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Abstract. The control of Unmanned Surface Vessel (USV) has been a hot topic recently years. To guarantee the good tracking properties and robustness of USV, exterior disturbance and inner uncertainty should be considered in the controller design. Exterior disturbance includes wind and wave forces, while inner uncertainty includes the variation of physical parameters and unmodelled parts of USV. Considering the external disturbance, the nonlinear model of USV is established based on Abkowitz model. Then the wave compensation is proposed for large exterior disturbance, and an adaptive sliding mode controller with disturbance estimation is designed for all uncertain disturbances. The method can estimate the uncertainty and adjust the controller gains by adaptive law. Next, the stability of the system is verified by Lyapunov theory. Finally, simulation results demonstrate the effectiveness of the proposed control approach.

Keywords: USV, heading control, environmental disturbance, adaptive sliding mode control

1 Introduction

In recent years, the studies on USV have attracted wide attention all over the world due to its small size, flexibility, intelligence, and modular advantages. With the continuous progress of science and technology, the research on USV has increased rapidly [1-2], and the application field is more and more extensive in diversified forms and intelligent control.

The heading control under the disturbance of wind and wave is the core problem of USV control, which has become the research hotspot of scholars at home and abroad. The most common control methods now are fuzzy control, predictive control and robust control. Aicardi et al. in [3] first based on the polar coordinate transformation and designed a path tracking controller when the direction of flow disturbance is known. However, it only considers the kinematic model of the ship, not the dynamic model. The line of sight (LOS) method proposed by Oh et al. in [4] used predictive control to design the control input of rudder angle. It does not consider the closed-loop control of longitudinal velocity, external disturbance and parameter perturbation. Zhang et al. in [5] transformed the mathematical model of the underactuated ship, and then proposes a sliding mode control method which has invariability to the external disturbance. Liang et al. studied the trajectory control of autonomous underwater vehicle in [6]. The controller is designed based on the idea of sliding mode control and backstepping control, and the fuzzy logic theory is used to approximate the unknown system function. Qin et al. in [7] estimated the speed by designing an observer. He proposed an improved guidance law to transform the underactuated control problem into the fully actuated control problem. But the control system is semi globally exponentially stable. Mu et al. studied the control of podded USV in [8]. He proposed a nonsingular terminal sliding mode (FNTSM) control method based on the separated ship model. The system can reduce the chattering phenomenon in the process of sliding mode control by introducing saturation function, and achieve fast convergence. Sun et al. relaxed the assumption of passive boundedness of rocking motion, and designed a new virtual control method based

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on backstepping in [9]. Ma et al. in [10] proposed an improved PID control method based on RBF neural network algorithm. By designing a predictive controller to predict and adjust the three parameters of PID, the parameters of PID can be obtained quickly.

These papers provided theoretical support for USV heading control, however with several areas for improvement. First of all, most of the studies are nonlinear control based on MMG model, which still have some limitations. However, environmental disturbances to USV have their own particularities, the above studies did not consider these particularities in the control process. They overcame large and small disturbances together with improved controller, so these methods usually require a lot of computation. Accordingly, this paper explores a new control idea. The main contributions include the following aspects:

(i) The mathematical model of USV is improved based on Abkowitz model. Combined with the force of the USV in the wind and wave environment, the control model is obtained through the calculation and nonlinear processing.

(ii) According to the different types of disturbances in USV's operation environment, the control schemes are designed respectively. Aiming at the large wave disturbance, the active compensation of wave is introduced through the prediction and estimation.

(iii) Aiming at the uncertain and unknown disturbance, an adaptive robust controller with disturbance estimation is designed. By introducing disturbance estimation, the uncertain part of the control system can be estimated in real time. Then an adaptive parameter adjusting law is designed to adjust the parameters of the controller online.

Finally, the performance of the proposed method is tested by simulation. The adaptive sliding mode controller can improve the convergence speed of the system and enhance the robustness and applicability of the system.

