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Novel disturbance compensating dynamic positioning of dredgers based on adaptive backstepping

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Abstract: In order to deal with the dynamic positioning system control problems of dredgers working under strong dredging reaction or harsh environments, an adaptive backstepping method is proposed. Disturbances are estimated and compensated for by the adaptive method without extra sensors on dredging equipment, and the control mechanism is simplified. Adaptive control is used to compensate for the reaction and environmental disturbances on the dredger, so the dredger can maintain the desired position with a minimum error and shock. The proposed adaptive robust controller guarantees the global asymptotic stability of the closed-loop system and rapid position tracking of the dredger. The simulation results show that the proposed controller has superior performance in position tracking and robustness to large disturbances.

Key words: dynamic positioning (DP); adaptive backstepping; nonlinear control; dredger; disturbance compensating

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Dredgers play a crucial role in the port dredging industry, and dredgers with dynamic positioning systems (DPS) are of high efficiency. So the DPS is essentially necessary to improve the efficiency of the port dredging operation and working conditions in harsh marine environments.

As there are large disturbances caused by dredging operations, it is difficult to maintain the stability and accuracy of the DP systems. In order to solve these problems, force-and-torque sensors are applied to compensate for these kinds of reactions caused by dredging operations in traditional dredger DP systems. But this will increase complexity and unreliability. Based on such considerations, an adaptive backstepping technique is proposed in this paper to solve this problem without extra sensors for the dredger DPS.

A dynamically positioned vessel maintains its position (fixed location or predetermined track) exclusively by means of active thrusters. However, in a conventional chain and anchor mooring system, the length of lines becomes excessive so that maintaining the position of an offshore platform becomes difficult both technically and economically. Therefore, DP systems with thrusters are often used for those applications. The first DP system was introduced in the early 1960s[1]. The conventional DP systems are based on the linearized system which is widely used in the DP systems for ships[2–3]. Because of the limitations of linear control techniques, such as complexity in tuning control gains and no global stability results due to linearization, recently, some researchers have applied the nonlinear control theory to design control systems for the DP of the surface vessels. Krstic et al.[4] developed a backstepping approach of a step-by-step design procedure. The Lyapunov technique[5–7] and the backstepping technique[8–9] are used to design a DP controller system. Recently, the adaptive backstepping techniques have developed rapidly[10–12].

In this paper, the adaptive backstepping method is used in the dredger DPS. The adaptive method can estimate the value of disturbances and change the feedback to guarantee stability. Comparisons are carried out to verify the advantages of the adaptive backstepping technique over the conventional backstepping control technique in the dredger DPS.

1 Problem Statement

First, a symmetrical xz-plane is defined to describe the problem, where the z-axis points to the geocentric. As shown in Fig. 1, $O_E X_E Y_E$ is the earth-fixed frame, OXY is the body-fixed frame, and O_c is the center of gravity of the vessel.

Assume that the following conditions hold:

1) The ship is symmetrical in the xz-plane;

2) The surge is decoupled from sway, yaw and heave;

3) The pitch and roll modes are ignored;

4) The body-fixed frame coordinate origin is on the centre-line of the ship (see Fig. 1).

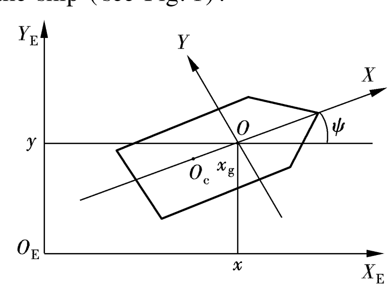

Fig. 1 Definition of the earth-fixed frame $O_E X_E Y_E$ and the body-fixed frame OXY

The mathematical model of the ship used for the DP in a horizontal plane is described as[13]

$$\left.\begin{aligned} \dot{\boldsymbol{\eta}} &= \boldsymbol{J}(\psi)\boldsymbol{v} \\ \boldsymbol{M}\dot{\boldsymbol{v}} &= -\boldsymbol{D}\boldsymbol{v} + \boldsymbol{\tau} + \boldsymbol{\tau}_{dis} \end{aligned}\right\} \tag{1}$$

where $\boldsymbol{\tau}_{dis}$ represents the environmental disturbances; $\boldsymbol{\eta} = [x \quad y \quad \psi]^T$ denotes the position (x, y) and heading ψ of

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the ship coordinated in the earth-fixed frame; $\boldsymbol{v} = [u \quad w \quad r]^{\mathrm{T}}$ indicates the surge, sway and yaw velocities of the ship coordinated in the body-fixed frame.

