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ADAPTIVE SELF-REGULATION PID CONTROL OF COURSE-KEEPING FOR SHIPS

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ABSTRACT

To solve the nonlinear control problems of the unknown time-varying environmental disturbances and parametric uncertainties for ship course-keeping control, this paper presents an adaptive self-regulation PID (APID) scheme which can ensure the boundedness of all signals in the ship course-keeping control system by using the Lyapunov direct method. Compared with the traditional PID control scheme, the APID control scheme not only is independent of the model parameters and the unknown input, but also can regulate the gain of PID adaptively and resist time-varying disturbances well. Simulation results illustrate the effectiveness and the robustness of the proposed control scheme.

Keywords: ships, course-keeping control, self-regulation PID, adaptive control, Lyapunov

INTRODUCTION

Research on ship course-keeping control is important in the field of ship motion control, in which the accuracy of the ship course-keeping control has always been a hot issue [25, 7].

Due to uncertain environmental disturbances such as wind, waves, current and the effect of large inertia, delay and nonlinearity of the ship itself, which make the ship parameters uncertain and perturbed, ship course-keeping control encounters certain difficulties. When pilots are boarding or disembarking, the manoeuvring mode of the ship needs to be stable on a certain course [6]; the berthing angle needs to be adjusted continuously during berthing, and to achieve this, the course-keeping control model needs to be converted to a course-tracking control model, which means that the course-keeping control needs to be more precise and multimodal. In addition, with the gradual promotion of research on intelligent unmanned commercial ships, course-keeping also needs to be further extended to the field of manoeuvring in port.

To make the ship course controller highly efficient or easy-to-implement for its task, a lot of research work has been done, such as PID [6, 12], sliding mode [22, 26], nonlinear feedback [23], adaptive backstepping [5, 24] and adaptive neural network/fuzzy [3, 19, 2]. It was noted that although the control methods proposed in [5, 24, 3, 19, 2] did not need accurate models, their inherent complexities brought certain difficulties to engineering practice. In contrast, the PID control has a simple structure, fewer adjustment parameters, does not depend on an accurate model, and so on. However, it was found to be difficult to reflect the advantages of PID due to the poor robustness of traditional PID to external time-varying environmental disturbances. Therefore, to improve the course control performance, various PID control schemes have been proposed, such as an iterative sliding mode variable structure PID [1] and integral compensation PID [11]. But the algorithms of these schemes cannot resist the effect of time-varying disturbances. Moreover, intelligent optimisation algorithms have also been used to adjust the gain of PID, such as fuzzy logic [14] and firefly swarm optimisation [20], simulated annealing [4], improved genetic [15], and so on. However, the fuzzy logic method needed to set the fuzzy relationship in advance, and its applicability was not universal; glowworm swarm optimisation, simulated annealing and the improved genetic algorithm are offline optimisation algorithms that cannot fulfill the real-time requirements of course-keeping control.

An adaptive controller is a controller that modifies its characteristics to accommodate changes in the dynamics of disturbances. Due to the unique advantages of the adaptive PID control method in dealing with nonlinear control problems, many researchers have paid much attention to it in the field of ship motion control. In [11], an integral compensation PID and parameter adaptive algorithm were proposed for eliminating the steady-state error resulting from outside disturbances, and the problems of overshoot and parameters adjustment resulting from conventional PID control were circumvented in the proposed algorithm. To get better closed-loop response parameters, a method of PID-like adaptive fuzzy control design for a linear time-invariant single-input and single-output dynamic plant is proposed in [10]. In [16], an adaptive proportional-integral-derivative (PID) distributed power control algorithm (DPCA) for next-generation passive optical networks (NG-PON) is investigated. Using adaptive tuning procedures to calibrate the PID gains (proportional, integral, and derivative), the PID block control scheme is designed, to improve the response speed and stability of a self-propelled model, a fuzzy self-adapting PID control algorithm is proposed in [8].

In order to give the controller the advantages of high efficiency or being easy-to-implement for its task, many adaptive PID controllers have been proposed, such as adaptive robust proportional-integral-derivative (PID) [18], adaptive fuzzy proportional-integral-derivative (AFPID) [17], and adaptive fuzzy PID [21].

