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Steering Controller Design for Smart Autonomous Surface Vessel Based on CSF L2 Gain Robust Strategy

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ABSTRACT During the mission at sea, the yaw motion of the smart autonomous surface vessel (SASV) is always subject to the external disturbances. These issues make the design of a robust controller for steering autopilot system a quite challenging task. This paper focuses on the utilization of closed-loop shaping filter (CSF) to improve the SASV steering L2 gain robust control scheme. First, the mathematical model of the SASV is proposed and the parameters of the SASV model are obtained by the recursive least squares method (RLSM) based on the SASV turning test. Then the CSF L2 gain nonlinear robust controller design for SASV steering autopilot is described, and the stability and robustness of the proposed controller are proved based on the Lyapunov synthesis. Finally, the strong robustness and superior control performance are demonstrated through the practical SASV experiments. At the same time, the concise controller structure and definite physical meaning of SASV controller parameters are also concluded.

INDEX TERMS Smart autonomous surface vessel (SASV), ship model identification, closed-loop shaping filter (CSF), recursive least squares method (RLSM), L2 gain robust control.

I. INTRODUCTION

Due to the uncertainty of wind, wave, current and so on, a ship always presents a nonlinear motion. To design an adaptive and robust steering controller for the ship steering yaw control system is not an easy work, and it has received enormous amount of attention from many researchers. Robustness of the steering control system is the first thing to be considered. Many studies of robust steering controller have been proposed. Movahhed et al proposed an adaptive sliding mode control law for an underactuated autonomous surface vessel steering control [1]. Alfi et al presented a robust H_∞ steering controller for a container ship against modeling uncertainties and external disturbances [2]. Zhang developed a nonlinear closed loop robust control strategy for steering controller design by using a sine function [3]. Li described the design steps of a robust QFT ship autopilot for the course-keeping and course-changing control in the presence of disturbances [4]. Li proposed a robust steering controller with sliding mode to improve the performance of the closed-loop system and deal with the steering saturation constraints [5]. Lei proposed an ADRC-based cascaded integrator predictor scheme for ship steering system with uncertain time delay [6]. Fossen and Lauvdal designed a globally convergent adaptive robust ship autopilot by using a stable minimum phase transfer function from rudder angle to yaw angle [7]. Rigatos and Tzafestas proposed an adaptive fuzzy H_∞ steering controller, which aims to decrease the influence of the modeling errors and the external disturbances [8]. Yang proposed an adaptive fuzzy robust tracking control algorithm for a class of nonlinear systems with the uncertain system function and uncertain gain function [9]. In addition to the above research, there are other studies of robust steering controller below. Das proposed a control strategy based on Backstepping technique to enhance the robustness of ship steering controller with the uncertainty and disturbance estimator [10]. Wei presented an integrated direct-drive volume control electro-hydraulic servo system with the advantages of high efficiency and energy conservation [11]. Hu proposed a robust adaptive control scheme with the global asymptotic stability with respect to positioning errors for dynamic positioning of ships in the presence of time-varying unknown bounded environmental disturbances [12]. Fossen and Grovlen proposed an

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exponentially stable nonlinear robust steering controller based on the Backstepping design methodology and Lyapunov stability theory [13]. In recent years, with the development of computer information and the emergence of artificial intelligence, the application of intelligent algorithm has penetrated into the aspects of the ship steering control. Wang et al designed an intelligent steering autopilot based on radial basis function (RBF) neural network optimized by genetic algorithm [14]. Tung investigated feedback propagation multilayered architecture of artificial neural network to approximate the inverse model of the ship, so the steering autopilot just acted as an optimization of the artificial neural network training data [15]. Yuan adopted networks to determine the parameters of the unknown part of ideal virtual backstepping control, even the weight values of neural network are updated by adaptive technique [16]. Wu utilized the fuzzy neural network to improve the ship steering Bang-Bang controller design [17]. Liu developed a new nonlinear course keeping controller based on RBF neural network adaptive control for ship model uncertainty and the unknown control gain nonlinear ship course control problem [18]. McGookin studied an optimization of nonlinear control systems by genetic algorithm for the motion control of a ship [19]. Zhao performed the longitudinal nonlinear PID controller parameter optimization of general aircraft autopilot based on the longitudinal channel model and genetic algorithm [20]. Since the nonlinear control problem of ship steering automatic control is complicated by the unmodeled dynamics of nonlinearity, uncertainty and external environmental disturbances of ship motion model, there are some nonlinear steering controllers design methods to solve those problems. Lin developed a nonlinear adaptive fuzzy output feedback controller for dynamic positioning system of ships to maintain the ship at desired position and heading with arbitrary accuracy [21]. Lin proposed a novel PID-based nonlinear feedback algorithm based on a practical ship mathematic model (maneuvering modeling group model) driven by bipolar sigmoid function that was proposed with the advantages of robustness, energy saving and safety in berthing practice [22]. Zhang proposed an improved concise Backstepping controller based on Lyapunov candidate function by introducing different nonlinear functions of course error to replace the course error in the feedback [23], [24].