The rotation matrix $\boldsymbol{J}(\psi)$, the mass matrix $\boldsymbol{M}$, and the damping matrix $\boldsymbol{D}$ are given by

$$\boldsymbol{J}(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{M} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{w}} & mx_{\mathrm{g}} - Y_{\dot{r}} \\ 0 & mx_{\mathrm{g}} - N_{\dot{w}} & I_z - N_{\dot{r}} \end{bmatrix}$$

$$\boldsymbol{D} = -\begin{bmatrix} X_u & 0 & 0 \\ 0 & Y_w & Y_r \\ 0 & N_w & N_r \end{bmatrix}$$

where m is the vessel mass; I_z is the moment of inertia about the body-fixed z-axis; x_{g} is the distance from the origin O of the body-fixed frame to the center of gravity of the vessel. The other symbols can be referred to Ref. [14].

The control input vector $\boldsymbol{\tau} \in \mathbf{R}^3$ of forces and moments provided by the actuator system, and the disturbance vector $\boldsymbol{\tau}_{\mathrm{dis}}$ of forces and moments induced by waves, wind and ocean currents are given by

$$\boldsymbol{\tau} = \boldsymbol{G}\boldsymbol{h}, \quad \boldsymbol{\tau}_{\mathrm{dis}} = \boldsymbol{J}^{\mathrm{T}}(\psi)\boldsymbol{b}$$

where $\boldsymbol{h} \in \mathbf{R}^n$ is the control input with $n \geqslant 3$ denoting the number of independent actuators, and $\boldsymbol{G} \in \mathbf{R}^{3\times n}$ is a constant matrix describing the actuator configuration. Unmolded external forces and moments due to waves, wind, ocean currents, and ship parameters perturbation are lumped together into an earth-fixed constant vector $\boldsymbol{b} \in \mathbf{R}^3$.

To simulate the marine environment disturbance, the following model is adopted. The environmental force model in the fixed coordinate system is [15]

$$\dot{\boldsymbol{b}} = -\boldsymbol{T}^{-1}\boldsymbol{b} + \boldsymbol{E}_{\mathrm{b}}\boldsymbol{\omega}_{\mathrm{b}} \tag{2}$$

where $\boldsymbol{b}$ is a three-dimensional vector; $\boldsymbol{T}$ is a three-dimensional time-constant diagonal matrix; $\boldsymbol{\omega}_{\mathrm{b}}$ is a zero-mean white noise vector; and $\boldsymbol{E}_{\mathrm{b}}$ is a three-dimensional diagonal matrix which denotes the amplitude of the environmental forces.

The problem in this paper is to design a robust adaptive backstepping controller $\boldsymbol{\tau}$ of system (1), which makes the output $\boldsymbol{\eta}$ asymptotically track its reference signal.

2 Controller Design

The two-step realization process of the controller is derived in this section.

Step 1 $\boldsymbol{\eta}_{\mathrm{d}}$ is defined as the desired position, then the position error is

$$\boldsymbol{e}_1 = \boldsymbol{\eta} - \boldsymbol{\eta}_{\mathrm{d}} \tag{3}$$

The derivative of $\boldsymbol{e}_1$ is

$$\dot{\boldsymbol{e}}_1 = \dot{\boldsymbol{\eta}} - \dot{\boldsymbol{\eta}}_{\mathrm{d}} = \boldsymbol{J}(\psi)\boldsymbol{v} - \dot{\boldsymbol{\eta}}_{\mathrm{d}} \tag{4}$$

Take $\boldsymbol{v}$ as a virtual controller, then a new error is defined as

$$\boldsymbol{e}_2 = \boldsymbol{v} - \boldsymbol{a}_1 \tag{5}$$

where $\boldsymbol{a}_1$ is a stabilizing function which will be designed later.

