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Nonlinear adaptive design for course-tracking control of ship without a priori knowledge of control gain

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Abstract: A nonlinear adaptive control strategy is proposed to solve the problem of uncertainty and nonlinearity of the ship steering mathematical model. The presented method which incorporates Nussbaum gain technique into adaptive backstepping algorithm is especially useful in dealing with the unknown sign of uncertain control coefficient. It is at first proved theoretically that the presented adaptive controller guarantees that all signals in the parameter uncertain nonlinear ship motion system without *a priori* knowledge about control directions are uniform bounded, and the output of the controlled uncertain nonlinear ship motion system asymptotically tracks the output of the ship course reference model. Then, simulation studies are carried out by utilizing Matlab's Simulink toolbox. The results of the simulation of two ships' steering models show that the designed controller can be applied to the ship course tracking with good compatibility and robustness.

Key words: ship course tracking control; adaptive control; nonlinear; parameter uncertainty; backstepping algorithm; Nussbaum gain

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控制增益未知的船舶航向非线性自适应跟踪控制

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摘要: 针对参数不确定的船舶运动非线性控制系统控制方向未知的困难,将逆推算法与 Nussbaum 增益方法相结合,提出一种新的自适应非线性控制策略,从而实现船舶运动航向跟踪控制.首先,从理论上证明了所设计的自适应控制器保证最终的控制系数符号未知的参数不确定船舶运动非线性系统中所有信号一致有界,船舶的实际航向全局自适应地渐近跟踪期望的参考航向.对两条船舶数学模型的仿真实验结果表明,所设计的自适应非线性跟踪控制器具有良好的适应性及鲁棒性.

关键词: 船舶航向跟踪控制; 自适应控制; 非线性; 参数不确定; 逆推算法; Nussbaum 增益

1 Introduction

Shiphandling, in general, is a complicated control problem. The ship course control directly influences the maneuverability, economy and security of ship navigation and the combat capacity of warship[1]. Since the application of PID control law in ship navigation control in 1920's, the navigation controls have been highly emphasized due to the navigation safety, energy-saving and lowering working intensity of the crew. Many advanced control algorithms, such as model reference adaptive control[2], neural network adaptive control[3,4], have been applied to ship steering since the 1980s. So far, Nomoto linear model has been widely used in most ship motion control designs. However, under some steering conditions like a course-changing operation, it is necessary to consider the hydrodynamic nonlinearities. Hence, the ship control system model becomes nonlinear. For a certain model, a state feedback linearizing control law can be designed according to reference [5], while feedback linearization with saturating and slew rate limiting actuators is discussed by Tzeng et al[6]. But it does not possess the robustness to the changes of parameter and model, because the feedback linearization method requires that system parameters and structure should be accurately known. It is obvious that the mathematic model of ship steering system is uncertain when the variation of speed, loading condition and environment are considered. Now, the study and development of nonlinear adaptive autopilot with robustness is a hot research topic in the field of ship motion control. A robust

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adaptive nonlinear control algorithm was presented for ship steering autopilot with both parametric uncertainty and unknown bound of input disturbance based on projection approach by using Lyapunov stability theory in [7]. However, the design procedure proposed in [7] requires a priori knowledge of the sign of unknown control coefficient.

Backstepping approach is a new algorithm that has been well developed in recent years. It can be used to design the adaptive controller of a large class of nonlinear control system with unknown constant parameter[8]. It is one of the most efficient ways to solve the control problem of uncertain nonlinear systems, and thus has drawn special attention of many theorists. This paper assumes that the nonlinearity of ship course model is considered and the assumption that the parameters of the model are uncertain and the control direction is unknown. It proposes a new adaptive control algorithm for ship course nonlinear system by incorporating the technique of Nussbaum-type function[9] into backstepping design. Its objectives include that the problem that the parameters are uncertain and the sign of control coefficient is unknown in course-controlling system will be solved by the algorithm proposed, the asymptotic stability of ship movement course error system will be achieved and the goal of course-changing adaptive tracking control of vessels will be realized. Finally, simulation studies on two vessels' mathematic model are performed to prove the feasibility and robustness of the proposed control algorithm.