2 Mathematical model of USV in wind and wave environment

The motion equation of the USV is shown as follows:

$$\begin{cases} m(\dot{u} - vr - x_g r^2) = X, \\ m(\dot{v} - ur - x_g \dot{r}) = Y, \\ I_{ZZ}\dot{r} + m x_g(\dot{v} + ur) = N, \end{cases} \tag{1}$$

where m is the mass of the USV. u is the forward velocity. v is the roll velocity and r is the angular velocity. x_g is the distance between the center of gravity and the center of the ship. I_{zz} is the torque of inertia on the Z-axis. X, Y, N respectively represent the nonlinear forces (torque) along the axis X, Y and Z. The forces (torque) include hydrodynamic force (torque), thrust force (torque) and wind force (torque).

After linearization, the Abkowitz model of USV motion can be obtained [11] as follows:

$$\begin{cases} (m - X_{\dot{u}})\dot{u} = X_u \Delta u, \\ (m - Y_{\dot{v}})\dot{v} + (m x_g - Y_{\dot{r}})\dot{r} = Y_v v + (Y_r - mu)r + \tau_Y, \\ (m x_g - N_{\dot{v}})\dot{v} + (I_{zz} - N_{\dot{r}})\dot{r} = N_v v + (N_r - m x_g u)r + \tau_N, \end{cases} \tag{2}$$

where, $X_{\dot{u}}, X_u, Y_{\dot{v}}, Y_{\dot{r}}, Y_v, Y_r, N_{\dot{v}}, N_v, N_r$ are the hydrodynamic parameters that can be obtained by experiment. τ_Y and τ_N are the control force and torque, which are provided by the thrust of USV. When the deflection angle δ is positive to the left, the USV will produce a positive angular velocity r. The value of a range from $-35°$ to $35°$ and is about $(-0.61 \sim 0.61)\,rad$. So, when the speed of the propulsion motor is kept constant, there are:

$$\begin{cases} \tau_Y = F \sin\delta \\ \tau_N = FL \sin\delta \end{cases} \approx \begin{cases} \tau_Y = F\delta, \\ \tau_N = FL\delta, \end{cases} \tag{3}$$

where, δ is the deflection angle, F is the thrust, L is the longitudinal distance from the center line to the middle of USV.

Equation (2) only considers the hydrodynamic force, the wind force, and the control force. In fact, the disturbance of waves fails to be ignored during the operation of USV. The disturbance of waves to ship is recorded as wave force vector F_W, so the wave disturbance forces (torque) on the X, Y and Z axes are X_W, Y_W, N_W.

The wave disturbance forces (torque) are substituted into the model of equation (2). When only the motion of USV in pitch and yaw are considered, the motion equation in wind and wave environment is as follows:

$$\begin{cases} (m - Y_{\dot{v}})\dot{v} + (mx_g - Y_{\dot{r}})\dot{r} - Y_v v - (Y_r - mu)r = \tau_Y + Y_W. \\ (mx_g - N_{\dot{v}})\dot{v} + (I_{zz} - N_{\dot{r}})\dot{r} - N_v v - (N_r - mx_g u)r = \tau_N + N_W. \end{cases} \tag{4}$$

Through the transformation of the above equation, $\dot{v}$ and v are eliminated by simplification. Finally, an improved K-T model about the control force τ_Y and angular velocity r with wave disturbance force term is obtained as follows:

$$T_1 T_2 \ddot{r} + (T_1 + T_2)\dot{r} + r = K T_3 \dot{\tau}_Y + K\tau_Y + W, \tag{5}$$

where T_1, T_2, T_3, K are the operability indexes, and there are:

$$T_1 T_2 = \frac{(m - Y_{\dot{v}})(I_{zz} - N_{\dot{r}}) - (mx_g - Y_{\dot{r}})(mx_g - N_{\dot{v}})}{-Y_r(N_r - mx_g u) - N_v(Y_r - mu)}, \tag{6}$$

$$T_1 + T_2 = \frac{(Y_r - mu)(mx_g - N_{\dot{v}}) - Y_v(I_{zz} - N_{\dot{r}})}{-Y_r(N_r - mx_g u) - N_v(Y_r - mu)} + \frac{N_v(mx_g - Y_{\dot{r}}) - (m - Y_{\dot{v}})(N_r - mx_g u)}{-Y_r(N_r - mx_g u) - N_v(Y_r - mu)}, \tag{7}$$

