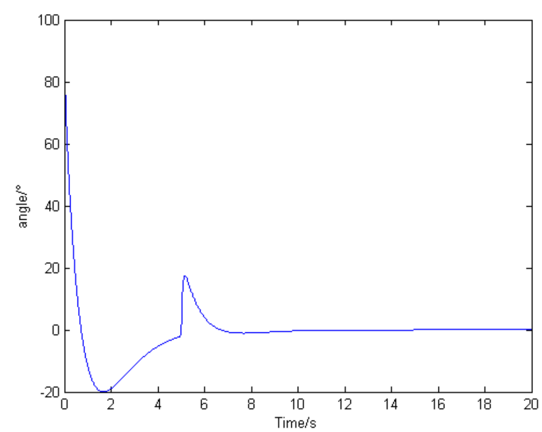

Fig. 10. The fin angle.

The disturbance is chosen as step signal.

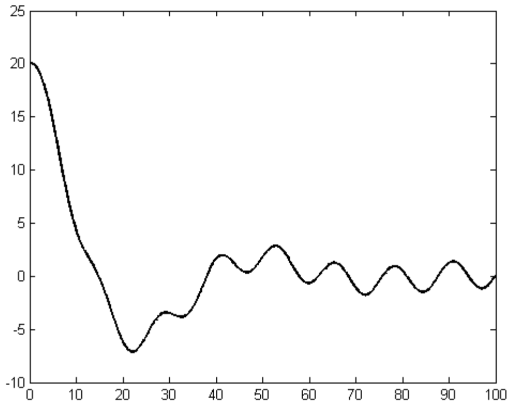

Fig. 11. Ship rolling angle.

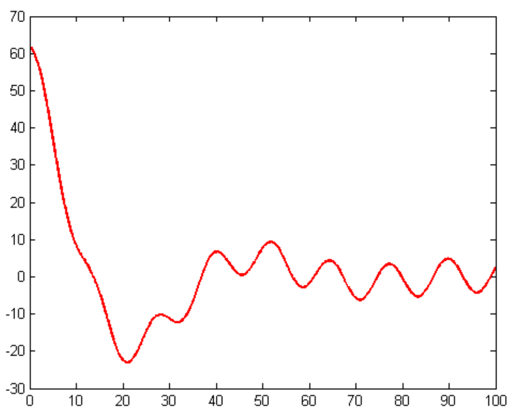

Fig. 12. The fin angle.

The Fig.11 and Fig.12 are the results of the neural network control scheme and the disturbance chosen as $d = 0.35\sin(0.8t)$. According to the results of Fig.2, Fig.5, Fig.8, the proposed controller in this paper can reduce the rolling motion effectively. The anti-rolling control performs better than the neural network control according to Fig.11. Fig.3, Fig.6, Fig.9, indicating that the DOB can provide high-level estimation of the disturbance in the system and the rapid time varying disturbances can also be estimated very well. It can be seen from the Fig.4, Fig.7 and Fig.10 that the response time of the controller designed in this paper is merely close to 2s, while the neural network control requires almost 10s in Fig.12. It is concluded that the average response time is greatly decreased by the DOB. The steady control input of the fin stabilizer system is almost 5 degrees according to Fig.4, which is smaller than its counterpart of the neural network control illustrated in Fig.12. Therefore, the crews on board may enjoy better comfort. Furthermore, the safety of the ship will be guaranteed and the energy cost will be lowered during the voyage.

V. Conclusion

In this paper, an adaptive backstepping control scheme is proposed for uncertain nonlinear fin stabilizer system, and the nonlinear DOB is designed to estimate the disturbance of the system. The proposed scheme can solve the problems of unknown parameters and unknown disturbance with the guarantee of better anti-rolling effectiveness and robustness. All the signals in the closed loop of the nonlinear fin stabilizer system are guaranteed to be uniform ultimate boundedness in the sense of Lyapunov stability. The simulation shows that good tracking performance and robust control can be obtained by means of the proposed algorithm.

References

[1] Y. Zhang, W. Shi and L. Yin, "Adaptive backstepping and sliding model control of fin stabilizer based on the RBF neural network," *Proceedings-Electric Power Applications*, vol.149, no.3, 2002, pp. 184-194.

[2] H. Jin, Y. Gu, B. Wang, X. Hou, "Variable parameters PID controller design of fin stabilizer," *SHIP ENGINEERING*, no3, 1994, pp. 55-60.

[3] S. Surendran, S.K. Lee, S.Y. Kim, "Studies on an algorithm to control the roll motion using active fins," *Ocean Engineering*, vol. 34, no. 3-4, 2007, pp. 542-551.

[4] Hui Li, Hongzhang Jin, Chen Guo, "PID control based on wavelet neural network identification and tuning and its application to fin stabilizer," *Proceedings of the IEEE International Conference on Mechatronics & Automation*, 2005, pp. 1907-1911.