2 Mathematical models of ship steering

The linear Nomoto model has been widely used to design ship course controller[10].

$$\frac{r(s)}{\delta(s)} = \frac{K}{1 + Ts}, \tag{1}$$

that is

$$T\dot{r} + r = K\delta, \tag{2}$$

where r is the yaw rate, δ is rudder angle, T is time constant, K is rudder gain. This is mainly attributed to its simple structure and relative easiness in obtaining the model parameters from standard trial data of a ship. Despite its popularity, the Nomoto model is only valid for small rudder angles and low frequencies of rudder action. In order to better describe the ship steering dynamic behavior so that steering equation is also valid for rapid and large rudder angles, a nonlinear characteristic for r is added to equation (2). The following nonlinear model is suggested in this paper.

$$T\dot{r} + r + \alpha r^3 = K\delta, \tag{3}$$

where α is called Norrbin coefficient. The value of α can be determined via a spiral test[10].

The model parameters vary significantly with operating conditions such as the forward speed. Under these varying operating conditions, it is tedious and difficult to determine properly the parameters of the controller. So we assume that T, K, α are unknown constant parameters in the design.

Noting the heading angle, we have

$$\dot{\Psi} = r. \tag{4}$$

We select state variable as $x_1 = \Psi, x_2 = r$. $u = \delta$ is control variable. And then, equations (3) and (4) are transformed into the followings:

$$\dot{x}_1 = x_2, \tag{5a}$$

$$\dot{x}_2 = \sum_{j=1}^{2} \theta_j \varphi_{2,j}(x_2) + \theta_0 u, \tag{5b}$$

$$y = x_1, \tag{5c}$$

where $\theta_1 = -1/T, \theta_2 = -\alpha/T, \theta_0 = K/T, \varphi_{2,1} = x_2, \varphi_{2,2} = x_2^3$. The heading angle Ψ is the output of ship course control system. The model in equations (5) will be used for our proposed autopilot design. Evidently, this is a matching uncertain nonlinear system of single input-single output (SISO) in which nonlinear function is known. When the parameter θ_0 is known, e.g., $\theta_0 = 1$, it is just in parametric strict-feedback form[8].

Parameter $T > 0$ when a ship is line movement stable, whereas $T < 0$. In this paper, an adaptive tracking control design procedure of ship course-changing is developed which does not require *a priori* knowledge about the sign of control coefficient θ_0 in equation (5b).

The control objective of this paper is to make the output y of the system (5) asymptotically track a desired time-variant reference trajectory Ψ_d, while all the closed-loop signals stay bounded. First, we make the following assumptions.

Assumption 1 $x_1 = \Psi, x_2 = r$ are both measurable.

Assumption 2 The smooth reference trajectory Ψ_d and its first 2 derivatives $\dot{\Psi}_d, \ddot{\Psi}_d$ are known and bounded.

3 Design of ship nonlinear adaptive controller

During the course-changing operation it is desirable to specify the dynamics of the desired heading rather than use a constant reference signal. One simple way to achieve this is to apply model reference techniques. The objective of a course-changing operation is to perform the operation quickly with minimum overshoot. The ideal performance can be given by reference model (6)[11] such as

$$\Psi_d = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}\Psi_r, \tag{6}$$

where ξ and ω_n are the parameters to be determined that describe the closed-loop system response characteristics; the input Ψ_r of the reference model is the course-changing heading command, and the output Ψ_d of the reference model is the desired smooth course-changing signal.

The reference model (6) can be interpreted as a pre-filter for the commanded heading. The pre-filter ensures that numerical difficulties associated with large step inputs are avoided. A second-order model is sufficient to generate the desired smooth course signal Ψ_d with known and bounded derivatives $\dot{\Psi}_d, \ddot{\Psi}_d$.

The adaptive controller of course tracking of the system (5) is designed as follows. Our design consists of 2 steps through the backstepping algorithm. The designs of both the control law and the adaptive laws are based on the change of coordinates

$$z_1 = \Psi - \Psi_d = x_1 - \Psi_d, \tag{7a}$$

$$z_2 = x_2 - \phi_1(z_1, \dot{\Psi}_d), \tag{7b}$$

where the function ϕ_1 is referred to as the intermediate control function which will be designed later by using an appropriate Lyapunov function V_1, while z_1 is just course tracking error. At the second step, the actual control u appears and the design is completed.

Step 1 Let us study the following subsystem (5a)

$$\dot{x}_1 = x_2. \tag{8}$$

In light of (7a), equation (8) becomes

$$\dot{z}_1 = x_2 - \dot{\Psi}_d, \tag{9}$$

where x_2 is taken as a virtual control input.

