To cite this article: Zhao Z P, Zhang Q. Adaptive self-regulation PID tracking control for the ship course[J/OL]. Chinese Journal of Ship Research, 2019, 14(3). http://www.ship-research.com/CN/Y2019/V14/I3/145.

DOI:10.19693/j.issn.1673-3185.01305

Adaptive self-regulation PID tracking control for the ship course

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Abstract: [**Objectives**] For the ship-course nonlinear control system subject to time-varying environmental disturbances with parametric uncertainties, to achieve the real-time requirements for course control, [**Methods**] an adaptive self-regulation PID ship course tracking control scheme not depending on model parameters and unknown input is proposed by using adaptive technique. With Lyapunov direct method to verify the designed control law, it can guarantee all signals in the closed-loop system of course control are bounded. [**Results**] Simulation results show that the controller can adaptively regulate the gain of PID. It not only inherits the advantages of the traditional PID controller, but also has good robustness to unknown time-varying disturbances. [**Conclusions**] The study results can provide reference for the course tracking control design of ships.

Key words: ship course; tracking control; uncertainty; self-regulation PID; adaptive control

CLC number: U664.82

0 Introduction

As an effective, economic and environmentally friendly mode of transport, ships are an important support for international trade and national economy [1]. At present, ships are developing in the direction of large scale, automation and intelligence, and ship motion control is the key technology to realize the intelligent navigation of the ships, which will directly affect the safety, economy and comfort of the ships' maritime navigation. How to accurately and quickly adjust the ship course has become a research hotspot in the field of ship motion control [1-2].

Ships sailing on the sea will inevitably be affected by environmental factors such as wind, waves and currents, as well as the large inertia of the ship itself, large time lag, nonlinearity, etc., which makes the ship parameters uncertain and disturbed. Therefore, it is difficult to accurately control the tracking of ship course. With the development of intelligent unmanned merchant ship technology, the course control technology commonly used in marine ships also needs to be further extended to the field of manipulation within the port. At present, when the pilots get aboard or get ashore, the ship needs to maintain a stable attitude under a certain course[3]. When the ship is berthing, it is necessary to continuously adjust the berthing angle, which puts forward precise and multi-modal requirements for the tracking control of the course. In order to solve the above problems, control strategies such as PID[3-4], sliding mode[5-6], nonlinear feedback [7], adaptive backstepping [8-9] and adaptive neural network/fuzzy[10-12] can be used in the field of ships. It is worth noting that although the control method proposed in References[8-12] does not require an accurate calculation model, its inherent complexity will bring certain difficulties to engineering applications. In contrast, the PID control

Received: 2018 - 05 - 29

Supported by: Shandong Provincial Key Research and Development Program (2018GGX105014, 2018GGX105003); Scientific Research Program of Colleges and Universities in Shandong Province (J18KA010, J18KA043); Transportation Science and Technology Project of Shandong Province (2018B69)

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structure is simple, does not depend on accurate models, and has fewer adjustment parameters. But the traditional PID is less robust to external time-varying environmental disturbances, and it is difficult to reflect the advantages of PID control. To this end, the researchers have proposed a variety of PID control strategies, such as iterative sliding mode-PID[13] and integral compensation PID [14], both of which can improve the course control performance, but cannot resist the influence of time-varying disturbance. In addition, intelligent optimization algorithms can also be used to adjust the gain of PID, such as fuzzy logic [15], firefly swarm optimization[16], simulated annealing[17] and improved genetics[18]. However, the fuzzy logic method needs to set the fuzzy relationship in advance, and it does not have universal applicability. Firefly swarm optimization, simulated annealing and improved genetic algorithm are all offline optimization algorithms, and can not meet the real-time requirements of course control.

Based on this, this paper proposes a new adaptive self-regulation PID control strategy. Firstly, considering the unknown time-varying environmental disturbance and model parameters of a ship, the mathematical model of nonlinear ship motion is established. Then, the adaptive technology is used to design the adaptive control law with traditional PID structure, and the Lyapunov stability analysis method is used to verify the boundedness of the designed control law. In the end, the simulation experiments under the condition of unknown model parameters and time-varying disturbances are carried out to verify the effectiveness of the control strategy proposed in this paper.