Based on the above analysis, a new self-regulating PID control scheme is proposed in this paper. This control scheme mainly includes the design of the control law, and self-adaptive law. The control law and self-adaptive law are designed by using the newly defined variables, Lyapunov function and Young's inequality. The main contributions of this paper can be summarised as follows:

(1) Considering the unknown time-varying environmental disturbances and using adaptive technology, the APID control scheme is designed.
(2) The designed control scheme does not require prior knowledge of the model parameters.
(3) The APID course-keeping control is effective and has good robustness for unknown time-varying disturbances.

The rest of this paper is organised as follows. In Section 2, the mathematical model and problem formulation are given. Section 3 is devoted to stability analysis for the proposed controller. In Section 4, the training ship "YULONG" of Dalian Maritime University is used as the test object to verify the effectiveness of the proposed control scheme.

NONLINEAR SHIP MODEL

In the nonlinear ship motion mathematical model, the relationship between the rudder angle δ and the course ψ can be described by the following Eq. (1) [7]:

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

where T and K are the ship manoeuvring indexes, ξ is the external unknown time-varying disturbance, and the nonlinear function $F(\dot{\psi})$ can be approximated as $F(\dot{\psi}) = a\dot{\psi} + b\dot{\psi}$, where a and b are constants.

Assume $x_1 = \psi$, $x_2 = \dot{\psi} = r$, $u = \delta$.

According to Eq. (1), we have

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

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

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

where $y \in R$ is the output of the control system, signalis the input of the control system, $\omega = \frac{K}{T}$, $\theta = [\frac{a}{T}, \frac{b}{T}]^T$, $f(x_2) = [x_2, x_2^3]^T$.

Assumption 1: The external disturbances ξ are unknown, bounded and also satisfy $|\xi| \le \Delta$, where Δ is a positive constant.
Assumption 2: Reference course y_d is smooth. The signals $\dot{y}_d$ and $\ddot{y}_d$ are available.
Assumption 3: Model parameters θ and ω are unknown.
Based on the mathematical model of the ship motion (1) and considering the unknown time-varying disturbances the ships may encounter, a robust course-keeping controller is designed in this paper. The designed controller can ensure that the actual output course signals track the designed course signals and guarantee all signals are bounded in the whole closed-loop control system.

CONTROLLER DESIGN AND STABILITY ANALYSIS

Fig. 1 shows the configuration of the APID controller in ship motion, where the structure of the APID is the same as that of the PID, but the APID has an adaptive control law, which can achieve adaptive control in the face of external disturbances, and has better robustness. Considering the disturbances and the unknown model parameters, we will employ the Lyapunov

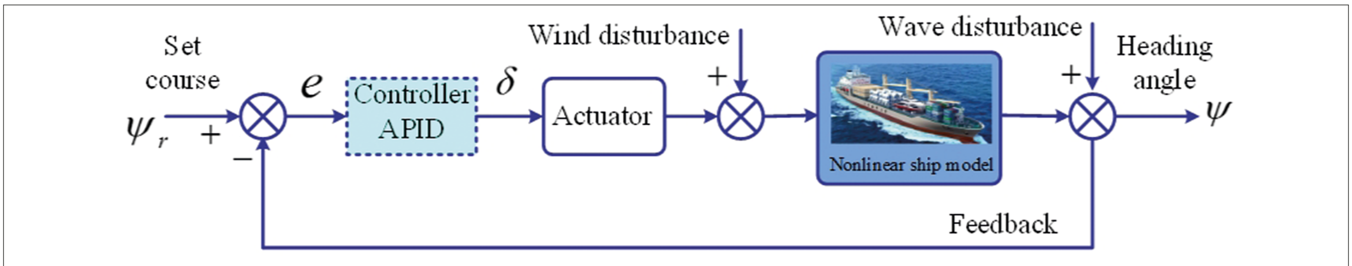


Fig. 1. Configuration of APID controller

direct method and the adaptive technology to design the ship course-keeping control law and its adaptive law. The stability analysis of the closed-loop control system will be given later.