Consider a Lyapunov function candidate V_1:

$$V_1 = \frac{1}{2}z_1^2. \tag{10}$$

The time derivative of V_1 along the solution of (9):

$$\dot{V}_1 = z_1(x_2 - \dot{\Psi}_d). \tag{11}$$

Let the intermediate control function ϕ_1 be

$$\phi_1(z_1, \dot{\Psi}_d) = -c_1 z_1 + \dot{\Psi}_d, \tag{12}$$

where the design constant $c_1 > 0$ will be chosen later. Using (12), a direct substitution of $x_2 = z_2 + \phi_1$ into (11) yields

$$\dot{V}_1 = -c_1 z_1^2 + z_1 z_2. \tag{13}$$

The "undesired" effects of z_2 on $\dot{V}_1$ will be dealt with at the next step.

Step 2 In light of (7b), (9) and (12), the derivative of z_2 is

$$\dot{z}_2 = \theta_0 u + \sum_{j=1}^{2}\theta_j\varphi_{2,j} + c_1(-c_1 z_1 + z_2) - \ddot{\Psi}_d = \theta_0 u + \sum_{j=1}^{2}\theta_j\varphi_{2,j} + \varphi_{2,3}, \tag{14}$$

where $\varphi_{2,3} = -c_1^2 z_1 + c_1 z_2 - \ddot{\Psi}_d$ is a smooth function of $(z_1, z_2, \ddot{\Psi}_d)$.

In order to cope with the unknown sign of uncertain control coefficient θ_0, the Nussbaum gain technique which was originally proposed in [9] is employed in this paper. A function $N(\cdot)$ is called a Nussbaum-type function[9] if it has the following properties:

$$\limsup_{s\to\infty}\frac{1}{s}\int_0^s N(k)\mathrm{d}k = \infty, \tag{15a}$$

$$\liminf_{s\to\infty}\frac{1}{s}\int_0^s N(k)\mathrm{d}k = -\infty. \tag{15b}$$

Commonly used Nussbaum functions include: $\exp(k^2)\cos((\pi/2)k)$, $k^2\cos(k)$, and $k^2\sin(k)$.

We now give the following lemma regarding to the property of Nussbaum gain which is used in the controller design. The proof can be found in [12].

Lemma 1 Let $V(\cdot)$ and $k(\cdot)$ be smooth functions defined on $[0, t_f)$ with $V(t) \geqslant 0$, $\forall t \in [0, t_f)$, $N(\cdot)$ be an even smooth Nussbaum-type function, and θ be a nonzero constant. If the following inequality holds

$$V(t) \leqslant \int_0^t (\theta N(k) + 1)\dot{k}(\tau)\mathrm{d}\tau + C, \ \forall t \in [0, t_f), \tag{16}$$

where C represents some suitable constant, then $k(t)$, $V(t)$, and $\int_0^t (\theta N(k) + 1)\dot{k}(\tau)\mathrm{d}\tau$ must be bounded in $[0, t_f)$.

Let the control input be designed as the following actual adaptive control:

$$u = N(k)(c_2 z_2 + \varphi_{2,3} + \sum_{j=1}^{2}\hat{\theta}_j\varphi_{2,j}) \tag{17}$$

with

$$N(k) = k^2\cos(k), \tag{18}$$

$$\dot{k} = c_2 z_2^2 + \varphi_{2,3}z_2 + \sum_{j=1}^{2}\hat{\theta}_j\varphi_{2,j}z_2, \tag{19}$$

where c_2 is a positive design constant and $N(\cdot)$ is an even smooth Nussbaum-type function. $\hat{\theta}_j (1 \leqslant j \leqslant 2)$ are the parameter estimates of the unknown parameters θ_j, $1 \leqslant j \leqslant 2$.

Let the parameter adaptation laws be

$$\dot{\hat{\theta}}_j = \varphi_{2,j}z_2, \ 1 \leqslant j \leqslant 2. \tag{20}$$

The distinguishing feature in (17) ~ (20) is that $\hat{\theta}_j (1 \leqslant j \leqslant 2)$ are contained in the update law of $k(t)$, which is the argument of the Nussbaum-type gain $N(k)$[12].