1 Mathematical model

In the mathematical model of nonlinear ship motion, the relationship between rudder angle δ and course ψ is as follows [2]:

$$\ddot{\psi}+\frac{1}{T}F(\dot{\psi})=\frac{K}{T}\delta+\xi \tag{1}$$

Where $\dot{\psi}$ is heading rate; T and K are the ship maneuverability indexes, which are related to the ship type, loading and speed; $F(\dot{\psi})=a\dot{\psi}+b\dot{\psi}^3$ is a nonlinear function of $\dot{\psi}$, where a and b are proportionality coefficients; ξ is external unknown disturbance.

Assuming $x_1=\psi$, $x_2=\dot{\psi}=r$, $u=\delta$ and according to Eq. (1), there is

$$\dot{x}_1=x_2 \tag{2}$$

$$\dot{x}_2=\boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{f}(x_2)+\omega u+\xi \tag{3}$$

$$y=x_1 \tag{4}$$

Where $\boldsymbol{\theta}=\left[\frac{a}{T},\frac{b}{T}\right]^{\mathrm{T}}$; $\boldsymbol{f}(x_2)=[-x_2,-x_2^3]^{\mathrm{T}}$; $\omega=\frac{K}{T}$; u is the control law of the system; $y\in\mathbf{R}$ is the system output.

To simplify the calculation, this paper sets the following assumptions:

1) Assumption 1: the external environmental disturbance ξ is unknown, bounded, and satisfies $|\xi|\leqslant\Delta$, where the unknown constant Δ is the upper bound of the disturbance.

2) Assumption 2: the reference course y_{d} is smooth, and $\dot{y}_{\mathrm{d}}$ and $\ddot{y}_{\mathrm{d}}$ are valid values.

3) Assumption 3: model parameters $\boldsymbol{\theta}$ and ω are both unknown.

The control objective of this paper is to design a robust course tracking controller for the mathematical model of ship motion shown in Eq. (1) with considering its unknown time-varying environmental disturbance. Thus, the actual output course of the ship can track the expected course, and it can guarantee that all signals in the closed-loop control system are bounded.

2 Control design

For the nonlinear ship course control system, in view of the external environmental disturbance and the unknown model parameters, this paper will adopt adaptive technology and Lyapunov method to construct an adaptive control law with traditional PID standard form. And it can realize adaptive self-regulation parameters and high control accuracy for ship course tracking under the condition of external disturbance and model uncertainty. The design of the control law is as follows.

2.1 Design of control law

The course error variable e_1 is defined as

$$e_1=y-y_{\mathrm{d}} \tag{5}$$

Then, there is

$$e_2=\dot{e}_1=x_2-\dot{y}_{\mathrm{d}} \tag{6}$$

A new variable s is defined as

$$s=\lambda_1 e_1+\lambda_2\int e_1\mathrm{d}\tau+\dot{e}_1 \tag{7}$$

Where $\lambda_1>0$ and $\lambda_2>0$ are design parameters; τ is a time constant.

According to Eq. (5) and Eq. (6), time derivative is taken for s:

$$\dot{s}=\lambda_1\dot{e}_1+\lambda_2 e_1+\dot{x}_2-\ddot{y}_{\mathrm{d}} \tag{8}$$

Substituting Eq. (3) into Eq. (8), we can obtain that

$$\dot{s}=\lambda_1\dot{e}_1+\lambda_2 e_1-\ddot{y}_{\mathrm{d}}+\boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{f}(x_2)+\omega u+\xi \tag{9}$$

According to Eq. (9) and combined with Reference [19], the control law u and the adaptive law $\dot{\hat{\vartheta}}$ are designed as follows:

$$u = -(k_d + \hat{\vartheta} h^2(\mathbf{z}))s \tag{10}$$

where

$$\dot{\hat{\vartheta}} = \kappa h^2(\mathbf{z}) s^2 - \delta \hat{\vartheta} \tag{11}$$

Where k_d is the design parameter; κ is the learning law of the adaptive law; $\hat{\vartheta}$ is the estimator of ϑ, where $\vartheta = \max\{\|\boldsymbol{\theta}\|, \Delta, 1\}$; $h(\mathbf{z}) = |\lambda_1 \dot{e}_1 + \lambda_2 e_1 - \ddot{y}_d| + \|\boldsymbol{f}(x_2)\| + 1$, and $\mathbf{z} = [e_1, x_2, \dot{y}_d, \ddot{y}_d]^T$.