Define the following error:

$$e_1 = y - y_d \tag{5}$$

$$e_2 = \dot{e}_1 = x_2 - \dot{y}_d \tag{6}$$

Define the new variable s as:

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

where $\lambda_1 > 0$, $\lambda_2 > 0$ are the design parameters.

According to (5)–(6), the time derivative of s is given by

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

Then, substituting Eq. (3) into Eq. (8), we obtain

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

According to (9), the control law and adaptive law are designed as

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

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

where k_d, r and δ are the designed parameters, function $\hat{\vartheta}$ is the estimation of ϑ, $h(z)$ and ϑ will be given later.

We consider the following Lyapunov function candidate:

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

where $\tilde{\vartheta} = \vartheta - \omega\hat{\vartheta}$, and value r is the designed parameter.

According to assumption 1 and Eqs. (9)–(12), we can obtain

$$\begin{aligned} V &= s(\lambda_1 \dot{e}_1 + \lambda_2 e_1 - \ddot{y}_d + \theta^T f(x_2) + \omega u + \xi) - \frac{\omega}{r} \tilde{\vartheta}\dot{\hat{\vartheta}} \\ &\le |s|(|\lambda_1 \dot{e}_1 + \lambda_2 e_1 - \ddot{y}_d| + \|\theta\| \|f(x_2)\| + \xi) + s\omega u - \frac{\omega}{r} \tilde{\vartheta}\dot{\hat{\vartheta}} \\ &\le |s| \vartheta h(z) + s\omega u - \frac{\omega}{r} \tilde{\vartheta}\dot{\hat{\vartheta}} \end{aligned} \tag{13}$$

where:

$$\vartheta = \max\{\|\theta\|, \xi, 1\} \tag{14}$$

$$h(z) = |\lambda_1 \dot{e}_1 + \lambda_2 e_1 - \ddot{y}_d| + \|f(x_2)\| + 1 \tag{15}$$

$$z = [e_1, x_2, \dot{y}_d, \ddot{y}_d]^T \tag{16}$$

Using Young's inequality ($p \cdot q \le k_1 p^2 q^2 + \frac{1}{4\omega}$ ($k_1 > 0$)), we can get the following Eq. (17):

$$|s|\, h(z) \le \omega h^2(z) s^2 + \frac{1}{4\omega} \tag{17}$$

Substituting Eqs. (9)–(10) and (17) into Eq. (13), we can get

$$\begin{aligned} V &\le \omega\vartheta h^2(z) s^2 + s\omega u - \frac{\omega}{r} \tilde{\vartheta}\dot{\hat{\vartheta}} + \frac{\vartheta}{4\omega} \\ &\le -\omega k_d s^2 + \omega\tilde{\vartheta} h^2(z) s^2 - \frac{\omega}{r} \tilde{\vartheta}\, [r h^2(z) s^2 - \delta\hat{\vartheta}] + \frac{\vartheta}{4\omega} \\ &= -\omega k_d s^2 + \frac{\omega\delta}{r} \tilde{\vartheta}\hat{\vartheta} + \frac{\vartheta}{4\omega} \end{aligned} \tag{18}$$

Using $\tilde{\vartheta} = \vartheta - \omega\hat{\vartheta}$ and $\hat{\vartheta} = \frac{1}{\omega}(\vartheta - \tilde{\vartheta})$, we have

$$\tilde{\vartheta}\hat{\vartheta} = \frac{1}{\omega} \tilde{\vartheta}(\vartheta - \tilde{\vartheta}) = \frac{\tilde{\vartheta}\vartheta}{\omega} - \frac{\tilde{\vartheta}^2}{\omega} \le \frac{\vartheta^2}{\omega} - \frac{\tilde{\vartheta}^2}{\omega} \le \frac{\vartheta^2}{2\omega} - \frac{\tilde{\vartheta}^2}{2\omega} \tag{19}$$

Substituting Eq. (19) into Eq. (18), we can obtain

$$\begin{aligned} V &\le -\omega k_d s^2 - \frac{\delta\vartheta^2}{2r} + \frac{\vartheta}{4\omega} \\ &\le -\Theta V + C \end{aligned} \tag{20}$$

where $\Theta = \min\{2\omega k_d, \delta\}$ and $C = \frac{\delta\vartheta^2}{2r} + \frac{\vartheta}{4\omega}$.

