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Nonlinear Improved Concise Backstepping Control of Course Keeping for Ships

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ABSTRACT The backstepping control is a kind of nonlinear controller design algorithm. To simplify the nonlinear controller design process, decrease the number of undetermined parameters, improve the robustness, and reduce the energy consumption of the course-keeping controller for ships, an improved concise design method is proposed by introducing an arctan nonlinear function passed through by course error signal under the backstepping design framework, while the design process of the controller is simplified to only one step. The simulation results indicate that, compared with the backstepping-based controller, the maximum response performance (quantified by the mean absolute error) under the proposed controller increases by 57.8%, the maximum energy cost performance (quantified by the mean integral absolute) reduces by 28.6% and the maximum smoothness performance (quantified by the mean total variation) reduces by 44.3% with the strong ability of disturbances rejection. The algorithm given in the note has advantages of the simple design process, strong robustness, and low energy consumption.

INDEX TERMS Ships, course-keeping control, nonlinear feedback, backstepping, arctan function.

I. INTRODUCTION

Backstepping is a design methodology for construction of a feedback control law through a recursive construction of a control Lyapunov function [1]. Due to its unique advantages in dealing with nonlinear control problems, backstepping method has drawn much attention in the field of ship motion control. In [2], backstepping and Lyapunov's direct methods were applied to global robust adaptive path-tracking control of under-actuated ships under stochastic disturbances, while in [3], the backstepping was also employed to globe stable tracking control of under-actuated ships with input saturation. In [4] and [5], an adaptive neural networks (NNs) backstepping control algorithm was proposed for a nonlinear ship course-keeping control system based on dynamic surface control (DSC) and Nussbaum gain function, while the problem of course control for under-actuated surface ship was solved by adopting robust neural network backstepping method for determining the parameters of the unknown part of ideal virtual backstepping control in [6], then the Lyapunov stability theory was employed to prove the uniform stability for the convergence of course tracking errors. An optimal backstepping controller using firefly optimization algorithm and disturbance observer was proposed by Muhammad and Mou for the ship trajectory tracking [7]. To realize the collision avoidance of multiple under-actuated ships, the backstepping was also employed to design the tracking controller [8]. In [9] and [10], the backstepping was employed to design station-keeping controllers for an unmanned surface vehicle, which showed the effectiveness in practical marine control systems. While in the ship dynamic positioning research field, the backstepping algorithm was widely used in combination with constructed observer [11], [12], fuzzy output-feedback control [13] and sequential quadratic programming [14].

In order to make the ship steering controller highly efficient or easy-to-implement for its burden, many researchers had done a lot of work [15]. However, to obtain the robustness

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and design flexibility, nonlinear backstepping designs were strongly related to the cancellation of all nonlinearities, which was important in industrial control system for the cancellation requires precise model, which was difficult to obtain in practice [1]. The problems of cancellation of the nonlinearities and high controller output energy were basically solved by using a ship course-keeping controller which combined nonlinear feedback algorithm [16] or nonlinear decoration algorithm [17] and backstepping algorithm. It was noted that the output performance of the control system can not be significantly changed by the nonlinear feedback control, but it could achieve equivalent or even better control effects with smaller amounts of energy [18]. The descriptive function theory was used to prove the effectiveness of the nonlinear feedback function, while the satisfactory energy-saving effect of the sine function-driven ship course-keeping control was pointed out [19]. Moreover, the nonlinear decoration technology driven by bipolar sigmoid function based on the Nomoto ship model was employed to achieve the same energy saving effect [20], while a novel PID-based nonlinear feedback algorithm based on a practical ship mathematic model (maneuvering modeling group model) driven by bipolar sigmoid function was proposed with the advantages of robustness, energy saving and safety in berthing practice [21].

Based on the above observations, the nonlinear feedback algorithm driven sine or bipolar sigmoid function has been employed normally, but the arctan function was rarely used for nonlinear feedback algorithm combined with backstepping. In this note, our attention is devoted to developing a kind of arctan nonlinear feedback to simplify the backstepping controller design process, decrease the number of undetermined parameters, improve the robustness and save the energy output of the controller. Moreover, the outstanding merits of the proposed algorithm can be summarized as follows:

i. A concise feedback algorithm based on arctan nonlinear function is firstly designed.

ii. The design process of backsteeping controller is simplified to only one step by using Lyapunov candidate function. Then the reasonable parameters in navigation practice are taken into account for stability proof of closed-loop system.

iii. The fresh sea trail data of new launched training ship YUPENG (Dalian Maritime University, China) are used for determining the parameters of ship model and the foundation of simulation experiments.