Based on the above observations, the combination of time domain robust controller design method (L2 gain robust control) and frequency domain control strategy (closed-loop shaping filtering control) was firstly reported under the Lyapunov stability theory. Moreover, the proposed L2 gain robust controller was applied to a practical SASV steering control system to verify the proposed idea of the paper.

II. MATHEMATICAL MODEL OF SHIP MOTION

A. MODEL INTRODUCTION

For the purpose of designing the SASV yaw steering controller, a second-order Nomoto mathematical model that was shown in equation (1) would be satisfactory [25].

$$T_1T_2\ddot{r} + (T_1 + T_2)\dot{r} + r = K\left(T_3\dot{\delta} + \delta\right) \tag{1}$$

where r represents the SASV yaw rate, δ is the SASV steering control angle, T_1, T_2, T_3 are the time constant of SASV maneuverability, and K is defined as the steering control gain constant of SASV maneuverability.

B. THE RESPONSE MODEL OF SASV

Let the steering control angle δ as the system input, and the SASV yaw angle ψ as the system output, and then the transfer function describing the steering to the yaw is given by

$$G_{\psi\delta}(s) = \psi(s)/\delta(s) = K(1 + T_3s)/s(1 + T_1s)(1 + T_2s) \tag{2}$$

Considering the SASV large inertia characteristics and the dynamics operation in the low frequency range, we can assume $s = j\omega \to 0$ in the above equation. Then the high order terms of Taylor series expansion for the equation (2) can be ignored, the simplified SASV steering to yaw motion model is shown as

$$G_{\psi\delta}(s) = K/s(Ts + 1) \tag{3}$$

where $T = T_1 + T_2 - T_3$.

C. THE NONLINEAR MATHEMATICAL MODEL OF SASV

The differential equation of the second-order response model as shown in equation (3) is

$$T\ddot{\psi} + \dot{\psi} = K\delta \tag{4}$$

The linear mathematical model is sufficient to describe the SASV steering-to-yaw motion when the yaw angle change is small. However, if the change of the yaw angle becomes larger, the equation (4) will not be satisfied any more, and should be modified [26]. Hence the SASV yaw rate term can be replaced by a nonlinear function $H\left(\dot{\psi}\right) = \dot{\psi} + \alpha\dot{\psi}^3$, the nonlinear mathematical model of SASV is obtained as

$$\ddot{\psi} + \alpha_1\dot{\psi} + \alpha_2\dot{\psi}^3 = \beta\delta \tag{5}$$

where α is the coefficient of nonlinear term, $\alpha_1 = 1/T, \alpha_2 = \alpha/T, \beta = K/T$. For a robust steering controller design, the generalized uncertainties $\Delta_1\left(\psi, \dot{\psi}, \delta\right)$ which may result from the parameter perturbation and some unmodelled dynamics should be considered. Moreover, the bounded external disturbances K_d induced by waves, winds and other environmental elements should also be considered in the controller design process. Hence the equation (5) can be described as equation (6) for robust steering controller design,

$$\ddot{\psi} + \alpha_1\dot{\psi} + \alpha_2\dot{\psi}^3 + \Delta_1 = \beta\delta + K_d \tag{6}$$

III. SASV PARAMETERS IDENTIFICATION

The identification of SASV dynamic parameters is described in this section including two subsections: (1) mathematical model discretization (MMD) and (2) parameters identification technique (PIT) based on recursive least squares method (RLSM) [27].