According to Eqs. (8) and (11), we have

$$\begin{aligned} u &= -(k_d + \hat{\vartheta} h^2(z))(\lambda_1 e_1 + \lambda_2 \int e_1 d\tau + \dot{e}_1) \\ &= -\lambda_1 (k_d + \hat{\vartheta} h^2(z)) e_1 - \lambda_2 (k_d + \hat{\vartheta} h^2(z)) \\ &\quad \int e_1 d\tau + (k_d + \hat{\vartheta} h^2(z)) \dot{e}_1 \end{aligned} \tag{21}$$

Let $k_p = \lambda_1 k_d$, $k_p(\cdot) = \lambda_1 \hat{\vartheta} h^2(z)$, $k_i = \lambda_2 k_d$, $k_i(\cdot) = \lambda_2 \hat{\vartheta} h^2(z)$, $k_d(\cdot) = \hat{\vartheta} h^2(z)$, then Eq. (21) can be written as:

$$u = -(k_p + k_p(\cdot)) e_1 - (k_i + k_i(\cdot)) \int e_1 d\tau - (k_p + k_p(\cdot)) \dot{e}_1 \tag{22}$$

From Eq. (22), the control law u which is designed in this paper has a similar structure to that of the traditional PID control law. However, unlike the traditional PID, the control law (22) has adaptive adjustment performance, and its adaptive adjustment performance is mainly reflected in adaptive law (11), $k_p(\cdot)$, $k_i(\cdot)$ and $k_d(\cdot)$. When $k_p(\cdot)$, $k_i(\cdot)$ and $k_d(\cdot)$ converge to zero, the control law (22) is the same as the traditional PID control law.

According to the above analysis, there is the following lemma.

Lemma [1]: Under assumptions 1 and 2, the control law (10) and self-adaptive law (11) can ensure that the design ship's course tracks the reference course y_d, and guarantee that all the signals of the ship's course control closed-loop system are bounded. In addition, the ship's course-keeping error can be adjusted to a smaller neighbourhood by selecting appropriate parameters λ, k_d, r, and δ.

Proof: based on Eq. (18), there is

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

where $V(0)$ is the initial value of V, and, according to Eq. (23), we know that when $\lim_{t\to\infty} V \leq C/\Theta, V$ is bounded. And C/Θ will decrease with the increase of k_d and r. According to Eq. (13) and the boundedness of V, we can that obtain s and $\tilde{\vartheta}$ are bounded. Following that, we can get $\hat{\vartheta}$. According to [9], the boundedness of s can guarantee the boundedness of e_1, $\int e_1 d\tau$ and $\dot{e}_1$; thus, signal x^2 is bounded. According to assumption 2, we can obtain the boundedness of $h(z)$; thus, u is bounded in Eq. (11). Therefore, all the signals of the closed-loop system are bounded.

ILLUSTRATIVE EXAMPLE

To verify the effectiveness of the proposed control scheme, the training ship "YULONG" of Dalian Maritime University is used as the test object [25]. Firstly, the relevant parameters of the simulation are $K = 0.478[s^{-1}]$, $T = 216[s]$, $a = 1$ and $b = 30$. Secondly, in the simulation process, we often need a differentiable reference course ψ_r. However, the actual reference signal is generally a step signal. So, to obtain the desired smooth continuous signal and to improve the control effect, the given actual reference signal is usually pre-filtered. The specific filtering process is as follows (24), which can achieve the performance requirement of control system quickly [13].

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

where ψ_r is the input signal and ψ_m is an ideal course.

To verify the effectiveness of the designed control scheme, simulation comparisons are carried out with two cases.