[5] X. Zhang, H. Jin, H. Zhang, G. Li, M. Ji. Robust, "Sliding Mode Control for a Class of Uncertain Nonlinear Singularly Perturbed Systems," *Proceedings of the 41st SICE Annual Conference,* vol. 4, 2002, pp. 2616-2621.

[6] H. Jin, Y. Luo, Z. Wang, "Design of Sliding Mode Variable Structure Controller for Electric Servo System of Fin Stabilizer," *Intelligent Control and Automation,* 2006, pp. 2086-2090.

[7] T. Perez, "Constrained predictive control of ship fin stabilizers to prevent dynamic stall," *Control Engineering Practice,* vol. 16, 2008, pp. 482–494.

[8] Safak C. Karakas, M. Sc., "Control design of fin roll stabilization in beam seas based on Lyapunov's direct method," *POLISH MARITIME RESEARCH,* vol. 19, no. 2, 2012, pp. 25-30.

[9] Wen S., Zeng Z., Huang T., "H∞ Filtering for Neutral Systems With Mixed Delays and Multiplicative Noises;" *IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—II: EXPRESS BRIEFS*, vol.59, no. 11, 2012, pp. 820-824.

[10] N.A. Hickey, M.J. Grimble, M.A. Johnson, M.R. Katebi, and R. Melville, "Robust fin roll stabilisation of surface ships," *Decision and Control, 1997, Proceedings of the 36th IEEE Conference*, vol. 5, 1997, pp. 4225-4230.

[11] Fuat Alarçïn, "Internal model control using neural network for ship roll stabilization," *Journal of Marine Science and Technology*, vol. 15, no. 2, 2007, pp. 141-147.

[12] T. Z. Kang, D. Luo, X. Yan, Y. Niu, "The Study of Neural Network Control System of the Fin Stabilizer," *SHIP EGINEERING*, vol.34, no. 2, 2012, pp. 278-301.

[13] W. Bai, T. Li, X. Gao, K. Myint, "Neural Network Based Direct Adaptive Backstepping Method for Fin Stabilizer System," *10th International Symposium on Neural Networks*, 2013, pp. 212-219.

[14] P. Yu, S. Liu, "Nonlinear Auto-disturbance Rejection Controller for Fin Stabilizer System," *Journal of Harbin Engineering University,* vol. 23, no. 5, 2002, pp. 7-11.

[15] H. Shim, Y. Joo, "State space analysis of disturbance observer and a robust stability condition," *IEEE Conf. Decision Control*, 2007, pp. 2193-2198.

[16] J. Back, H. Shim, "Adding robustness to nominal output feedback controllers for uncertain nonlinear version of disturbance observer," *Automatica*, vol. 44, no. 10, 2008, pp. 2528-2537.

[17] A.Nikoobin, R.Haghighi. Lyapunov, “Based Nonlinear Disterbance Observer for Serial n-Link Robot Manipulator,” *Journal of Intelligent and Robotic Systems,* vol. 55, 2009, pp. 135-153.

[18] Y. Zhang, W. Shi, M. Qiu, “Sliding backstepping control for fin stabilizer with nonlinear disturbance observer,” *Control and Decision,* vol. 25, no. 8, 2010, pp. 1255-1260.

[19] T. Piraisoodi, S. Sadhu, “Characteristic analysis of high order disturbance observer,” *IEEE INDICON,* 2005, pp. 431-436.

[20] Khac Duc Do, Jie Pan, “Nonlinear robust fin roll stabilization of surface ships using neural networks,” *Decision and Control, 2001. Proceedings of the 40th IEEE Conference*, vol. 3, 2001, pp. 2726-2731.

[21] Y.S. Yang, X.L. Jia, “Robust control and application of uncertain system,” *Dalian: Dalian Maritime University Press,* vol. 15, no. 7, 2003, pp. 1057-1059.

[22] Qu, Z., “Robust Control of Nonlinear Uncertain Systems,’’ *New York:Wiley*, 1998.

[23] W. Chen, D. Ballance, “A nonlinear Disturbance Observer for Robotic Manipulators,” *IEEE Trans on Industrial Electronics,* vol. 47, no. 4, 2000, pp. 932-938.

[24] T. Mita, M. Hirata, K. Murata, H. Zhan, “H-infinity control versus disturbance-observer-based control,” *IEEE Trans. Ind. Electron*, vol. 45, no. 3, 1998, pp. 488-495.

[25] Reza Ghaemi, Jing Sun and Ilya V. Kolmanovsky, “Robust Control of Ship Fin Stabilizers Subject to Disturbances and Constraints,” *American Control Conference,* 2009, pp. 537-542.