This note is organized as follows: After this introduction, in the second section, the nonlinear ship model is given. In the third section, an improved backstepping controller is designed for a ship course keeping control system. Section IV presents the effects analysis of the proposed algorithm in the course-keeping and course-tracking control simulations. The robustness analyses are demonstrated in Section V by taking external environmental disturbances rejection test and internal parameter perturbation rejection test to show the effectiveness of the proposed algorithm. Finally, the paper is terminated by the conclusion part in Section VI.

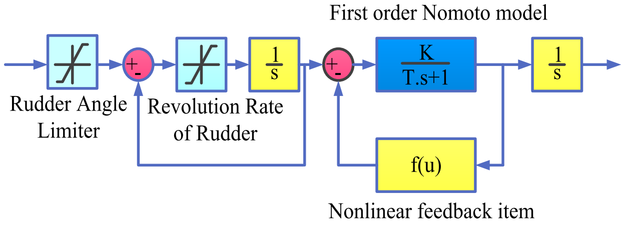


FIGURE 1. **The nonlinear ship model with a rudder servo system.**

FIGURE 2. **Turning test of the training ship YUPENG.**

II. NONLINEAR SHIP MODEL

This note adopts a ship response mathematical model with rudder servo system [22], [23] showed in FIGURE 1, which is composed of a first order item of the Nomoto model and a compensating item of nonlinear feedback. To make the control simulation closer to navigation practice at sea, a set of rudder servo system with the limiter of rudder angle and revolution rate is employed. The rudder angle is $\delta \in [-35°, 35°]$, and swing rate of rudder is 5°/s. The first order item of the Nomoto model from rudder angle δ to yaw rate r is shown as

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

where the compensating item of nonlinear feedback $f(u)$ is expressed as

$$f(u) = (\alpha - 1/K)\dot{\psi} + \beta\dot{\psi}^3 \tag{2}$$

where K and T are the ship maneuverability parameters, α and β are the proportional coefficients of yaw rate $\dot{\psi}$. The parameters K, T, α, β are calculated by a Visual Basic program, utilizing the principle illustrated in [24] and [25].

Taking the new launched training ship YUPENG of Dalian Maritime University as an example (See FIGURE 2), the main ship parameters are shown in TABLE 1. Hence, the model parameters can be figured up, which are listed in TABLE 2.

TABLE 1. **Ship particulars of training ship YUPENG.**

Length between perpendiculars (LBP)	L (m)	189
Molded Breadth	B (m)	27.8
Molded draught	d (m)	11.0
Ballast draught	d (m)	6.313
Volume of displacement	∇ (m^3)	30000
Volume of ballast displacement	∇ (m^3)	22036.6
Trial speed	V (kn)	17.26
Rudder area	A_R (m^2)	38
Rudder area (ballast)	A_R (m^2)	31.67
Block coefficient	C_b	0.72
Block coefficient (ballast)	C_b	0.661
Longitudinal center of gravity (ballast)	x_c (m)	-4.043

TABLE 2. **Ship parameters under ballast condition.**

Turning ability index K (1/s)	0.21
Following index T (s)	107.76
α	13.17
β	16323.46

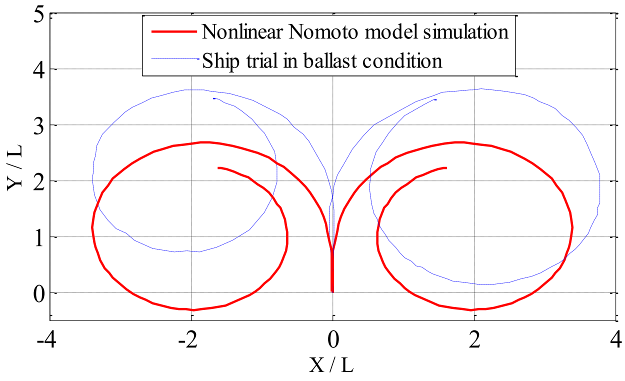


FIGURE 3. **Ship simulation and ship trial for turning test.**

To verify the accuracy of ship mathematical model, the conformity function C_{M} is introduced as [21].