Select the first Lyapunov function candidate as

$$V_1 = \frac{1}{2}\boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{e}_1 \tag{6}$$

Then the time derivative of V_1 can be obtained as

$$\dot{V}_1 = \boldsymbol{e}_1^{\mathrm{T}}\dot{\boldsymbol{e}}_1 = \boldsymbol{e}_1^{\mathrm{T}}(\boldsymbol{J}(\psi)(\boldsymbol{e}_2 + \boldsymbol{a}_1) - \dot{\boldsymbol{\eta}}_{\mathrm{d}}) \tag{7}$$

Take the first stabilizing function $\boldsymbol{a}_1$ as

$$\boldsymbol{a}_1 = \boldsymbol{J}^{-1}(\psi)\dot{\boldsymbol{\eta}}_{\mathrm{d}} + \boldsymbol{J}^{-1}(\psi)\boldsymbol{K}_1\boldsymbol{e}_1 \tag{8}$$

where $\boldsymbol{K}_1 = \mathrm{diag}\{a_{11}, a_{22}, a_{33}\}$ is a designed constant matrix, $a_{ii} > 0$, $i = 1, 2, 3$.

Substituting Eq. (8) into Eq. (7), we can obtain

$$\dot{V}_1 = -\boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{K}_1\boldsymbol{e}_1 + \boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{J}(\psi)\boldsymbol{e}_2 \tag{9}$$

Step 2 According to Eq. (5), the derivative of $\boldsymbol{e}_2$ is

$$\dot{\boldsymbol{e}}_2 = \dot{\boldsymbol{v}} - \dot{\boldsymbol{a}}_1 \tag{10}$$

Multiplying both sides of Eq. (10) by $\boldsymbol{M}$, we obtain

$$\boldsymbol{M}\dot{\boldsymbol{e}}_2 = \boldsymbol{M}\dot{\boldsymbol{v}} - \boldsymbol{M}\dot{\boldsymbol{a}}_1 \tag{11}$$

Substituting Eq. (1) into Eq. (11) results in

$$\boldsymbol{M}\dot{\boldsymbol{e}}_2 = -\boldsymbol{D}\boldsymbol{v} + \boldsymbol{\tau} + \boldsymbol{\tau}_{\mathrm{dis}} - \boldsymbol{M}\dot{\boldsymbol{a}}_1 \tag{12}$$

Select the second Lyapunov function candidate as

$$V_2 = V_1 + \frac{1}{2}\boldsymbol{e}_2^{\mathrm{T}}\boldsymbol{M}\boldsymbol{e}_2 + \frac{1}{2}\tilde{\boldsymbol{\tau}}_{\mathrm{dis}}^{\mathrm{T}}\boldsymbol{\rho}^{-1}\tilde{\boldsymbol{\tau}}_{\mathrm{dis}} \tag{13}$$

where $\boldsymbol{\rho} = \mathrm{diag}\{\lambda_{11}, \lambda_{22}, \lambda_{33}\}$ is the adaptive gain coefficient matrix, $\lambda_{ii} > 0$, $i = 1, 2, 3$; $\hat{\boldsymbol{\tau}}_{\mathrm{dis}}$ is the estimate of $\boldsymbol{\tau}_{\mathrm{dis}}$; and $\tilde{\boldsymbol{\tau}}_{\mathrm{dis}} = \hat{\boldsymbol{\tau}}_{\mathrm{dis}} - \boldsymbol{\tau}_{\mathrm{dis}}$ is the estimation error between $\hat{\boldsymbol{\tau}}_{\mathrm{dis}}$ and $\boldsymbol{\tau}_{\mathrm{dis}}$. The derivate of V_2 is

$$\dot{V}_2 = \dot{V}_1 + \boldsymbol{e}_2^{\mathrm{T}}\boldsymbol{M}\dot{\boldsymbol{e}}_2 + \tilde{\boldsymbol{\tau}}_{\mathrm{dis}}^{\mathrm{T}}\boldsymbol{\rho}^{-1}\dot{\hat{\boldsymbol{\tau}}}_{\mathrm{dis}} \tag{14}$$