$$K = \frac{N_v + L Y_v}{Y_r(N_r - mx_g u) + N_v(Y_r - mu)}, \tag{8}$$

$$T_3 = \frac{(mx_g - N_{\dot{v}}) + L(m - Y_{\dot{v}})}{N_v + L Y_v}, \tag{9}$$

$$W = \frac{\dot{N}_W(m - Y_{\dot{v}}) - \dot{Y}_W(mx_g - N_{\dot{v}}) - N_W Y_v + Y_W N_v}{-Y_r(N_r - mx_g u) - N_v(Y_r - mu)}. \tag{10}$$

It can be seen that the influence of waves is directly added to the force analysis in the form of a disturbance force. Then by involving it in the derivation of the model, a maneuvering response model containing the wave disturbance term W is finally constructed.

Since the wave disturbance forces (torque) are positively correlated with the wave height a [12], the forces (torque) can be expressed as follows:

$$\begin{cases} X_{WD} = 0.5\rho g L a^2 \bar{X}_W, \\ Y_{WD} = 0.5\rho g L a^2 \bar{Y}_W, \\ N_{WD} = 0.5\rho g L^2 a^2 \bar{N}_W, \end{cases} \tag{11}$$

where ρ is the density of water and L is the captain. $\bar{X}_W, \bar{Y}_W, \bar{N}_W$ are the disturbance force coefficients which are finally determined according to the sea conditions. Substitute equation (11) into equation (10), it can be concluded that the wave disturbance on the ship is as follows:

$$W_D = \frac{\dot{N}_{WD}(m - Y_{\dot{v}}) - \dot{Y}_{WD}(mx_g - N_{\dot{v}}) - N_{WD} Y_v + Y_{WD} N_v}{-Y_r(N_r - mx_g u) - N_v(Y_r - mu)}. \tag{12}$$

When the rudder angle is large, the proportion of nonlinear high-order term of force (torque) in Taylor expansion will increase. Therefore, we introduce a nonlinear term to modify the model. $H(r)$ is a nonlinear function of r. Finally, the nonlinear model of USV in wind and wave environment is obtained as follows:

$$T_1 T_2 \ddot{r} + (T_1 + T_2)\dot{r} + H(r) = K T_3 \dot{\tau}_Y + K\tau_Y + W_D. \tag{13}$$

3 Design of heading controller

3.1 The control method of USV

As the heading environment of USV is more complex, various exterior disturbances and inner uncertainties should be considered in the controller design. Exterior disturbances include wave force and some other unknown external disturbances, while inner uncertainties include the variation of physical parameters and unmodeled parts. Among them, wave force is the main disturbance term, while other disturbances are all unknown uncontrollable disturbances. Therefore, this paper considers the different types of disturbance factors when designing the control method.

If the wave disturbance is overcome directly by the controller, it requires a higher requirement on the controller and will lead to a large amount of calculation. Therefore, the wave feedforward compensation is introduced in this paper, which can compensate the larger disturbance by prediction and estimation. The method can eliminate the influence of a large number of disturbances quickly and effectively, and improve the control accuracy of the system.

Then, an adaptive robust controller with disturbance estimation is designed for all unknown uncontrollable disturbances. Based on sliding mode control, disturbance estimation is introduced. Therefore, the uncertain part is estimated online without knowing the boundary of the disturbances. Then an adaptive parameter adjustment law is designed. The real-time adjustment of controller parameters improves the robustness of the system. The specific control method can be summarized as Fig. 1:

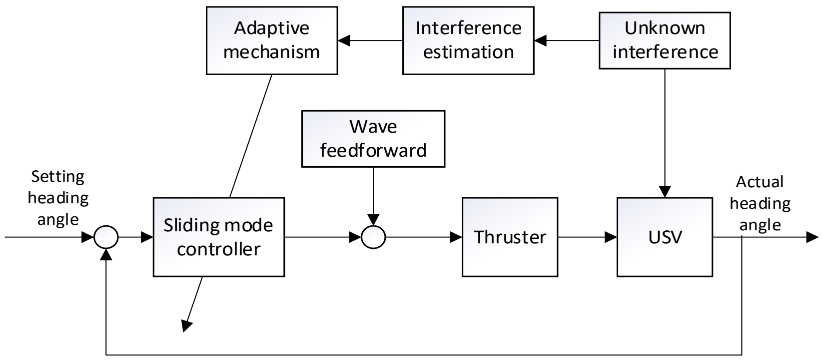

Fig. 1. Heading control structure of USV.

3.2 The heading control model of USV

To guarantee the good tracking properties of the ship, the wave disturbance forces can be calculated approximately according to equation (11). Then, the disturbance force can be eliminated directly by the control force of ship maneuvering.

Therefore, we redefine the control force τ_{YD} and torque τ_{ND} of the motor outputs, which are the force and torque needed to control the ship's course and counteract the disturbance of waves.

$$\begin{cases} \tau_{YD} = \tau_Y + Y_{WD}. \\ \tau_{ND} = \tau_N + N_{WD}. \end{cases} \tag{14}$$

Substituting the above equation into equation (13), the model with control force τ_{YD} as input and heading angle ψ as output is obtained by calculating. The equation is as follows:

$$T_1T_2 \dddot{\psi} + (T_1+T_2)\ddot{\psi} + H(\psi) = KT_3(\dot{\tau}_Y + \dot{Y}_D) + K(\tau_Y + Y_D) = KT_3\dot{\tau}_{YD} + K\tau_{YD}. \tag{15}$$

Therefore, the research of heading control is transformed into the research of motor output control force.

In order to improve the accuracy of the model description, we introduce an unknown disturbance $d(t)$. Moreover, considering the low frequency characteristics caused by the large inertia of the ship, we can reduce the order of the model in equation (15). Then, the operation coefficients of the model are reconfigured according to reference [13]. The final control model can be written as follows:

$$\ddot{\psi} = A\dot{\psi} - H(\dot{\psi}) + B\tau_{YD} + d, \tag{16}$$

where $A = -\frac{1}{T_1}, B = \frac{K}{T_1}$.

3.3 Design of adaptive sliding mode controller

$\psi(t)$ and $\dot{\psi}(t)$ are the measurable states. If the heading angle is set as $\psi_d(t)$, the heading deviation is then defined as:

$$e(t) = \psi(t) - \psi_d(t). \tag{17}$$

In order to get the second-order error system, the reference state $\bar{\psi}(t)$ is defined

$$\dot{\bar{\psi}}(t) = \ddot{\psi}_d(t) - K_1^* e(t) - K_2^* \dot{e}(t), \tag{18}$$

where K_1^* and K_2^* are the parameter variables that can be designed. But in order to satisfy the stability of the system, the parameters should be designed to satisfy certain conditions: the solution of the Helwitz polynomial $\left(s^2 + K_2^* s + K_1^* = 0\right)$ should have the negative real part.

Sliding mode control makes the sliding mode function converge to $s(t) = 0$ by the control law. When the error is accurately limited on the sliding surface, the change of the error is also limited on the sliding surface $s(t)$.

The sliding surface $s(t)$ is defined as follows:

$$s(t) = \dot{\psi}(t) - \bar{\psi}(t). \tag{19}$$

Take the derivative of equation (19).

$$\dot{s}(t) = \ddot{\psi}(t) - \dot{\bar{\psi}}(t) = \ddot{\psi}(t) - \ddot{\psi}_d(t) + K_1^* e(t) + K_2^* \dot{e}(t). \tag{20}$$

When $\dot{s}(t) = 0$, we can get the following result:

$$\ddot{\psi}(t) - \ddot{\psi}_d(t) + K_1^* e(t) + K_2^* \dot{e}(t) = \ddot{e}(t) + K_1^* e(t) + K_2^* \dot{e}(t) = 0. \tag{21}$$