$$C_{\mathrm{M}} = \frac{\min(S_{\mathrm{D}}, R_{\mathrm{D}})}{\max(S_{\mathrm{D}}, R_{\mathrm{D}})} \times 100\% \tag{3}$$

where S_{D} is the ship simulation parameter, including $S_{\mathrm{D-AD}}$ (advance diameter) and $S_{\mathrm{D-TD}}$ (transverse diameter), R_{D} is the real ship parameter of sea trial, including $R_{\mathrm{D-AD}}$ (advance diameter) and $R_{\mathrm{D-TD}}$ (transverse diameter). The comparison results of ship trial and simulation test with the maximum rudder angle ($\delta = \pm 35°$) under ballast condition are showed in the FIGURE 3 and TABLE 3. Generally, the ship speed will inevitably decrease during ship turning. Therefore, to make the simulation test more accurate, the compensation technology of ship speed reduction is introduced to correct the parameters K, T, α, β [25]. Here, the ship speed of real ship turning test reduces from 17.26kn to 7.71kn when the ship completes one turning circle. The sea trail results of turning test show that the K (turning ability index) is proportional to the ship speed, while T (turning lag index) and α, β (nonlinear parameters) are inversely proportional to the ship speed. In the starboard turning test, the $S_{\mathrm{D-AD}}$ and $R_{\mathrm{D-AD}}$ are $2.67L$ and $3.63L$, respectively. Then the conformity function of advance diameter $C_{\mathrm{M-AD}}$=73.55%; The $S_{\mathrm{D-TD}}$ and $R_{\mathrm{D-TD}}$ are 3.39 L and $3.78L$, respectively. Then the conformity function of transverse diameter $C_{\mathrm{M-TD}}$=89.68%. Meanwhile, in the port turning test, the $S_{\mathrm{D-AD}}$ and $R_{\mathrm{D-AD}}$ are $2.67L$ and $3.63L$, respectively. Then the conformity function of advance diameter $C_{\mathrm{M-AD}}$=73.55%; The $S_{\mathrm{D-TD}}$ and $R_{\mathrm{D-TD}}$ are $3.39L$ and $3.39L$, respectively. Then the conformity function of transverse diameter $C_{\mathrm{M-TD}}$=100%. As is showed in the TABLE 3, the average conformity function $\bar{C}_{\mathrm{M}}$ in the port and starboard turning test is 84.2%. Therefore, the simulation results are satisfactory for the ship maneuvering with large inertia and strong nonlinearity. (It is undeniable that there are some discrepancies caused by the simplified Nomoto ship model itself, which is easy to employ and satisfy the requirements for marine practice).

TABLE 3. **Comparison results.**

	Starboard turn		Port turn	
Test state	Advance diameter	Transverse diameter	Advance diameter	Transverse diameter
Turning test on sea	3.63 L	3.78 L	3.63 L	3.39 L
Nonlinear ship	2.67 L	3.39 L	2.67 L	3.39 L
C_{M}	73.55%	89.68%	73.55%	100%
$\bar{C}_{\mathrm{M}}$	84.2%			

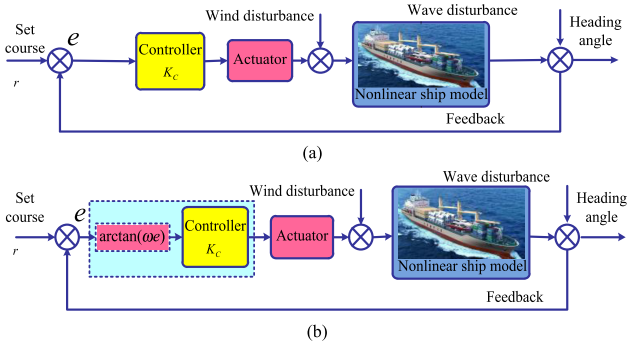


FIGURE 4. **Configuration of backstepping controller and improved backstepping controller. (a) Backstepping controller. (b) Improved backstepping controller.**

III. IMPROVED BACKSTEPPING CONTROLLER DESIGN

FIGURE 4 shows the configuration of backstepping controller and improved backstepping controller in ship motion. Considering that the parameters of some ship motion models are uncertain or immeasurable, the nonlinear ship course keeping control law is designed firstly.