A. MMD OF SASV

In order to identify the parameters of SASV, the MMD of SASV mathematical model should be carried out firstly. Then the SASV discrete mathematical model can be obtained by using the explicit Euler mether from equation (5)

$$\psi(t+1) = \alpha_1\psi(t) + \alpha_2\psi^3(t) + \beta_1\delta(t-1) \tag{7}$$

where α_1, α_2 and β_1 are the SASV parameters to be identified. Then the SASV maneuverability indices K, T and model nonlinear coefficient α can be obtained by

$$\begin{cases} T = (\alpha_1 - 1)/\Delta t \\ K = \beta_1 T/\Delta t \\ \alpha = -\alpha_2 T/\Delta t \end{cases} \tag{8}$$

where Δt is sampling interval.

Let $Y(t) = \psi(t+1), \varphi(t) = \left[\psi(t), \psi^3(t), \delta(t-1)\right]^T$, $\theta(t) = [\alpha_1, \alpha_2, \beta_1]^T$, then equation (7) can be transformed into a RLSM regression model

$$Y(t) = \varphi^T(t)\theta(t) \tag{9}$$

B. PIT BASED ON RLSM

The RLSM algorithm is taken as the PIT to capture the dynamics of SASV maneuverability parameters due to its advantages of small calculation burden and easy to implement [28]. For equation (9), the process identified by the RLSM is

$$\begin{cases} \theta(t) = \theta(t-1) + P(t)\varphi(t)e(t) \\ e(t) = Y(t) - \varphi^T(t)\theta(t-1) \\ P^{-1}(t) = P^{-1}(t-1) + \varphi(t)\varphi^T(t) \end{cases} \tag{10}$$

where $\theta(t)$ is the estimated value of θ at time t. $P(t)$ is the covariance matrix. $P(t)\varphi(t)$ is the gain matrix for RLSM. $e(t)$ is the modifying innovation sequence of RLSM, and its value can be calculated by deviation between the SASV actual output yaw angle and the output estimates $\varphi^T(t)\theta(t-1)$ by using the previous time identification parameters. Therefore, the entire RLSM process for SASV PIT could be summarized as [28]:

(1) Assign the output vector $Y(t)$ and the information vector $\varphi(t)$ in equation (9) by using the ship maneuvering test data.

(2) Estimate the SASV parameters according to equation (10), and get the SASV parameter $\theta(t)$.

(3) Calculate the SASV maneuver parameters K, T and nonlinear coefficient α according to equation (8).

IV. SASV STEERING CONTROLLER DESIGN

For the mathematical model in equation (6), the Backstepping controller design method and the Lyapunov stability theory controller design was used to ensure the stability and robustness of the controller, and the concept of CSF in the classical closed-loop control theory is introduced. To increase the ability of the proposed controller suppressing external disturbance, the L2 gain robust control strategy is introduced by combining the frequency domain and time domain design concepts.

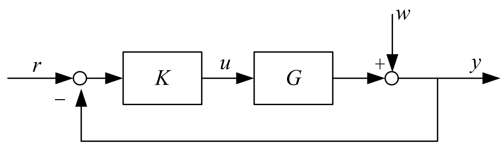

FIGURE 1. Diagram of closed loop shaping filter system.

A. FEEDBACK LINEARIZATION

Let the output of the system be $y = \psi$, and the output of command signal for ship yaw angle be $y_r = \psi_r$. According to the practical SASV steering control conditions, we can.assume $\dot{y}_r = \ddot{y}_r = 0$, and define the tracking error variable of the system as $e = \psi_r - \psi$. Then the control input δ can be defined as equation (11),

$$\delta = \left(\alpha_1\dot{\psi} + \alpha_2\dot{\psi}^3 + u_1\right)\Big/\beta \tag{11}$$

where u_1 is the virtual control variable to offset the generalized uncertainty $\Delta_1\left(\psi, \dot{\psi}, \delta\right)$ and the bounded external disturbance K_d. Finally, equation (6) can be rewritten as

$$\ddot{\psi} = u_1 - \Delta_1 + K_d \tag{12}$$

B. CLOSED LOOP SHAPING FILTER

In Figure 1, G and K are the transfer functions of the controlled plant and the closed-loop system controller respectively. w is the external disturbance of the system. The understanding of Figure 1 can be understood from two different views: controller design concept (understanding 1) and filter design concept (understanding 2):

Understanding 1: From the view of controller design, the main purpose of the controller K designed in the system of Figure. 1 is to make the output signal of the whole system y to track the input demanded signal r, which can be expressed as a transfer function $GK/(1+GK)$.