Case 1: The value of constant disturbances is chosen as $\xi = 7$;

Case 2: Let the time-varying disturbances be

$$\xi = \varpi(t)\hbar(t) + 180 \times (0.05 \sin 0.8t - 0.02 \cos 0.02t + 0.1) / \pi \quad (25)$$

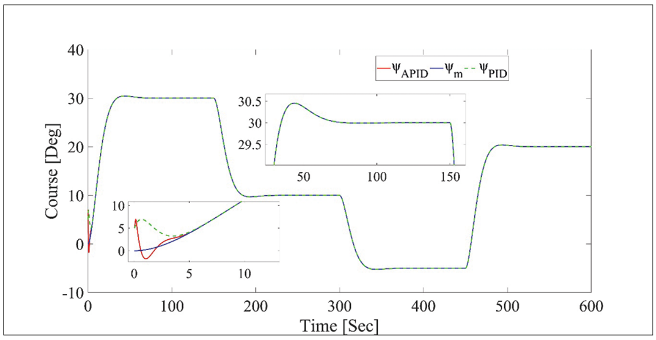
where $\hbar(t)$ is Gaussian white noise, $\varpi(t) = \frac{0.42s}{s^2 + 0.36s + 0.37}$.

The traditional PID control law is designed as:

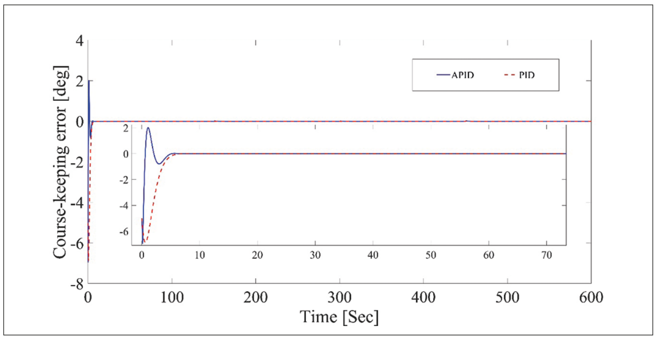
$$u_{PID} = K_p e_1 + K_i \int e_1 d\tau + K_d e_1 \quad (26)$$

We compare the proposed control scheme with the traditional *PID* control method. In addition, the design parameters of the control law in the two cases are selected as: $k_d = 4$, $\lambda_1 = 3$, $\lambda_2 = 5$, $r = 0.5$, $\sigma = 0.1$. Meanwhile, the traditional *PID* parameters are set as $K_p = 45$, $K_i = 25$ and $K_d = 45$. The initial conditions of the ship's course control system are $\hat{\vartheta}(0) = 0$, $\psi(0) = 5 \times 180/\pi$ and $\dot{\psi}(0) = 0$. The simulation results of the two control schemes are shown in Figs. 2 and 3.

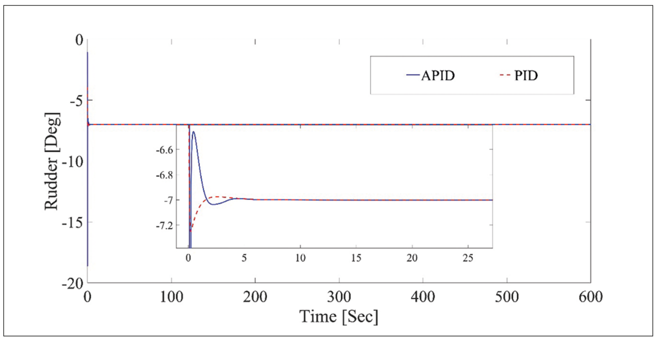
The comparison results of the two control schemes under the constant disturbances are shown in Fig. 2. As is shown in Fig. 2 (*a*), from 0s to 4s, the solid line of course-keeping controlled by the *APID* scheme is closer to the reference course and faster than the *PID*. And the dynamic performance of the *APID* accords with the actual situation from 4s to the end. In addition, the course-keeping error duration curve shown in Fig. 2 (*b*) indicates that the keeping accuracy under the two control schemes is satisfactory. Fig. 2 (*c*) shows the rudder angle response. From Fig. 2 (*c*) we can see that the rudder angle response in the steady-state of the two control schemes is almost the same. Fig. 2 (*d*) shows the adaptive response curve of $k_p(\cdot)$, $k_i(\cdot)$ and $k_d(\cdot)$ controlled by the *APID* control scheme.