The following coordinate transformations can be chosen [4]:

$$\begin{aligned} e &= \psi_r - \psi \\ x_1 &= \psi \\ x_2 &= \dot{x}_1 = \dot{\psi} = r \end{aligned} \tag{4}$$

where ψ is the ship heading, ψ_r is the set course, e is the course error, r is the yaw rate.

Then, the system state of (4) can be transformed into

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f(x_2) + bu \\ y &= x_1 \end{aligned} \tag{5}$$

where y is the system output, $f(x_2)$ is the nonlinear function, which can be transformed as

$$\begin{aligned} f(x_2) &= -\frac{K}{T} H(\dot{\psi}) \\ H(\dot{\psi}) &= \alpha\dot{\psi} + \beta\dot{\psi}^3 \\ b &= \frac{K}{T} \\ u &= \delta \end{aligned} \tag{6}$$

where δ is the rudder angle (input of the control system); u is the designed control law for course keeping.

Assuming

$$\begin{aligned} z_1 &= x_1 - \psi_r \\ z_2 &= x_2 \end{aligned} \tag{7}$$

where z_1 and z_2 are the state variables. Assuming that the designed controller can stabilize at z_1 and z_2, the original control system achieves uniform asymptotic stability at equilibrium point:

$$\begin{aligned} x_1 &= \psi_r \\ x_2 &= 0 \end{aligned} \tag{8}$$

The following Lyapunov function candidate can be chosen as [21]:

$$V_1 = \frac{1}{2} z_2^2 \tag{9}$$

Taking the time derivative of V_1, then, substituting Equations (6) and (7) into it, we can get

$$\dot{V}_1 = z_2 \dot{z}_2 \tag{10}$$

$$\dot{z}_2 = \dot{x}_2 = f(x_2) + bu \tag{11}$$

Then, we choose the control law u as follows.

$$u = \frac{1}{b}[f(x_2) - k_1 \arctan(\omega z_1)] \tag{12}$$

where ω, k_1 are designed parameters of controller, $k_1 > 0$, $\omega \in (0, 1)$. By using the Taylor series expansion and remaining to the third order item, Equation (13) is derived.

$$\arctan(\omega z_1) \approx \omega z_1 - \frac{(\omega z_1)^3}{3} \tag{13}$$

Substituting Equation (13) into Equation (12), we obtain Equation (14).

$$\begin{aligned} \dot{V}_1 &= z_2 \left(f(x_2) + bu\right) \\ &= z_2 \left\{ f(x_2) + b \cdot \frac{1}{b}\left[f(x_2) - k_1\omega z_1 + \frac{k_1\omega^3 z_1^3}{3} \right] \right\} \\ &= 2x_2 f(x_2) - k_1\omega z_1 z_2 + \frac{k_1\omega^3 z_1^3 z_2}{3} \\ &\approx -2b(\alpha x_2^2 + \beta x_2^4) - k_1\omega \frac{x_1 - \psi_r}{h} h x_2 \\ &\quad + \frac{k_1\omega^3}{3}\left(\frac{x_1 - \psi_r}{h}\right)^3 h^3 x_2 \\ &= -2b(\alpha x_2^2 + \beta x_2^4) - k_1\omega h x_2^2 + \frac{k_1\omega^3 h^3}{3} x_2^4 \\ &= -\left(2b\alpha + k_1\omega h\right) x_2^2 - \left(2b\beta - \frac{k_1\omega^3 h^3}{3}\right) x_2^4 \end{aligned} \tag{14}$$

where b, α, β, h are positive parameters in marine practice, h is the parameter of sample time. Considering that the first item of $\dot{V}_1$ as

$$-\left(2b\alpha + k_1\omega h\right) x_2^2 \leq 0 \tag{15}$$

In marine practice, $\omega \in (0, 1)$, $h \leq 1$s, if taking $k_1 \leq 0.3$, then Equation (16) can be derived