Substitute equation (16) into equation (21), then,

$$A\dot{\psi}(t) - H(\dot{\psi}) + B\tau(t) + d(t) - \ddot{\psi}_d(t) + K_1^* e(t) + K_2^* \dot{e}(t) = 0. \tag{22}$$

Therefore, the control law can be designed as follows:

$$\tau_1(t) = \frac{1}{B}\left[-A\dot{\psi}(t) + H(\dot{\psi}) + \ddot{\psi}_d(t) - K_1^* e(t) - K_2^* \dot{e}(t)\right]. \tag{23}$$

In the traditional sliding mode control, $Ksgn(s)$ is designed to eliminate the disturbance of the system. In this system, the range of unknown disturbances fail to be obtained accurately. Therefore, this paper designs a robust sliding mode controller with disturbance estimation. We introduce a disturbance estimation term instead of $Ksgn(s)$ to compensate the unknown disturbance in the system.

By integrating $s(t)$, we can approximate the estimator $\hat{d}(t)$ of the unknown disturbance.

$$\hat{d}(t) = \alpha \int s(t)dt, \tag{24}$$

where α is constant coefficient.

At the same time, the error of disturbance estimation is defined as $e_2(t)$, then the error of disturbance estimation as follows:

$$e_2(t) = \hat{d}(t) - d(t). \tag{25}$$

The design of control law should make the change of error converge to the sliding surface, then,

$$B\tau_2(t) + \hat{d}(t) + \beta s(t) = 0. \tag{26}$$

The final controller is designed as follows:

$$\begin{aligned}\tau(t) &= \tau_1(t) + \tau_2(t) \\ &= \frac{1}{B}\left[-A\dot{\psi}(t) + H(\dot{\psi}) + \ddot{\psi}_d(t) - K_1^* e(t) - K_2^* \dot{e}(t) - \beta s(t) - \alpha \int s(t)dt\right].\end{aligned} \tag{27}$$

The controller shown in the above equation includes the PD control part. In order to obtain fine transient performance, the parameters of the controller can be adjusted online.

The PD control is shown as follows:

$$\tau_{PD}(t) = \frac{1}{B}\left[K_1 e(t) + K_2 \dot{e}(t)\right]. \tag{28}$$

where,

$$K_1 = K_1^* + \Delta K_1, \tag{29}$$

$$K_2 = K_2^* + \Delta K_2. \tag{30}$$

As K_1^* and K_2^* are the nominal values, we can get:

$$\Delta\dot{K}_1 = \dot{K}_1, \tag{31}$$

$$\Delta\dot{K}_2 = \dot{K}_2. \tag{32}$$

Then, the adaptive learning laws are designed to adjust the parameters K_1 and K_2 of the controller.

Theorem 1. *Let the adaptive learning rate be as follows:*

$$\dot{K}_1 = -\lambda_1 s e, \tag{33}$$

$$\dot{K}_2 = -\lambda_2 s \dot{e}, \tag{34}$$

where, λ_1 and λ_2 are the learning rates, and $\lambda_1 > 0, \lambda_2 > 0$. Then the closed-loop system is stable. □

3.4 System stability analysis

Proof. Take the Lyapunov function in the adaptive sliding mode control as follows:

$$V = \frac{1}{2}s^2 + \frac{1}{2}\alpha^{-1}e_2^2 + \frac{1}{2}\lambda_1^{-1}\Delta {K_1}^2 + \frac{1}{2}\lambda_2^{-1}\Delta {K_2}^2. \tag{35}$$

The derivation of V is as follows:

$$\begin{aligned}\dot{V} &= s\dot{s} + \alpha^{-1}e_2\dot{e}_2 + \lambda_1^{-1}\Delta K_1 \Delta\dot{K}_1 + \lambda_2^{-1}\Delta K_2 \Delta\dot{K}_2 \\ &= s\dot{s} + \alpha^{-1}e_2\dot{e}_2 + \lambda_1^{-1}\Delta K_1 \dot{K}_1 + \lambda_2^{-1}\Delta K_2 \dot{K}_2.\end{aligned} \tag{36}$$