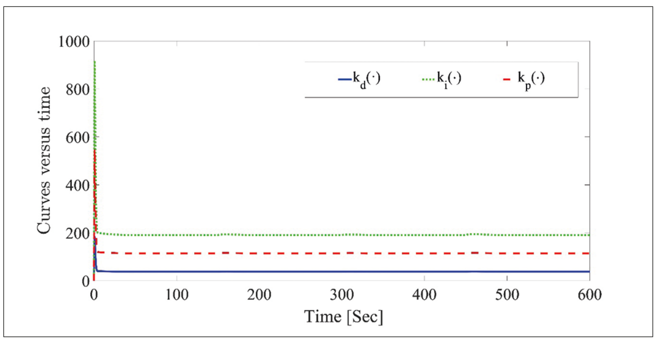
(a) Course-keeping



(b) Course-keeping error



(c) Rudder angle



(d) Curves of $k_p(\cdot)$, $k_i(\cdot)$ and $k_d(\cdot)$ versus time

Fig. 2. The simulation results under constant disturbances

As is shown in Figs. 2 (*c*)–(*d*), both the control input δ, $k_p(\cdot)$, $k_i(\cdot)$ and $k_d(\cdot)$ are bounded.

The comparison results of the two control schemes under the time-varying disturbances are shown in Fig. 3. It can be seen from Fig. 3 (*a*) that the ship course response performance of the *APID* is the same as that of the traditional *PID*. But the dynamic adjustment performance of the traditional *PID* is poor from 0s to 5s. As is shown in Fig. 3 (*b*), the error of the *APID* control course-keeping is less, which means that the *APID* control can ensure satisfactory control accuracy. The simulation results of the rudder angle response under the two control schemes are plotted in Fig. 3 (*c*). It is clearly seen from Fig. 3 (*c*) that in the initial stage, the rudder angle of the *PID* changes more than the *APID*, which indicates that the *PID* control consumes more energy. Fig. 3 (*d*) shows the adaptive duration curve of $k_p(\cdot)$, $k_i(\cdot)$ and $k_d(\cdot)$ under the *APID* control scheme. From Figs. 3 (*c*)–(*d*), the control input δ, $k_p(\cdot)$, $k_i(\cdot)$ and $k_d(\cdot)$ are bounded.

To further quantify the control effect, two popular performance specifications are used to evaluate the performance of the closed-loop system. As is shown in Eqs. (27)–(28), the two specifications are the integrated absolute error (IAE) and the mean integrated absolute control (MIAC), designed as:

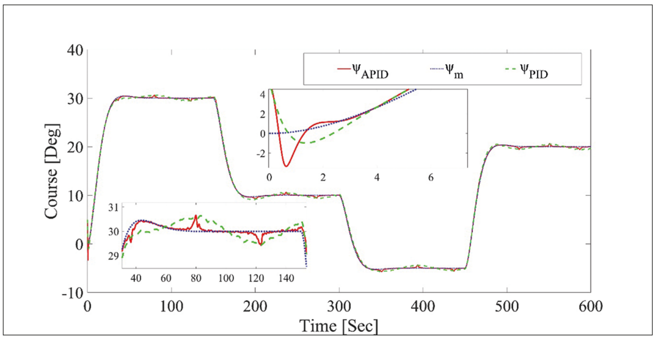
$$\mathrm{IAE} = \int_{t_0 0}^{t_f} |e_1(t)| dt \tag{27}$$

$$\mathrm{MIAC} = \frac{1}{t_f - t_0} \int_{t_0 0}^{t_f} |\delta(t)| dt \tag{28}$$

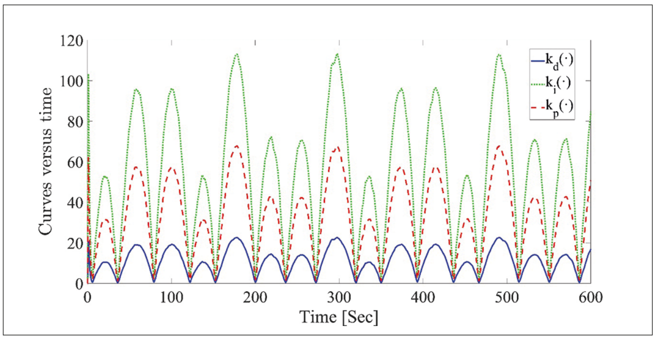
where IAE and MIAC are used to assess the transient, the steady-state performance and the properties of energy consumption in course-keeping control.