Understanding 2: From the view of filter, the controller K and the controlled plant G can be combined together to realize the output signal y tracking the target signal r under the action of the external disturbance w. That can be expressed as a transfer function $1/(1+GK)$.

Since $GK/(1+GK) + 1/(1+GK) = I$, it is observed that if the appropriate controller K is defined, the control problem of the system of Figure. 1 will be better solved (understanding 1). Meanwhile, the controller K can also better solve the filtering problem of the system shown in Figure 1 (understanding 2). Based on this idea, the following assumptions about the closed loop feedback control system can be defined as:

Hypothesis 1: The working frequency spectrum of the closed-loop system is low-pass, that is, the main work of the system is in the low-frequency region, and the high-frequency region is regarded as interference.

Hypothesis 2: The maximum singular value of the spectrum of the closed-loop system is set to 1, that is, the peak value of the spectrum of the system is 0. Then it can ensure the system is stable and track the reference signal without static error.

Hypothesis 3: The slope of the closed loop system spectrum can be set as −20dB/dec to suppress external disturbance.

Based on the assumptions above, in accordance with the understanding 1, the control performance of the entire closed-loop control system can be determined by the transfer function $T = GK/(GK+1)$. According to hypothesis 3, the entire closed-loop system can be described as a first-order low-frequency-pass filter $F(s)$.

$$F(s) = \frac{G(s)K(s)}{1+G(s)K(s)} = \frac{1}{\lambda s+1} \tag{13}$$

Therefore, it can be concluded that the performance of the entire closed-loop control system would be primarily determined by the bandwidth $1/\lambda$ of the closed-loop system. If the controlled plant of the closed-loop system is known, the controller K can be derived according to equation (14).

$$K(s) = \frac{1}{\lambda G(s)s} \tag{14}$$

Moreover, in combination with the understanding 1 and the understanding 2, it can be seen that the shaping filtering effect of the entire closed-loop system shown in Figure. 1 will be realized by the controller K described in equation (14).

For the ship steering control system, the transfer function of the controlled plant can be approximated as a second-order response model. In order to achieve the effect of closed-loop shaping filtering of the entire control system, the system feedback signal can be defined as

$$\eta = \frac{1}{\lambda_1}(\lambda_2 e + \dot{e}) \tag{15}$$

where $\lambda_1 = \lambda K/T$, $\lambda_2 = 1/T$, η is the system feedback signal, e is the system error signal.

Therefore, the system shaping filter can be realized by the introduction of equation (13), which can also simplify the process of the controller design. That is to say, the second-order equation (12) can be reduced to a first-order equation as

$$\lambda_1\dot{\eta} = \lambda_2\dot{e} - u_1 + \Delta_1 - K_d \tag{16}$$

Thus the entire steering to yaw motion control system can be described as a first-order equation (16) for the variable η and the virtual input u_1.

C. LYAPUNOV FUNCTION CONTROLLER DESIGN

Based on equation (12) and (16), the Lyapunov method is used to implement the controller design, and the Lyapunov function is defined as equation (17).

$$V_0 = \frac{1}{2}e^2 + \frac{1}{2}\lambda_1\eta^2 \tag{17}$$

Then the derivative of V_0 is

$$\dot{V}_0 = e\dot{e} + \eta\lambda_1\dot{\eta} = -\lambda_2 e^2 + \eta(\lambda_1 e + \lambda_2\dot{e} - u_1 + \Delta_1 - K_d) \tag{18}$$

D. CONTROLLER DESIGN BASED ON L2 GAIN ROBUST CONTROL SCHEME

In order to enable the proposed controller to suppress external disturbances K_d, the L2 gain robust performance function is defined as follows

$$\int_0^t \|E\|^2 \le \mu_1^2 \int_0^t K_d^2(\tau)\,d\tau + \mu_2 \tag{19}$$

where μ_1 and μ_2 are the small positive constants close to zero. In general, the smaller their values, the better to suppress external disturbances could be achieved and greater control torque is required. Considering that this paper mainly focuses on reducing the ship heading tracking error, the control performance evaluation variable E can be defined as $E = \begin{bmatrix} e & \dot{e} \end{bmatrix}$, then we can obtain

$$\begin{aligned}\|E\|^2 - \mu_1^2 K_d^2 &\equiv \frac{1}{4\mu_1^2}\eta^2 - \left(\frac{1}{2\mu_1}\eta + \mu_1 K_d\right)^2 + \|E\|^2 + \eta K_d \\ &\le \frac{1}{4\mu_1^2}\eta^2 + e^2 + (\lambda_1\eta - \lambda_2 e)^2 + \eta K_d \\ &= \frac{1}{4\mu_1^2}\eta^2 + e^2 + \lambda_1^2\eta^2 + \lambda_2^2 e^2 - 2\lambda_1\lambda_2\eta e + \eta K_d\end{aligned} \tag{20}$$