Then,

$$\begin{aligned}\dot{s}(t) &= \ddot{\psi}(t) - \ddot{\psi}_d(t) + K_1 e + K_2 \dot{e} \\ &= \ddot{\psi}(t) - \ddot{\psi}_d(t) + (K_1^* + \Delta K_1)e + (K_2^* + \Delta K_2)\dot{e}.\end{aligned} \tag{37}$$

By substituting equation (37) into equation (36), we can get:

$$\begin{aligned}\dot{V} &= s(\ddot{\psi} - \ddot{\psi}_d + K_1^* e + \Delta K_1 e + K_2^* \dot{e} + \Delta K_2 \dot{e}) + \alpha^{-1} e_2 \dot{e}_2 + \lambda_1^{-1} \Delta K_1 \dot{K}_1 + \lambda_2^{-1} \Delta K_2 \dot{K}_2 \\ &= s\left(A\dot{\psi} - H(\dot{\psi}) + B\tau + d - \ddot{\psi}_d + K_1^* e + \Delta K_1 e + K_2^* \dot{e} + \Delta K_2 \dot{e}\right) + \alpha^{-1} e_2 \dot{e}_2 \\ &+ \lambda_1^{-1} \Delta K_1 \dot{K}_1 + \lambda_2^{-1} \Delta K_2 \dot{K}_2 \\ &= s\left(\Delta K_1 e + \Delta K_2 \dot{e} - \beta s - \alpha \int s dt + d\right) + \alpha^{-1} e_2 \left(\dot{\hat{d}} - \dot{d}\right) + \lambda_1^{-1} \Delta K_1 \dot{K}_1 + \lambda_2^{-1} \Delta K_2 \dot{K}_2 \\ &= s\left(-\beta s - \alpha \int s dt + d\right) + \alpha^{-1} e_2 \dot{\hat{d}} - \alpha^{-1} e_2 \dot{d} + \Delta K_1 (es + \lambda_1^{-1} \dot{K}_1) + \Delta K_2 (\dot{e}s + \lambda_2^{-1} \dot{K}_2).\end{aligned} \tag{38}$$

Substitute equation (33) and equation (34) into equation (38). Finally, the results are as follows:

$$\begin{aligned}\dot{V} &= s\left(-\beta s - \alpha \int s dt + d\right) + \alpha^{-1} e_2 \dot{\hat{d}} - \alpha^{-1} e_2 \dot{d} \\ &= -\beta s^2 - s e_2 + e_2 s - \alpha^{-1} e_2 \dot{d} \\ &= -\beta s^2 - \alpha^{-1} e_2 \dot{d}.\end{aligned} \tag{39}$$

The system has eliminated most of the interference through wave compensation. Therefore, the unknown disturbance of the ship is small and changes slowly. Then,

$$\dot{d}(t) \approx 0. \tag{40}$$

Therefore, the result is as follows:

$$\dot{V} = -\beta s^2 < 0 \tag{41}$$

It can be seen that when $t \to \infty$, $s \to 0$. From equation (18) and equation (19), we can know that when $s \to 0$, the error $e \to 0$. Therefore, the system is asymptotically stable. Therefore, the system is asymptotically stable.

4 Simulation

The model is taking form the "iNav-II" USV of Wuhan university of technology [14] as an example. It is a speedboat with a design total length of 3.96m, a design width of 1.55m, a draft of 0.3m-0.5m and a full load displacement of 0.708t.

This paper sets the heading angle of the system as $\psi = 0.5rad$ (about 29°). Then performed system simulations at sea level 3 and 4 respectively and observe the responses of the system. The wave height is 0.5m-1.25m under level 3 sea condition. At this time, the wave is small, but the waveform is significant, which can make the ship shake. The wave height is 1.25m-2.5m under level 4 sea condition. The wave has obvious shape and can make the ship move distinctly. The initial value of K_1 is set to 4, and the initial value of K_2 is set to 3. The response results are shown in Figs. 2-3.