$$\frac{k_1\omega^3 h^3}{3} < 0.1 \tag{16}$$

Generally, $b \geq 5 \times 10^{-5}$, $\beta \geq 10^3$ in marine practice, then $2b\beta \geq 0.1$. Here, we chose the training ship YUPENG as the control plant (the parameters are shown in TABLE 2). Then, $b = K/T = 1.949 \times 10^{-3}$, $\beta = 16323.46$, $2b\beta$=63.6. The second item of $\dot{V}_1$ can be expressed as

$$-\left(2b\beta - \frac{k_1\omega^3 h^3}{3}\right) x_2^4 \leq 0 \tag{17}$$

According to Equations (14), (15) and (17), we have

$$\dot{V}_1 \leq 0 \tag{18}$$

Then, the control system will achieve uniform asymptotic stability at equilibrium point ($x_1 = \psi_r, x_2 = 0$). Therefore the control law of Equation (12) satisfies the control stability requirement while retaining the nonlinear item of control system without cancellation. Compared with the standard backstepping control method, in this note, a simple Lyapunov function candidate is selected to simplify the design process of the nonlinear controller from two steps to one step.

In addition, Equation (19) can be transformed into [25].

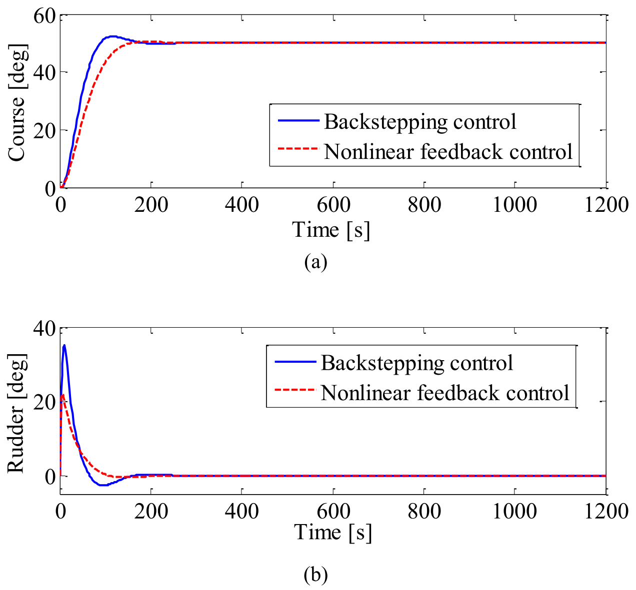
$$u = \frac{1}{b}[f(x_2) - k_1 z_1] \tag{19}$$

Compared with Equation (19), the arctan function of Equation (12) has the same controller construction with a mode of nonlinear feedback which is the key technology can improve the robustness and save the energy output of the controller. Even though the Equation (12) is more complex than Equation (19), the one-step backstepping design procedure can obviously simplify the nonlinear controller design process.

IV. EFFECTS ANALYSIS OF SIMULATION RESULTS

In this section, we use the Simulink toolbox to illustrate the effectiveness of the designed control law in MATLAB environment.

The energy saving effects of ship course keeping control and course tracking control are analyzed by using the standard backstepping method and nonlinear feedback method.



(a)

(b)

FIGURE 5. The control effects of backstepping control (solid line) and nonlinear feedback control (dashed line).

TABLE 4. Closed loop performance measures.