Consider the Lyapunov function candidate V_2:

$$V_2 = V_1 + \frac{1}{2}z_2^2 + \frac{1}{2}\sum_{j=1}^{2}(\hat{\theta}_j - \theta_j)^2. \tag{21}$$

The time derivative of V_2, computed with (18) ~ (21) in (14), is given by

$$\dot{V}_2 =$$
$$\dot{V}_1+z_2(\theta_0 u+\sum_{j=1}^{2}\theta_j\varphi_{2,j}+\varphi_{2,3})+\sum_{j=1}^{2}(\hat{\theta}_j-\theta_j)\dot{\hat{\theta}}_j =$$
$$-c_1z_1^2+z_1z_2+\theta_0z_2N(k)(c_2z_2+\varphi_{2,3}+\sum_{j=1}^{2}\hat{\theta}_j\varphi_{2,j})+$$
$$\sum_{j=1}^{2}\theta_j\varphi_{2,j}z_2+\varphi_{2,3}z_2+\sum_{j=1}^{2}(\hat{\theta}_j-\theta_j)\dot{\hat{\theta}}_j =$$
$$-c_1z_1^2+z_1z_2-c_2z_2^2+(\theta_0N(k)+1)(c_2z_2^2+\varphi_{2,3}z_2+$$
$$\sum_{j=1}^{2}\hat{\theta}_j\varphi_{2,j}z_2)+\sum_{j=1}^{2}(\hat{\theta}_j-\theta_j)(\dot{\hat{\theta}}_j-\varphi_{2,j}z_2) =$$
$$-(c_1-\frac{1}{4a^2})z_1^2-(c_2-a^2)z_2^2-$$
$$(\frac{1}{2a}z_1-z_2)^2+(\theta_0N(k)+1)\dot{k}\leqslant$$
$$-(c_1-\frac{1}{4a^2})z_1^2-(c_2-a^2)z_2^2+(\theta_0N(k)+1)\dot{k}. \tag{22}$$

So far the design procedure is complete. Due to the smoothness of the proposed adaptive control (17), the resulting closed-loop system (5), (17) ~ (20) admits a solution defined on its maximum interval of existence $[0, t_f)$. Using Lemma 1 to (22), when $c_1c_2 > 1/4$, we conclude that $\int_0^t(\theta_0N(k)+1)\dot{k}(\tau)\mathrm{d}\tau$, $V_2(t)$, and $k(t)$, hence, $z_1, z_2, \hat{\theta}_j (1 \leqslant j \leqslant 2)$ and $N(k)$ are bounded. Furthermore, z_1, z_2 is square integrable according to (22), all on $[0, t_f)$. In turn ϕ_1 and the original state x_1, x_2 are also bounded on $[0, t_f)$. Therefore, no finite-time escape phenomenon may occur and $t_f = \infty$. Thus, applying Barbalat's lemma, we conclude that $\lim_{t\to\infty}z_1(t) = \lim_{t\to\infty}z_2(t) = 0$. Since $z_1 = \Psi - \Psi_d$, $y = \Psi \to \Psi_d$, the actual heading of ship asymptotically tracks the desired changing reference heading. The above facts prove the following theorem.

Theorem 1 Suppose the feedback control law (17) is applied to the ship motion nonlinear system (5) of parametric uncertain strict feedback with complete unknown control coefficient θ_0, then all the signals in the resulting closed-loop adaptive system are ultimately bounded. Furthermore, the closed-loop error system

$$\dot{z}_1 = -c_1z_1+z_2,$$
$$\dot{z}_2 = \theta_0u+\sum_{j=1}^{2}\theta_j\varphi_{2,j}+\varphi_{2,3}$$

achieves uniform asymptotic stability. The tracking of state x_1 is achieved, and the feedback control law (17) forces the heading tracking error to converge to zero, i.e. $\lim_{t\to\infty}\Psi \to \Psi_d$.

4 Simulation studies

In this section, two simulation examples will be presented, which validate control law (17) ~ (20). In the simulation, let the input Ψ_r of the reference model be the square wave signal whose period is 400s and magnitude is 30°. The design parameters of the reference model (6) are chosen as $\omega_n = 0.05$ rad/s, $\xi = 0.8$.

Example 1 The ship dynamics parameters of equation (5) used in the simulation study are $T = 21$ s, $K = 0.23$ 1/s, $\alpha = 0.3$ s^2. These values are obtained from identification results of a frigate at a speed of 12 m/s[6].