2.2 Stability analyses

The Lyapunov direct method can be used to determine the parameter range of the control law and prove the stability (or boundedness) of the system. The Lyapunov function V of the course closed-loop control system is

$$V = \frac{1}{2}s^2 + \frac{1}{2\kappa}\tilde{\vartheta}^2 \tag{12}$$

Where $\tilde{\vartheta} = \vartheta - \omega \hat{\vartheta}$.

Time derivative is taken for Eq. (12). Combined with Assumption 1 and Eqs. (9)–(11), we can obtain that

$$\dot{V} = s\left(\lambda_1 \dot{e}_1 + \lambda_2 e_1 - \ddot{y}_d + \boldsymbol{\theta}^T \boldsymbol{f}(x_2) + \omega u + \xi\right) - \frac{\omega}{\kappa}\tilde{\vartheta}\dot{\hat{\vartheta}} \leqslant$$
$$|s|\left(|\lambda_1 \dot{e}_1 + \lambda_2 e_1 - \ddot{y}_d| + \|\boldsymbol{\theta}\|\|\boldsymbol{f}(x_2)\| + \Delta\right) + s\omega u -$$
$$\frac{\omega}{\kappa}\tilde{\vartheta}\dot{\hat{\vartheta}} \leqslant |s|\vartheta h(\mathbf{z}) + s\omega u - \frac{\omega}{\kappa}\tilde{\vartheta}\dot{\hat{\vartheta}} \tag{13}$$

According to Young's inequality, there is

$$|s| h(\mathbf{z}) \leqslant \omega h^2(\mathbf{z}) s^2 + \frac{1}{4\omega} \tag{14}$$

Substituting Eq. (9), Eq. (10) and Eq. (14) into Eq. (13), we have

$$\dot{V} \leqslant \omega \vartheta h^2(\mathbf{z}) s^2 + s\omega u - \frac{\omega}{\kappa}\tilde{\vartheta}\dot{\hat{\vartheta}} + \frac{\vartheta}{4\omega} \leqslant$$
$$-\omega k_d s^2 + \omega \tilde{\vartheta} h^2(\mathbf{z}) s^2 - \frac{\omega}{\kappa}\tilde{\vartheta}\left[\kappa h^2(\mathbf{z}) s^2 - \delta \hat{\vartheta}\right] + \frac{\vartheta}{4\omega} =$$
$$-\omega k_d s^2 + \frac{\omega \delta}{\kappa}\tilde{\vartheta}\hat{\vartheta} + \frac{\vartheta}{4\omega} \tag{15}$$

With Young's inequality again, and combined with $\tilde{\vartheta} = \vartheta - \omega \hat{\vartheta}$, there is

$$\tilde{\vartheta}\hat{\vartheta} = \frac{1}{\omega}\tilde{\vartheta}(-\tilde{\vartheta} + \vartheta) \leqslant -\frac{\tilde{\vartheta}^2}{2\omega} + \frac{\vartheta^2}{2\omega} \tag{16}$$

Substituting Eq. (16) into Eq. (15), we have

$$\dot{V} \leqslant -\omega k_d s^2 - \frac{\delta \tilde{\vartheta}^2}{2r} + \frac{\delta \vartheta^2}{2\kappa} + \frac{\vartheta}{4\omega} \leqslant -\Theta V + C \tag{17}$$

Where $\Theta = \min\{2\omega k_d, \delta \xi\}$; $C = \frac{\delta \vartheta^2}{2\kappa} + \frac{\vartheta}{4\omega}$.

According to Eq. (7) and Eq. (10), there is

$$u = -\left(k_d + \hat{\vartheta} h^2(\mathbf{z})\right)\left(\lambda_1 e_1 + \lambda_2 \int e_1 d\tau + \dot{e}_1\right) =$$
$$-\lambda_1\left(k_d + \hat{\vartheta} h^2(\mathbf{z})\right)e_1 - \lambda_2\left(k_d + \hat{\vartheta} h^2(\mathbf{z})\right) \times$$
$$\int e_1 d\tau + \left(k_d + \hat{\vartheta} h^2(\mathbf{z})\right)\dot{e}_1 \tag{18}$$