Combining equation (18) and (20), we can obtain

$$\begin{aligned}&\dot{V}_0 + \|E\|^2 - \mu_1^2 K_d^2 \le -\lambda_2 e^2 + \eta(\lambda_1 e + \lambda_2\dot{e} - u_1 + \Delta_1 - K_d) \\ &\quad + \frac{1}{4\mu_1^2}\eta^2 + e^2 + \lambda_1^2\eta^2 + \lambda_2^2 e^2 - 2\lambda_1\lambda_2\eta e + \eta K_d \\ &= \eta\left(\lambda_1 e + \lambda_2\dot{e} - 2\lambda_1\lambda_2 e - u_1 + \Delta_1 + \frac{1}{4\mu_1^2}\eta + \lambda_1^2\eta\right) \\ &\quad - \left(\lambda_2 - \lambda_2^2 - 1\right)e^2\end{aligned} \tag{21}$$

Then the virtual controller u_1 can be defined as

$$u_1 = \lambda_1 e + \lambda_2\dot{e} - 2\lambda_1\lambda_2 e + \frac{1}{4\mu_1^2}\eta + \lambda_1^2\eta - \lambda_1\eta - \frac{\rho_1^2}{|\eta|\rho_1 + \varepsilon_1}\eta \tag{22}$$

Assuming the system unmodelling error Δ_1 is bounded, and $|\Delta_1| \le \rho_1, \forall\rho_1 > 0$, then we can obtain

$$\dot{V}_0 + \|E\|^2 - \mu_1^2 K_d^2 \le -\left(\lambda_2 - \lambda_2^2 - 1\right)e^2 - \lambda_1\eta^2 + \varepsilon \tag{23}$$

where ε is positive number close to zero.

Let $a_0 = \min\left\{\left(\lambda_2 - \lambda_2^2 - 1\right), \lambda_1\right\}$, then inequality (23) can be simplified to

$$\dot{V}_0 + \|E\|^2 - \mu_1^2 K_d^2 \le -2a_0 V_0 + \varepsilon \tag{24}$$

Integrating inequality (24) from the initial state, we can get

$$\begin{aligned}V_0(t) + \int_0^t \|E\|^2 d\tau - \mu_1^2\int_0^t K_d^2 d\tau \le \frac{\varepsilon}{2a_0} \\ + \left(V_0(0) - \frac{\varepsilon}{2a_0}\right)\exp(-2a_0 t)\end{aligned} \tag{25}$$

TABLE 1. Particulars of the SAVA *BAICHUAN*.

Full Scale Data	Numerical Value
Length overall	145cm
Ship Breadth	35cm
Designed Draft	15cm
Molded volume	30kg
Block Coefficient	0.482
Rudder Area	31.68cm^2
Maximum Rudder Angle	25°
Rate Limitation	6.8°/s
Design Speed(V)	8m/s
Speed by rpm	16000

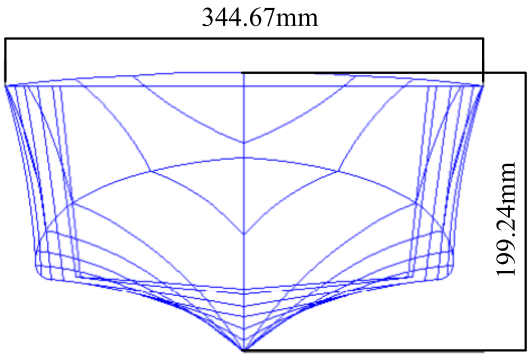

FIGURE 2. Body plan of the SAVA *BAICHUAN*.