Substituting Eqs. (9), (10) and (12) into Eq. (14), we obtain

$$\begin{aligned} \dot{V}_2 = & -\boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{K}_1\boldsymbol{e}_1 + \boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{J}(\psi)\boldsymbol{e}_2 + \\ & \boldsymbol{e}_2^{\mathrm{T}}(-\boldsymbol{D}\boldsymbol{v} + \boldsymbol{\tau} + \boldsymbol{\tau}_{\mathrm{dis}} - \boldsymbol{M}\dot{\boldsymbol{a}}_1) + \tilde{\boldsymbol{\tau}}_{\mathrm{dis}}^{\mathrm{T}}\boldsymbol{\rho}^{-1}\dot{\hat{\boldsymbol{\tau}}}_{\mathrm{dis}} \end{aligned} \tag{15}$$

According to Eq. (8), the derivative of $\boldsymbol{a}_1$ is

$$\begin{aligned} \dot{\boldsymbol{a}}_1 = & \dot{\boldsymbol{J}}^{-1}(\psi)(\dot{\boldsymbol{\eta}}_{\mathrm{d}} + \boldsymbol{K}_1\boldsymbol{e}_1) + \\ & \boldsymbol{J}^{-1}(\psi)\ (\ddot{\boldsymbol{\eta}}_{\mathrm{d}} + \boldsymbol{K}_1\boldsymbol{J}(\psi)\boldsymbol{v} - \boldsymbol{K}_1\boldsymbol{\eta}_{\mathrm{d}}) \end{aligned} \tag{16}$$

By substituting Eq. (16) into Eq. (15), Eq. (15) is transformed into

$$\begin{aligned} \dot{V}_2 = & -\boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{K}_1\boldsymbol{e}_1 + \boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{J}(\psi)\boldsymbol{e}_2 + \tilde{\boldsymbol{\tau}}_{\mathrm{dis}}^{\mathrm{T}}\boldsymbol{\rho}^{-1}\dot{\hat{\boldsymbol{\tau}}}_{\mathrm{dis}} + \\ & \boldsymbol{e}_2^{\mathrm{T}}[-\boldsymbol{D}\boldsymbol{v} + \boldsymbol{\tau} + \boldsymbol{\tau}_{\mathrm{dis}} - \boldsymbol{M}\dot{\boldsymbol{J}}^{-1}(\psi)(\dot{\boldsymbol{\eta}}_{\mathrm{d}} + \boldsymbol{K}_1\boldsymbol{e}_1) - \\ & \boldsymbol{M}\boldsymbol{J}^{-1}(\psi)(\ddot{\boldsymbol{\eta}}_d + \boldsymbol{K}_1\boldsymbol{J}(\psi)\boldsymbol{v} - \boldsymbol{K}_1\boldsymbol{\eta}_{\mathrm{d}})] \end{aligned} \tag{17}$$

Let the actual control $\boldsymbol{\tau}$ be

$$\boldsymbol{\tau} = \boldsymbol{D}\boldsymbol{v} - \hat{\boldsymbol{\tau}}_{\mathrm{dis}} + \boldsymbol{M}\dot{\boldsymbol{J}}^{-1}(\psi)(\dot{\boldsymbol{\eta}}_{\mathrm{d}} + \boldsymbol{K}_1\boldsymbol{e}_1) + \boldsymbol{M}\boldsymbol{J}^{-1}(\psi)(\ddot{\boldsymbol{\eta}}_{\mathrm{d}} + \boldsymbol{K}_1\boldsymbol{J}(\psi)\boldsymbol{v} + \boldsymbol{K}_1\boldsymbol{\eta}_{\mathrm{d}}) + \boldsymbol{J}(\psi)\boldsymbol{e}_2 + \boldsymbol{K}_2\boldsymbol{e}_2 \tag{18}$$

where $\boldsymbol{K}_2 = \mathrm{diag}\{b_{11}, b_{22}, b_{33}\}$ is a designed constant matrix, $b_{ii} > 0, i = 1, 2, 3$.