Assuming $k_p = \lambda_1 k_d$, $k_p(\cdot) = \lambda_1 \hat{\vartheta} h^2(\mathbf{z})$, $k_i = \lambda_2 k_d$, $k_i(\cdot) = \lambda_2 \hat{\vartheta} h^2(\mathbf{z})$, $k_d(\cdot) = \hat{\vartheta} h^2(\mathbf{z})$, Eq. (18) can be simplified to

$$u = -\left(k_p + k_p(\cdot)\right)e_1 - \left(k_i + k_i(\cdot)\right)\int e_1 d\tau - \left(k_d + k_d(\cdot)\right)\dot{e}_1 \tag{19}$$

It can be known from Eq. (19) that the control law u has a similar structure of the conventional PID control law and inherits the advantages of the conventional PID control law. However, unlike the traditional PID, the control law of Eq. (19) has the performance of adaptive self-regulation, mainly embodied as $\dot{\hat{\vartheta}}$, $k_p(\cdot)$, $k_i(\cdot)$, $k_d(\cdot)$. Among them, when $k_p(\cdot)$, $k_i(\cdot)$, $k_d(\cdot)$ are all 0, the control law of Eq. (19) is the same as the traditional PID. At the same time, the biggest advantage of the adaptive control law is that it is not necessary to determine the control gain through continuous trial and error, and only the learning law κ needs to be adjusted. In addition, the control scheme can overcome time-varying disturbances and has robust performance against environmental disturbances.

To further analyze the stability (boundedness) of the control law, Eq. (17) needs to be solved. First, Eq. (17) is multiplied by $e^{\Theta t}$ and integrated, and there is

$$\int_0^t \dot{V} e^{\Theta t} d\tau \leqslant -\int_0^t \Theta V e^{\Theta t} d\tau + \int_0^t C e^{\Theta t} d\tau \tag{20}$$

Where $e^{\Theta t}$ is the minimum error coefficient, t is time.

Eq. (20) is further solved, and there is

$$\int_0^t d\left(V e^{\Theta t}\right) \leqslant \int_0^t \frac{C}{\Theta} e^{\Theta t} d\tau \tag{21}$$

namely,

$$V e^{\Theta t} - V(0) \leqslant \frac{C}{\Theta} e^{\Theta t} - \frac{C}{\Theta} \tag{22}$$

Where $V(0)$ is the initial value of function V.

According to Eq. (12) and Eq. (22), there is

$$0 \leqslant V \leqslant \frac{C}{\Theta} + [V(0) - \frac{C}{\Theta}] e^{-\Theta t} \tag{23}$$

It can be seen from Eq. (23) that when $\lim_{t \to \infty} V \leqslant C/\Theta$, V is bounded, and the value of C/Θ can be reduced by increasing the design values of k_d and κ. According to Eq. (12) and the boundedness of function V, s and $\tilde{\vartheta}$ are also bounded, and k_d can be obtained. According to Reference [20], the boundedness of s can guarantee the boundedness of e_1, $\int e_1 d\tau$, $\dot{e}_1$, so x_2 is also bounded. Further, according to Assumption 2, the boundedness of $h(\mathbf{z})$ can be obtained, and according to Eq. (11), the boundedness of u can be obtained.

Therefore, under the conditions of Assumption 1 and Assumption 2, the control law u and the adaptive law $\dot{\hat{\vartheta}}$ (Eq. (10) and Eq. (11)) can cause the ship course control system (Eq. (1)) to track a given reference course y_d, while ensuring that all signals of the closed-loop control system are bounded. In addition, by selecting the appropriate parameters λ_1, λ_2, k_d, κ, δ, we can control the tracking error of the ship course within a smaller neighborhood.

3 Simulation research

In order to verify the effectiveness of the control strategy of this paper, the simulation research is performed on the teaching and training ship "Yulong" of Dalian Maritime University. The relevant parameters are set as follows[21]: K = 0.478, T = 216, a = 9.14, b = 10 836.12.

For ease of calculation, the selected reference signal model is [22]

$$\ddot{\psi}_m(t)+0.19\dot{\psi}_m(t)+0.015\psi_m(t)=0.015\psi_r(t) \quad (24)$$

Where ψ_m is the ideal course satisfying ship performance; ψ_r is the command input signal.

The simulation research contains two working conditions:

1) Condition 1: The disturbance is assumed to be a constant disturbance and $\xi = 7$.