Furthermore, it can be inferred that

$$\lim_{t\to\infty}\left(V_0(t)+\int_0^t \|E\|^2 d\tau-\mu_1^2\int_0^t K_d^2 d\tau-\frac{\varepsilon}{2a_0}\right)=0.$$

According to the definition of the Lyapunov function V_0, we can achieve $V_0(t)\geq \varepsilon/2a_0$. Therefore, it is proved that all the signals of entire closed-loop steering control system are semi-globally uniform and ultimately bounded, and the system error signal e,η could asymptotically converge to zero. Furthermore, we can obtain

$$\int_0^t \|E\|^2 d\tau-\mu_1^2\int_0^t K_d^2 d\tau\leq\varepsilon \tag{26}$$

Finally, it can be inferred that the proposed steering autopilot controller designed in this paper can satisfy the L2 gain robust performance index.

V. SAVA PIT AND CONTROL PERFORMANCE EXPERIMENT

In this part, a SASV *BAICHUAN* would be taken as an example for experiment. Its particulars and body plan are shown in table 1 and Figure 2 respectively. In order to verify the stability and effectiveness of the proposed steering control strategy in this paper, the experiment would contain two parts: (1) SASV PIT experiment based on RLSM and (2) steering controller performance test based on CSF L2 gain robust control strategy. The whole experiment was carried out in a relatively calm water condition as shown in Figure 3.

FIGURE 3. The scene of experiment.

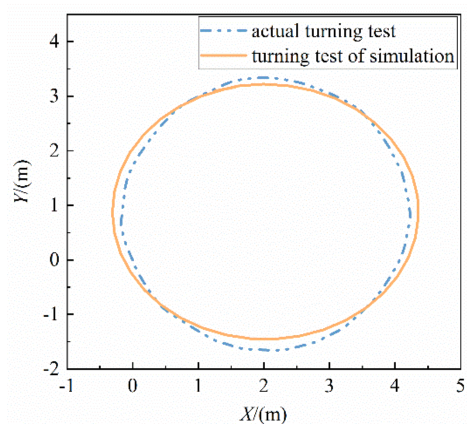

FIGURE 4. Comparison of SAVA turning test.

The GPS/GLONSS/BEIDOU signal was very strong at the scene of experiment. The wind direction of the day was southwest, and the wind velocity varied from 0.5-0.9 m/s. The temperature was about 12°C. The maximum wave height was about 0-0.15 m.

One of the most important indicators for identifying the SASV dynamic characteristics is the accuracy of the identification results. The PIT based on RLSM that described in part III would be utilized to identify ship dynamic parameters K, T and α. Furthermore, in order to verify the correctness of the PIT results, the turning simulation test based on a SAVA ship is carried out to compare with the actual tuning test. The comparison results of SAVA turning test is shown in Figure 4.

According to the SASV PIT based on RLSM, the dynamic parameters are obtained as shown in Figure 5, where $\alpha_1 = 1.0120$, $\alpha_2 = -1.012\times10^{-7}$, $\beta_1 = 0.0622$. Then the value of K and T can be calculated by equation (8). Due to the value of sample time (t) is 0.02, then we can get $K = 0.6$, $T = 1.866$, $\alpha = -9.44\times10^{-6}$.

As shown in Figure 4, a turning simulation test was implemented to compare with the SAVA actual turning test. In the simulation, the steering angle was set as 25°, the speed was set as 1.9m/s. It can be seen that, due to the influence of the ship lateral drift and wind direction, the actual turning curve is not a standard circle but is approximately an ellipse.

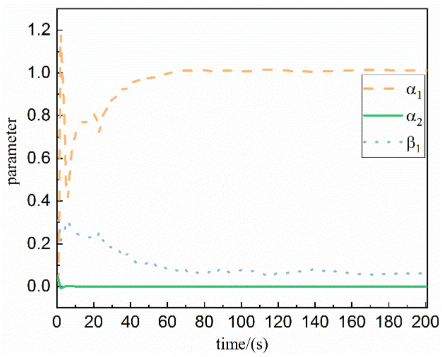

FIGURE 5. SASV dynamic parameters based on RLSM.

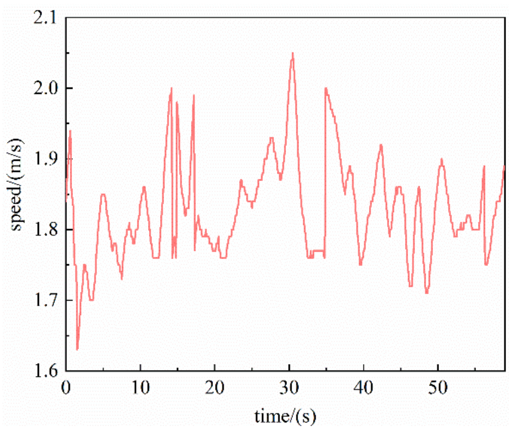

FIGURE 6. Speed variations of the SAVA in turning test.