Let the disturbances adaptive updating law be

$$\dot{\hat{\boldsymbol{\tau}}}_{\mathrm{dis}} = \boldsymbol{\rho}\boldsymbol{e}_2 \tag{19}$$

Substituting Eqs. (18) and (19) into Eq. (17), we can obtain

$$\dot{V}_2 = -\boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{K}_1\boldsymbol{e}_1 - \boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{K}_2\boldsymbol{e}_2 + \tilde{\boldsymbol{\tau}}_{\mathrm{dis}}^{\mathrm{T}}(\boldsymbol{\rho}^{-1}\dot{\hat{\boldsymbol{\tau}}}_{\mathrm{dis}} - \boldsymbol{e}_2) \tag{20}$$

Substituting Eq. (20) into Eq. (21), we obtain

$$\dot{V}_2 = -\boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{K}_1\boldsymbol{e}_1 - \boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{K}_2\boldsymbol{e}_2 \tag{21}$$

As $\boldsymbol{K}_1 > \boldsymbol{0}$ and $\boldsymbol{K}_2 > \boldsymbol{0}$ are selected, the system (1) is globally asymptotically stable.

3 Simulation Results

The performance of the closed-loop DP system is demonstrated by simulations using the Matlab/Simulink toolbox. The main dimensions of the example ship are given in Tab. 1.

Tab. 1 Parameters of the example ship

Parameter	Value
Ship length/m	286. 3
Waterline length/m	280. 5
Ship width/m	46. 89
Ship height/m	24. 5
Draft/m	17. 38
Displacement/t	205 326
Distance from gravity centre to the centre/m	4. 51

Based on the main parameters listed in Tab. 1, the non-dimensional system matrices describing the ship are estimated by the empirical formula[16] as

$$\boldsymbol{M} = \begin{bmatrix} 1.1254 & 0 & 0 \\ 0 & 1.8945 & -0.0734 \\ 0 & -0.0734 & 0.1287 \end{bmatrix}$$

$$\boldsymbol{D} = -\begin{bmatrix} 0.0360 & 0 & 0 \\ 0 & 0.1182 & -0.0125 \\ 0 & -0.0043 & 0.0305 \end{bmatrix}$$

The adaptive backstepping controller parameters are selected as $\boldsymbol{K}_1 = \mathrm{diag}\{2, 2, 2\}$, $\boldsymbol{K}_2 = \mathrm{diag}\{2, 2, 2\}$, and $\boldsymbol{\rho} = \mathrm{diag}\{5, 5, 5\}$ in simulations. The start position of the ship is $\boldsymbol{\eta}_0 = [-5 \quad -5 \quad 20]^{\mathrm{T}}$, and the desired position is $\boldsymbol{\eta}_{\mathrm{d}} = [0 \quad 0 \quad 0]^{\mathrm{T}}$. The traditional and adaptive backstepping control techniques are compared with each other. Especially large disturbances such as harsh sea conditions or the reaction forces of dredging are considered to demonstrate the robust performance of the controller.

According to Eq. (2), the parameters describing large disturbances are set as follows:

$$\boldsymbol{T} = \mathrm{diag}[1000 \quad 1000 \quad 1000]$$

$$\boldsymbol{E}_{\mathrm{b}} = \mathrm{diag}[10 \quad 10 \quad 10]$$

There are two types of disturbances in this section. One is the large amplitude representing the harsh sea conditions and the other is the dramatic change representing dredging operations. The maximum values of disturbances are listed in Tab. 2, and the y-axis disturbance waveform and its adaptive value waveform in adaptive backstepping are shown in Fig. 2, and outputs steady-state errors of backstepping and adaptive backstepping are listed in Tab. 3. Simulation results (y-axis) of the traditional and adaptive backstepping techniques are shown in Fig. 3 and Fig. 4, respectively. Simulation results show very similar performance in the x-axis, yaw and y-axis behaviours.