From Table 1, we can see that the MIAC of the two control schemes is the same under the constant and the time-varying disturbances, which means that the two schemes have the same energy consumption. In addition, we can see that under the constant disturbances, the IAE of the *PID* is larger than that of the *APID*, which means that the *PID* course-keeping error is larger than the *APID*, so the *APID* has better control performance. However, under the time-varying disturbances, the steady-state error of the traditional *PID* is too large, which proves that the *PID* control cannot resist the time-varying disturbances, whereas the *APID* control scheme has good robustness to resist environmental disturbances.

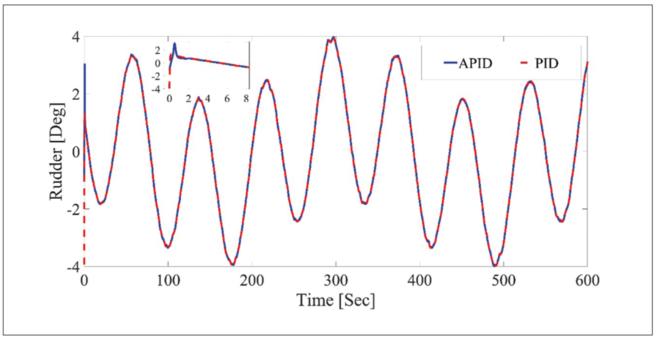
Furthermore, in order to meet the different needs of better control performance, we quantify the influence of design parameters k_d and r on the *APID* control scheme under the time-varying disturbances, and the results are shown in Table 2. As is shown in Tables 1 and 2, we can see that the effect of k_d and r on the MIAC can be almost neglected. In addition, k_d has little effect



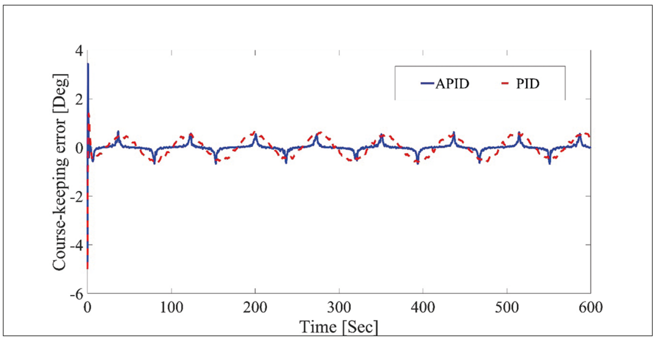
(a) Course-keeping



(b) Course-keeping error



(c) Rudder angle



(d) Curves of $k_p(\cdot)$, $k_i(\cdot)$ and $k_d(\cdot)$ versus time

Fig. 3. The simulation results under time-varying disturbance

Tab. 1. Comparison of control performance between APID and PID

	Disturbances	APID	PID
IAE	Constant	5.681	16.12
	Time-varying	54.33	204.1
MIAC	Constant	7	7
	Time-varying	1.84	1.84

Tab. 2. Influence of APID design parameters on control performance

	IAE	MIAC
$k_d = 1$, $r = 0.5$	55.99	1.84
$k_d=0.5$, $r = 0.5$	56.34	1.84
$k_d=4$, $r=1$	47.69	1.84
$k_d=4$, $r=0.15$	68.11	1.84

on the IAE, whereas r has an obvious effect on the IAE. Therefore, we can improve the control accuracy by increasing the value of r.

CONCLUSION

In this paper, an adaptive PID control scheme of course-keeping has been proposed for ships' motion control subject to the unknown time-varying disturbances, and then an adaptive course-keeping control law was designed based on an adaptive technique. Compared with the traditional PID control law, our proposed control law has fewer adjustment parameters and strong robustness to external time-varying disturbances.

Furthermore, our proposed control scheme improves the dynamic performance of the course-keeping control system, reduces the course-keeping error and has a lower calculation load. Therefore, this control scheme can be easily applied in engineering. In addition, it can also be used for ship trajectory tracking control and dynamic positioning control.

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