We choose the control design parameters as $c_1 = 0.3$, $c_2 = 8$. The initial values are selected as $k(0) = 0.6*\pi$, $x_1(0) = x_2(0) = \hat{\theta}_1(0) = \hat{\theta}_2(0) = 0$. The simulation results of a course-changing operation where a heading change of 60° is involved are plotted in Fig. 1 to Fig. 4.

Example 2 The test bed is a small ship with length of 45 m. The motion of the ship described by the model of equation (5) has the following set of dynamics parameters at a forward speed of 5 m/s: $T = 31$ s, $K = 0.5$ 1/s, $\alpha = 0.4$ s^2[4].

We adopt the same initial conditions and control design parameters as the counterparts of example 1 in the simulation. Fig. 5 to Fig. 8 depict the simulation results in this case.

It can be seen from Fig. 1 and Fig. 5 that the actual heading angle Ψ (solid-line) asymptotically tracks the output Ψ_d (dotted-line) of the reference model as desired, and the control rudder angle δ (dashdot-line) are smooth. In Fig. 2 to Fig. 4 and Fig. 6 to Fig. 8, the estimated parameters do not converge to the true value, the envelopes of their tracking curves are, however, convergent. They are bounded as proven in Theorem 1. Therefore, the proposed adaptive course autopilot is effective in that it makes the actual course of ship asymptotically track desired course changes for the ship motion system (5) with uncertain parameters and completely unknown control coefficient θ_0. Furthermore, the same initial conditions and control design parameters are applied to the two different ship steering models used in the simulation studies, so the robustness of the proposed adaptive controller to the parameter changes is obviously given from Fig. 1 to Fig. 8.