When calculating the relative error of the diameter of the turning circle, we take the average diameter of the turning circle, where the maximum diameter is 5.06 m, the minimum diameter is 4.51 m and the average value is 4.79 m. The speed of SASV actual turning test is demonstrated in Figure 6, and the average speed in the turning test is about 1.893 m/s. Although the diameter of the simulation turning curve is 5.07 m, the conformity of the simulation and SASV actual turning test is about 94.5%. The error between simulation test and actual turning test is very small. That is to say, the results of the SASV parameter identification results based on RLSM are credible.

To verify the control performance of the proposed algorithm, the course keeping experiment were carried out under the SASV automatic navigation conditions. According to the proposed closed loop shaping filtering concept, the reciprocal of the steering control system bandwidth is set as $\lambda = 10$, then the tuning parameters of CSF L2 gain robust controller can be obtained as $\lambda_1 = 0.322, \lambda_2 = 1.866$. The other parameters of the proposed SASV steering controller can be selected as $\mu_1 = 60, \rho_1 = 0.001, \varepsilon_1 = 10$ according to the control performance requirements. In order to verify the effectiveness of the proposed CSF L2 gain robust controller, the standard PID controller, which is the most widely used steering controller in the fields of marine vessels control, is utilized for performance comparison. The description of PID controller is shown in equation (27),

$$\delta = K_p e + K_d \dot{e} + K_i \int edt \tag{27}$$

where, K_p, K_d, K_i were positive design parameters for PID steering controller and their values were set as 1.6, 0.5 and 0.2 respectively.

CASE 1: In the experiment of steering control, the initial heading of the SASV was set as 200° and the target heading was set as 270°. The SASV speed was set as 1.80 m/s. The results of the experiment are shown in Figure 7. It can be seen that the proposed CSF L2 gain robust steering controller and PID controller have a similar course-changing control performance. The rising time of the two controllers are both about 7 seconds, although the PID controller has a bigger overshoot.

After 10 seconds, the SASV course angle and rudder became smoother, and the SASV entered into course-keeping status. To quantify the course-keeping performance of the steering controller, the mean absolute course error (*MACE*) is

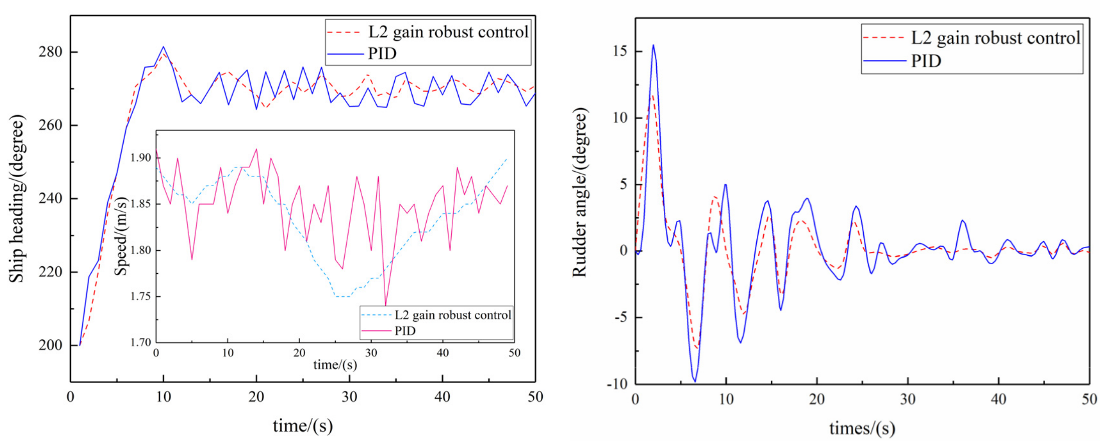

FIGURE 7. Experiment results (case one) of the SAVA course, speed and rudder control.