2) Condition 2: The disturbance is assumed to be a time-varying disturbance, and $\xi=\varpi(t)\hbar(t)+1+2\sin(0.2t)+\cos(0.5t)$. Where $\varpi(t)$ is a 6-level wave interference, which can be described by the second-order oscillation elements driven by the white noise recognized by the International Towing Tank Conference [23], and $\varpi(t)=\dfrac{0.419\,8s}{s^2+0.363\,8s+0.367\,5}$; $\hbar(t)$ is zero-mean Gaussian white noise; $1+2\sin(0.2t)+\cos(0.5t)$ is the equivalent interference of the marine environment [24].

Based on these two working conditions, the initial values of parameters of the ship course control system $\hat{\vartheta}$, ψ, $\dot{\psi}$ are set as $\hat{\vartheta}(0)=0$, $\psi(0)=10\times180/\pi$, $\dot{\psi}(0)=0$. The adaptive PID (APID) proposed in this paper is compared with the traditional PID control law (u_{PID}) shown in Eq. (25), where $k_d=4$, $k_p=\lambda_1 k_d$, $k_i=\lambda_2 k_d$, $\lambda_1=3$, $\lambda_2=5$, $\kappa=0.5$.

$$u_{PID}=K_p e_1+K_i\int e_1 d\tau+K_d\dot{e}_1 \quad (25)$$

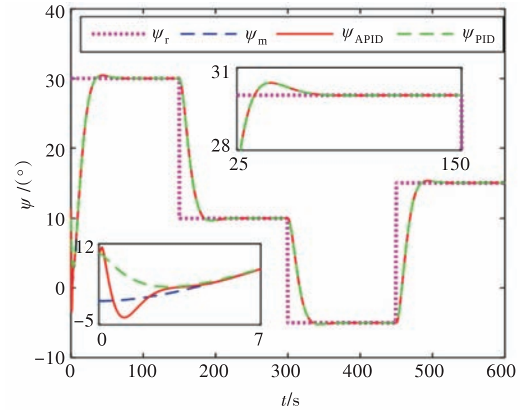
Where K_p =45, K_i =25, K_d =15 are the design parameters of the traditional PID control law.

The simulation results of the two control strategies are shown in Fig. 1 and Fig. 2. They are the tracking simulation results of ship course controlled by APID and traditional PID under constant disturbance and time-varying disturbance, respectively. It can be seen from Fig. 1(a) that the response performance of the ship course ψ_{APID} under APID control is relatively fast, but the dynamic performance of the ψ_{PID} in the initial stage controlled by traditional PID is more in line with the actual engineering needs. It can be seen from Fig. 1(b) that the tracking accuracy under two control schemes is satisfactory. It can be seen from Fig. 1(c) that it is easier to realize the rudder angle response under the traditional PID control in engineering applications. In the steady state phase, the rudder angle responses of the two control schemes are almost the same. Fig. 1(d) shows the adaptive duration curves of $k_p(\cdot)$, $k_i(\cdot)$, $k_d(\cdot)$ under APID control.

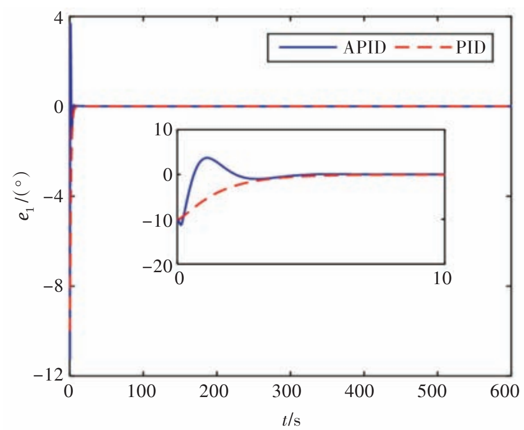
It can be seen from Fig. 2(a) that the ship course response performance under the APID and traditional PID control is basically the same, but the dynamic adjustment performance of the traditional PID in the initial stage is poor. As can be seen from Fig. 2(b), the tracking accuracy of the APID control is higher. It can be seen from Fig. 1(c) that the rudder angle responses of the two control strategies are completely identical. Fig. 2(d) shows the adaptive duration curves of $k_p(\cdot)$, $k_i(\cdot)$, $k_d(\cdot)$ under APID control.