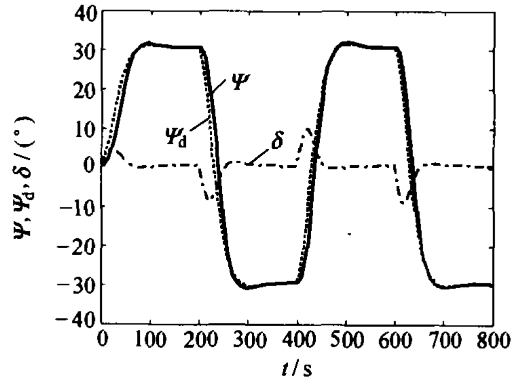

Fig. 1 Ψ, Ψ_d and δ curves of ship

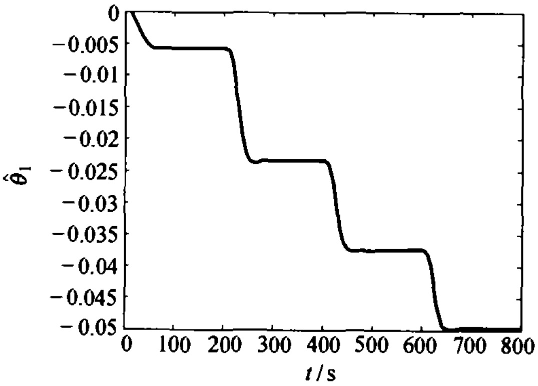

Fig. 2 $\hat{\theta}_1$ of ship course-tracking control system

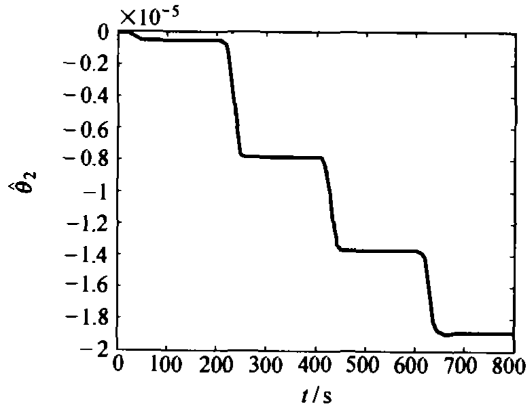

Fig. 3 $\hat{\theta}_2$ of ship course-tracking control system

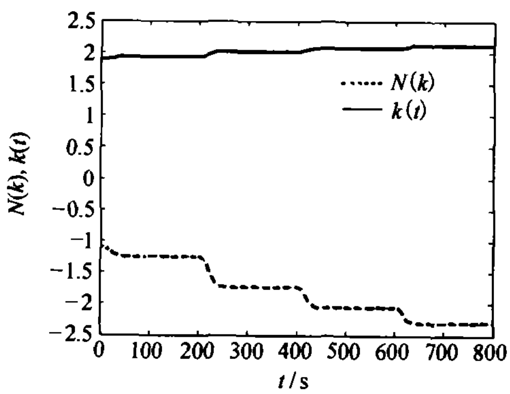

Fig. 4 $N(k)$ and its argument $k(t)$ adaptive curves

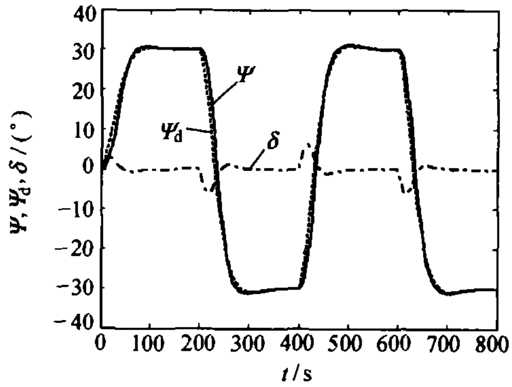

Fig. 5 Ψ, Ψ_d and δ curves of ship

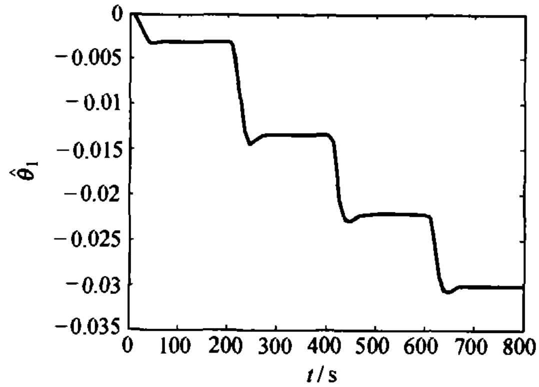

Fig. 6 $\hat{\theta}_1$ of ship course-tracking control system

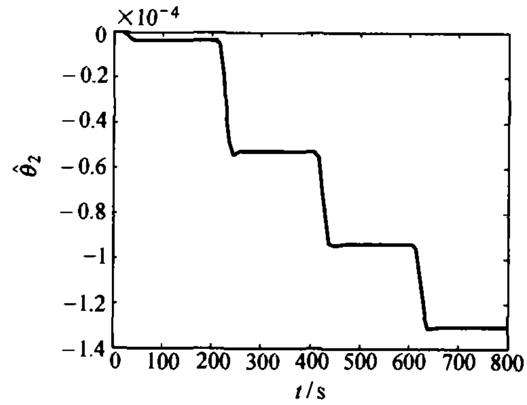

Fig. 7 $\hat{\theta}_2$ of ship course-tracking control system

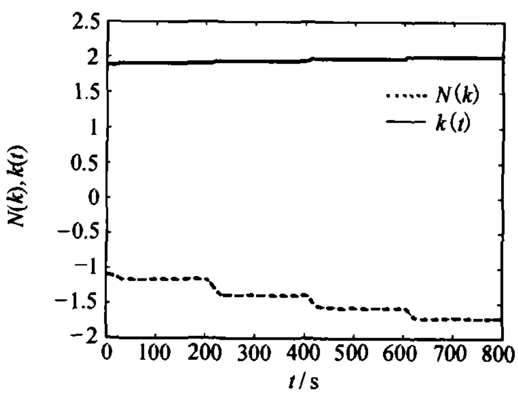

Fig. 8 $N(k)$ and its argument $k(t)$ adaptive curves

5 Conclusion

In order to improve the performance of ship autopilot, this paper firstly establishes nonlinear mathematic models of ship movement with uncertain parameters. Based on that, a new nonlinear adaptive control design scheme is put forward, which combines backstepping algorithm with Nussbaum-type function without a priori knowledge about the sign of control gain. As to the ship motion models with unknown parameters, the proposed method simultaneously designs adaptive nonlinear ship course-tracking controller and parameter estimator, and deals with the problems that the sign of control gain is unknown, and finally, accomplishes global adaptive tracking control of ship course. The control law of the adaptive algorithm is smooth. The simulation results show that the proposed control approach has the desired adaptability and robustness to uncertain parameters, and is practically effective.

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测PI控制算法,给出了它的结构形式和性能分析.这种方法控制结构简单,可调参数少,而且参数有明显的物理意义,便于参数的整定.仿真和实际应用,显示它有良好的跟踪性能和抗干扰性能,鲁棒稳定性能好.

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