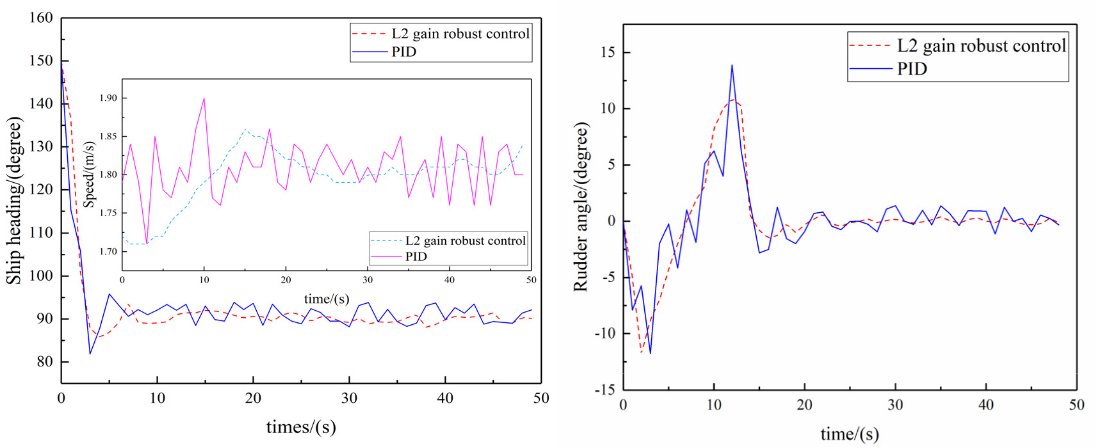

FIGURE 8. Experiment results (case two) of the SAVA course, speed and rudder control.

defined as the course-keeping error evaluation index. Moreover, the mean absolute rudder angle (*MARA*) is defined as the rudder control index to measure the control energy consumption. The calculation of the *MACE* and *MARA* can be carried out by equation (28),

$$MACE = \frac{1}{t_\infty - t_0}\int_{t_0}^{t_\infty} |e|dt$$
$$MARA = \frac{1}{t_\infty - t_0}\int_{t_0}^{t_\infty} |\delta|dt \quad (28)$$

Then we can get the MACE and MARA of the proposed CSF L2 gain robust steering controller are 2.12 and 0.72, and the MACE and MARA of the PID steering controller are 3.73 and 1.50. Furthermore, it is obvious that the proposed CSF L2 gain robust steering controller has a better course-keeping performance comparing with PID controller. The drastic change of the SASV speed induced by the ship course changing during the experiment should also be noted.

CASE 2: To further verify the proposed idea of this paper, another experiment was carried out. The initial heading of the SASV was set as 150° and the target heading was set as 90°. The SASV speed was also set as 1.80 m/s. The results of the experiment are shown in Figure 8. It can also be seen that the proposed CSF L2 gain robust steering controller and PID controller have a similar course-changing control performance. The rising time of the two controllers are both about 6 seconds, and the PID controller has a bigger overshoot. After 8 seconds, the SASV entered into course-keeping condition. Then we can calculate the *MACE* and *MARA* of the proposed CSF L2 gain robust steering controller are 1.91 and 0.93, and the MACE and MARA of the PID steering controller are 4.28 and 1.69. It is proved that the proposed steering controller has a satisfied course changing and keeping performance.

VI. CONCLUSION

In this paper, the SASV steering controller design for course changing and keeping was studied and a L2 gain robust control based on CSF concept is proposed. Conclusions of this study can be summarized as follows:

(1) The proposed L2 gain robust control based on CSF concept is a combination of the frequency domain robust strategy (CSF) and time domain robust control method L2 gain robust control. Taking the advantages of the above two methods, the steering controller design procedure is optimized and the SASV steering mechanism becomes more effectively.

(2) The stability of the proposed L2 gain robust control based on CSF concept can be guaranteed in the steering controller design process by using the Lyapunov stability theory, and the determined tuning parameters will be satisfied with the requirements of control performance.

(3) The SASV practical experiment for parameter identification based on RLSM and controller performance test were carried out, which confirmed the feasibility and potential application of the proposed idea of this paper.

This work cannot deal with every details of the control task, e.g., the relationship between SASV speed and steering control has not been explored, and this will be addressed in future research. Moreover, the SASV *BAICHUAN* equipped with the CSF L2 robust steering controller can be utilized as a platform for ship collision avoidance and other advanced vessel planning and control problems in the future work.

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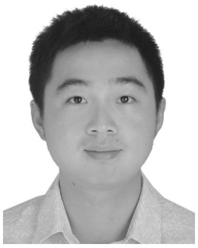

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