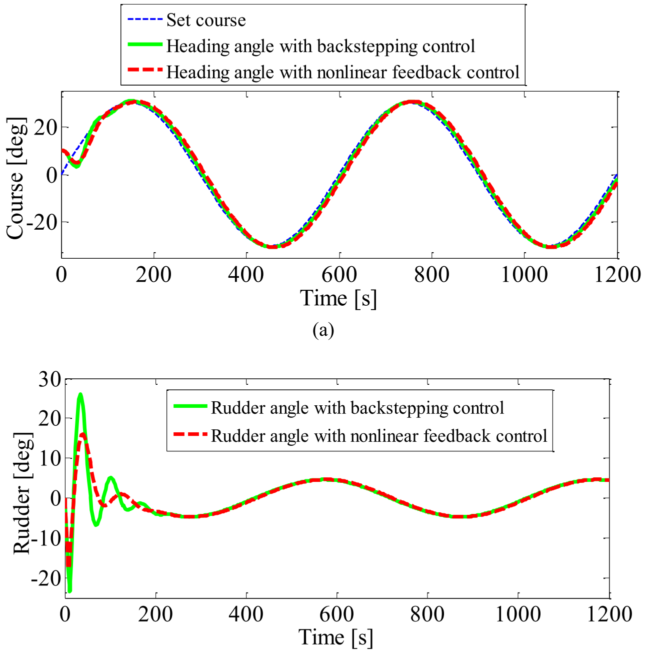
Control method	Course keeping control			Course tracking control	
	t_s	$\delta_{\max}$	$\bar{\delta}$	$\delta_{\max}$	$\bar{\delta}$
Backstepping control	185s	35°	0.31°	26°	3.93°
Nonlinear feedback control	157s	22°	0.21°	16°	3.58°
Decline (%)	15.1	37.1	32.2	38.5	8.9

V. COURSE KEEPING CONTROL

The parameters $k_1 = 0.017$ and $\omega = 0.6$ are chosen in designed control law (12), and set $\psi_r = 050°$, then the comparison results of two systems are showed in FIGURE 5 and TABLE 4. FIGURE 5(a) indicates that the output overshoot is eliminated, while the settling time t_s to the heading angle 050° drops from 185s to 157s under the co ntrol of nonlinear feedback. In FIGURE 5(b), the maximum rudder angle $\delta_{\max}$ drops from 35° to 22° while the mean rudder angle $\bar{\delta}$ falls from 0.31° to 0.21° by 32.2% down. As is shown in FIGURE 5(b), the dashed line of rudder angle controlled by nonlinear feedback method is smoother than standard backstepping, which means that the revolution amplitude of rudder blade is smaller, the wear of rudder is reduced, and the energy is saved indirectly.

A. COURSE TRACKING CONTROL

To verify the energy saving effect of the nonlinear feedback, the simulation experiment of sine wave course tracking is carried out. The control parameters are set as $\psi_r = 30\sin[(2\pi/600)t]$ deg, $\psi_0 = 010°$. Control law u remains the same as section IV(A), but $k_1 = 0.009$. FIGURE 6(a) shows that the sine wave course can be tracked by nonlinear feedback and standard backstepping control. However, the nonlinear feedback method has a small overshoot and then becomes smoother. FIGURE 6(b) shows that the input rudder angles decrease obviously, which also reduce the maximum rudder angle $\delta_{\max}$ from 26° to 16° in Table 4. The mean rudder angle $\bar{\delta}$ also drops from 3.58° to 3.93° by 8.9% down by using nonlinear feedback method. Therefore, the control effect of nonlinear feedback control is better than that of backstepping control.



(a)

(b)

FIGURE 6. The course tracking simulation results of standard backstepping control (solid line) and nonlinear feedback control (dash line).

To further quantify the control effect, three popular performance specifications are used to evaluate the performance of the closed-loop system [21], [26]. As is shown in Equation (20), the three specifications are Mean Absolute Error (MAE), Mean Integral Absolute (MIA) and Mean Total Variation (MTV) of the control system.

$$\begin{aligned} \mathrm{MAE} &= \frac{1}{t_\infty - t_0}\int_{t_0}^{t^\infty} |\psi_r - y(t)|\mathrm{d}t \\ MIA &= \frac{1}{t_\infty - t_0}\int_{t_0}^{t^\infty} |u(t)|\mathrm{d}t \\ MTV &= \frac{1}{t_\infty - t_0}\int_{t_0}^{t^\infty} |u(t) - u(t-1)|\mathrm{d}t \end{aligned} \tag{20}$$

MAE is used to measure the response performance of the system output, MIA and MTV are used for the energy consumption of the control input rudder angle and the smoothness of the corresponding algorithm.