Tab. 2 The maximum values of disturbances

x-axis force/MN	y-axis force/MN	Yaw torque/(MN · m)
100	80	135

Tab. 3 Outputs steady-state errors of backstepping and adaptive backstepping

Method	x-error/m	y-error/m	Yaw error/(°)
Backstepping	17	12	6
Adaptive backstepping	0. 2	0. 15	0. 1

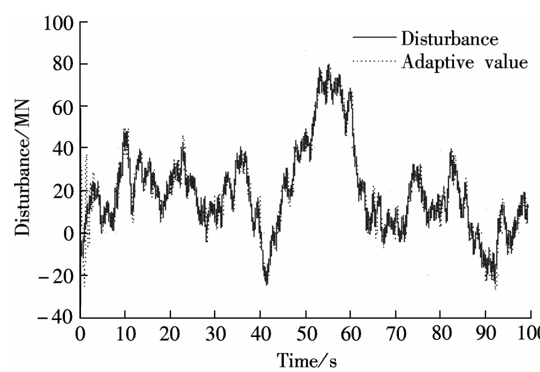

Fig. 2 y-axis disturbance waveform and its adaptive value waveform in adaptive backstepping

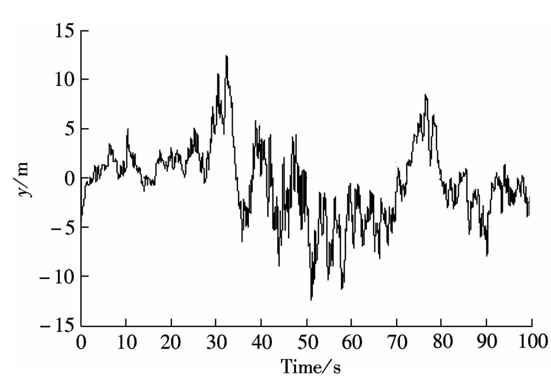

Fig. 3 Simulation results of y-axis using backstepping without compensation

Both approaches can maintain stability in the presence of disturbances. However, the adaptive one can obtain better performance. This is because the adaptive algorithm can estimate the disturbances and make compensation accurately.

4 Conclusion

Based on the perturbed nonlinear mathematical model

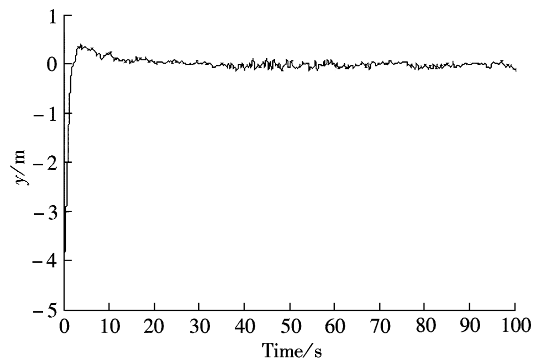

Fig. 4 Simulation results of y-axis using adaptive backstepping with compensation

using adaptive backstepping, a novel adaptive control strategy is presented in this paper to deal with the control difficulties of the DP system for the dredgers. The external disturbances are comprehensively considered in simulations. The global adaptive tracking is well achieved. Furthermore, the simulation results illustrate that the proposed control technique is practical, effective, and robust when facing the external disturbances.

An adaptive method is applied to compensate the external disturbances, guaranteeing the system stability under strong force reaction disturbances or under harsh sea conditions. So dredging reaction can be compensated for without extra sensors in the dredgers.

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基于自适应反步法的干扰补偿挖泥船动力定位控制

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摘要:为解决挖泥船在挖泥强反作用干扰或恶劣环境干扰下,动力定位控制系统不稳定的难题,提出采用自适应反步法来解决挖泥船的动力定位问题. 由于自适应算法采用实时估计干扰值并进行前馈补偿,而不是在挖泥机构上额外加装传感器的方法, 从而简化了控制机构并同时保证了控制的效果. 自适应控制能前馈补偿反作用干扰及环境干扰对船体的作用,使船体能以最小的误差与冲击稳定在指定位置. 定位控制在强干扰作用下依然能快速跟踪设定位置,而且保证控制系统全局渐近稳定. 仿真结果表明,动力定位系统在强干扰环境中依然能够保持良好跟踪的动静态性能.

关键词:动力定位;自适应反步;非线性控制,挖泥船;干扰补偿

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