From Fig. 1(c), Fig. 1(d), Fig. 2(c) and Fig. 2(d), the control input δ and the adaptive parameters $k_p(\cdot)$, $k_i(\cdot)$, $k_d(\cdot)$ are bounded.

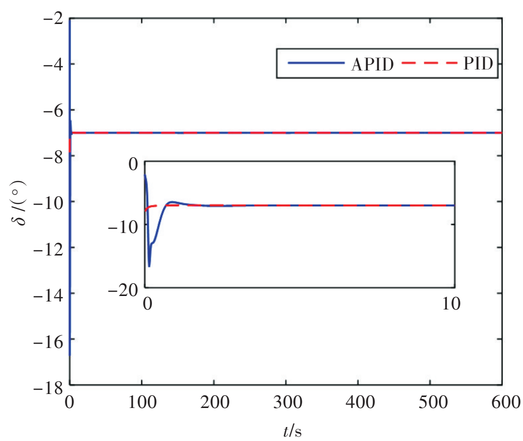
Table 1 shows the results of quantitative performance comparison of the two control schemes. In Table 1, Intergral of Absolute Error (IAE) = $\int_{t_0}^{t_f}|e_1(t)|dt$ can be used to evaluate the steady-state performance of the control scheme, where the start time is t_0 = 0 s and the end time is t_f = 600 s. Mean Integral of Absolute Control (MIAC) = $\dfrac{1}{t_f-t_0}\int_{t_0}^{t_f}|\delta(t)|dt$ can be used to evaluate the energy consumption of the control scheme. It can be seen from Table 1 that under the constant disturbance and the time-varying disturbance, the MIAC indices of the two control strategies are the same, namely that the system energy consumption is completely consistent. It can be seen from the IAE index that under the constant disturbance, the difference of the steady-state performance of the two control strategies is small. Under the time-varying disturbance, the steady-state error of the traditional PID is large, which also proves that it cannot resist the time-varying disturbance. This