Then we set the heading angle of the system as periodic change and simulate the system when the sea condition is level 3. The response results are shown in Figs. 4. During the control process, the controller gains are adjusted online, and the parameters adjustment process are shown in Fig. 5.

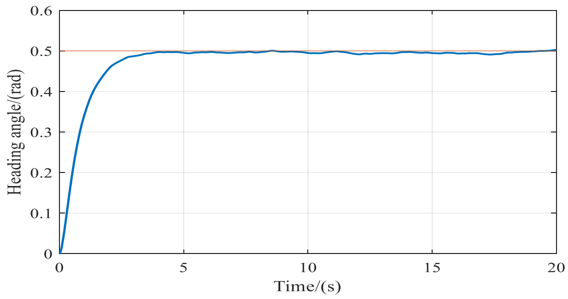

Fig. 2. System response at $\psi = 0.5rad$ in Level 3 sea state.

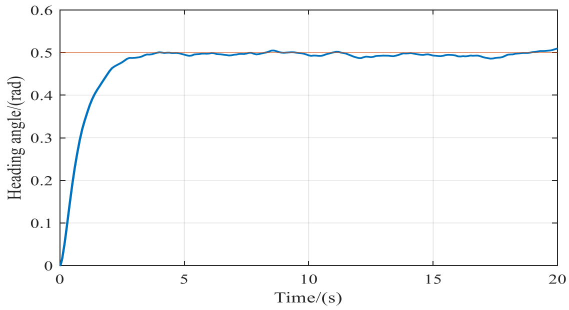

Fig. 3. System response at $\psi = 0.5rad$ in level 4 sea state.

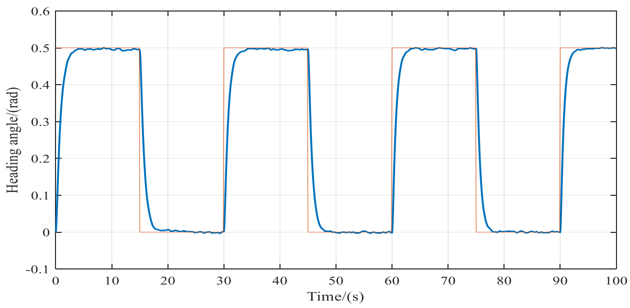

Fig. 4. System response when ψ changes periodically under level 3 sea state.

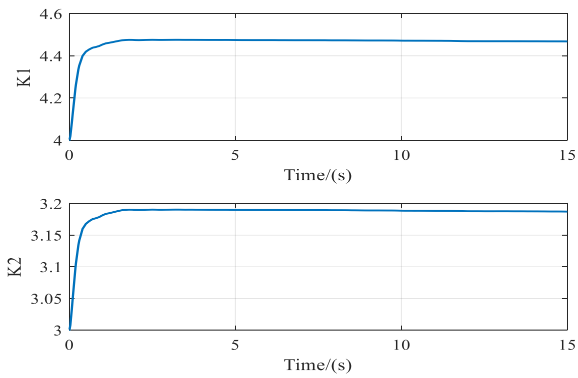

Fig. 5. The changing process of control gain K_1 and K_2

From the simulation results, it can be seen that the control system designed in this paper can ensure the USV to track the desired course accurately. As can be seen from Fig. 2 and Fig. 4, the whole control process is relatively stable under general sea state. Under the action of the adaptive rate, the control parameters of the system can promptly achieve the optimal control effect. Therefore, the system can quickly stabilize to the set heading angle and achieve good tracking effect. Fig. 3 shows the response of the system under large sea state perturbations. It can be seen that the output fluctuates to a lesser extent, and the large environmental disturbance fails to have a distinct effect on the heading control of the USV. The system can still achieve fast and accurate course tracking.

5 Conclusions

In this paper, we concentrate on the heading control of USV in wind and wave environment. First, we construct the nonlinear model including wave disturbance term and transform the heading control into the control of motor output force. Then we design an adaptive sliding mode controller with disturbance estimation, which can adjust the parameters of the controller online to achieve accurate heading control. The simulation results show that the proposed method is effective and the controller is robust and applicable.

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