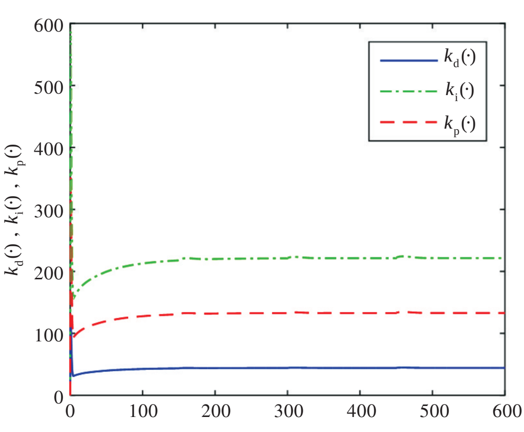
(a) Course tracking



(b) Tracking error

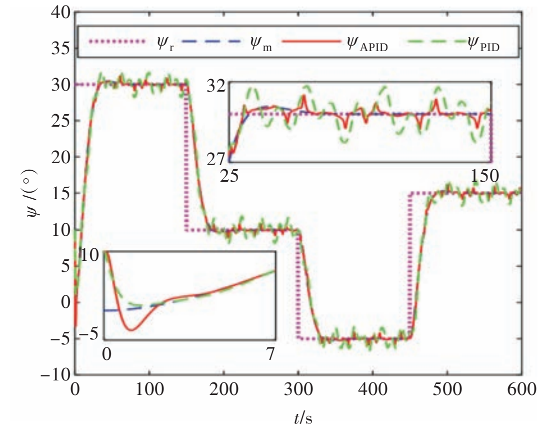


(c) Rudder angle

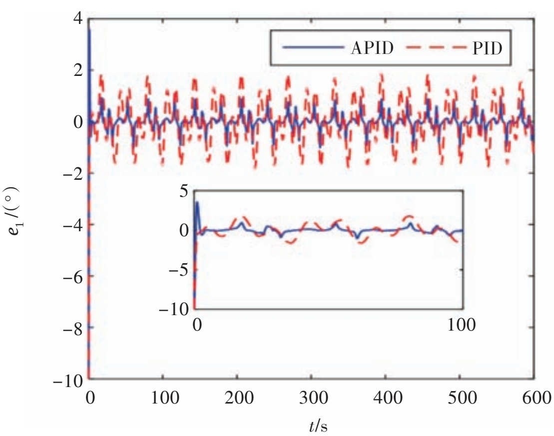


(d) Adaptive parameter

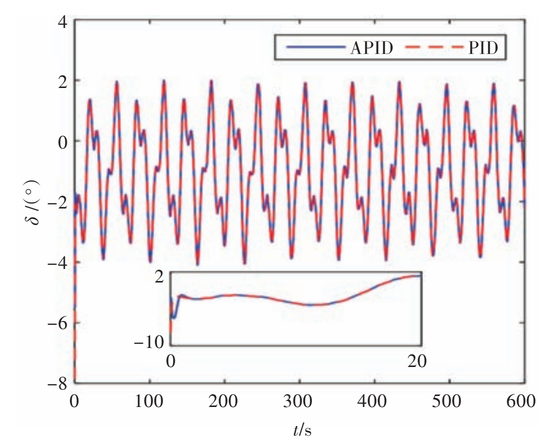
Fig.1 Simulation results under constant disturbance



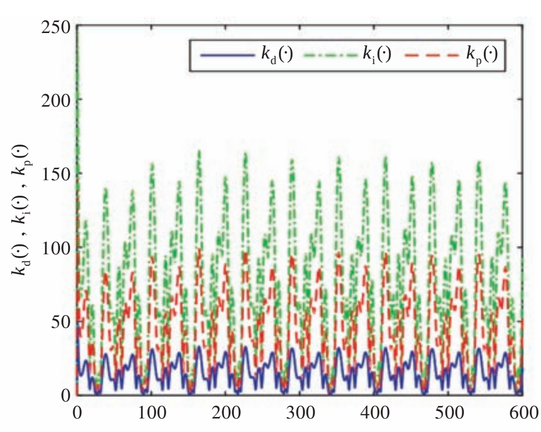
(a) Course tracking



(b) Tracking error



(c) Rudder angle



(d) Adaptive parameter

Fig.2 Simulation results under time-varying disturbance

Table 1 The performance comparison between APID and PID control

Control scheme	IAE		MIAC	
	Constant disturbance	Time-varying disturbance	Constant disturbance	Time-varying disturbance
APID	9.85	115.5	7.01	1.53
PID	16.09	442.7	7.01	1.53

conclusion further embodies the robustness of APID to uncertain disturbances.

In order to meet the different control performance requirements under time-varying disturbance conditions, the influences of k_d and κ on the control performance of APID are quantitatively analyzed. The results are shown in Table 2. It can be seen from Table 1 and Table 2 that k_d and κ have less influence on MIAC, and k_d has less influence on IAE, but κ has more obvious influence on IAE. Therefore, an appropriate increase in the κ value can improve the control accuracy.

Table 2 The influence of APID design parameters on control performance

Design parameter	IAE	MIAC
$k_d=1, \kappa=0.5$	116	1.53
$k_d=6, \kappa=0.5$	111	1.53
$k_d=4, \kappa=0.1$	148	1.53
$k_d=4, \kappa=1$	98	1.54

4 Conclusions

In this paper, based on the problem of ship's external environmental disturbance and model parameter uncertainty, adaptive self-regulation PID course tracking control law is designed by parameter adaptive technology, which can be used for ship course tracking control and dynamic positioning control. The control law not only has the advantages of simple PID structure, not depending on accurate model, fewer regulation parameters, but also has good robustness to parameter uncertainty and unknown input. At the same time, there are few online regulation parameters of the control scheme in this paper, so the calculation load is low, and it is of easy engineering implementation.

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船舶航向的自适应自调节PID跟踪控制

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摘　要:[**目的**] 针对遭受时变环境扰动且存在参数不确定性的船舶航向非线性控制系统,为满足其航向控制的实时性要求,[**方法**] 结合自适应技术,提出不依赖于模型参数与未知输入的自适应自调节的船舶航向跟踪控制方案,并利用Lyapunov直接方法验证该控制律的有界性。[**结果**] 仿真结果表明,该控制器可以自适应自调节PID的控制增益,不仅继承了传统PID控制器的优点,还对未知时变扰动具有良好的鲁棒性。[**结论**] 研究成果可为船舶航向的跟踪控制设计提供参考。

关键词:船舶航向;跟踪控制;不确定性;自调节PID;自适应控制