TABLE 5. **Control performances results.**

Control low	Course keeping control			Course tracking control		
	MAE	MIA	MTV	MAE	MIA	MTV
Backstepping control	0.0325	0.01599	0.00341	0.02338	0.06254	0.00762
Nonlinear feedback	0.0434	0.01142	0.00190	0.03689	0.05739	0.00519
Variable rate (%)	33.5%	-28.6%	-44.3%	57.8%	-8.2%	-41.9%

As is shown in TABLE 5, a quantitative comparison of the above control simulation results verifies the effectiveness of the proposed algorithm. It is obvious that the response performance specification MAEs increased by 33.5% and 57.8%, respectively. However, the energy cost performance specification MIAs decreased by 28.6% and 8.2%, respectively, while smoothness performance specification MTVs decreased by 44.3% and 41.9%, respectively. Therefore, compared with the standard backstepping method, the improved concise backstepping method with nonlinear feedback has the remarkable effects of quick response, energy saving, and smoothness, which is helpful to navigation safety.

VI. ROBUSTNESS ANALYSIS

A. EXTERNAL ENVIRONMENTAL DISTURBANCES REJECTION TEST

When ship navigates at sea, the external environmental disturbances such as winds, wave and ocean currents, mainly lead to the ship sway motion and heading deviation [27]. Therefore, the marine environmental disturbances test is an effective means to verify the robustness of course keeping controller.

In this simulation test, the sea wind and irregular wind-generated waves are considered. The wind interference is composed of impulse wind and average wind, wherein impulse wind is represented by white noise [28] and average wind is represented by equivalent rudder angle to wind force corresponding to Beaufort wind scale [29]. The purpose of the introduction of wind equivalent rudder angle is to make the simulation result more agree with the practical requirements of ship course-keeping and ship course tracking.

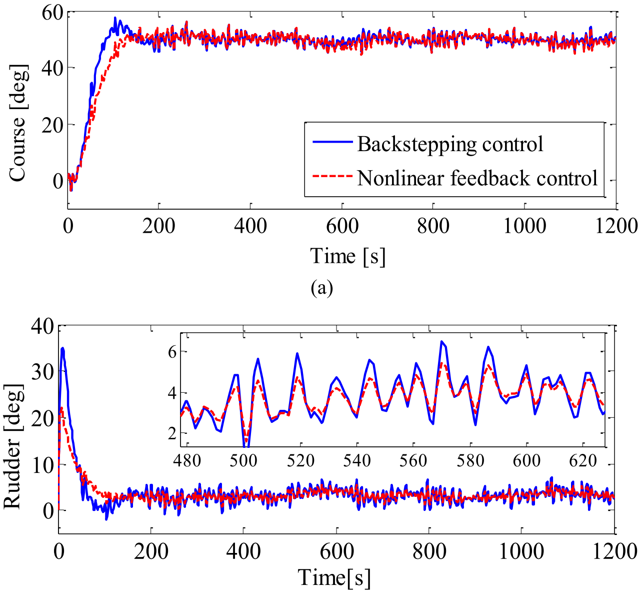
According to the references [30], δ_{wind} can be calculated by using the empirical formula:

$$\delta_{\text{wind}} = K^0 (\frac{V_R}{V})^2 \sin \gamma_R \tag{21}$$

where K^0 is leeway coefficient, V_R is relative wind speed, V is ship speed, and γ_R is wind bearing. $\delta_{\text{wind}} = 3°$ when wind bearing 30° and Beaufort wind scale 6, see [30].

To express the simulation of sea wave disturbance, the simplified transfer function model in Equation (22) can be used to simulate the wave disturbance in Beaufort 6 wind field, which is a second-order oscillation system driven by the white noise in finite frequency band, see [18].

$$h(s) = \frac{0.4198s}{s^2 + 0.3638s + 0.3675} \tag{22}$$



(a)

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FIGURE 7. **The control effects of backstepping method (solid line) and nonlinear feedback method (dashed line) under sea wind and wave disturbances.**

In this simulation, we set the white noise power 0.005, the sample time 3s, which are the same as the impulse wind. As is shown in FIGURE 7, the ship heading angles and rudder angles are given under backstepping control and nonlinear feedback control. The results indicate that two control methods get good performances of ship course keeping control under sea wind and sea wave disturbances. However, the nonlinear feedback control method (dashed line) has significantly smaller overshoot and smaller mean rudder angle than the backstepping control method (solid line). Thus, the simulation results show that the proposed method has good robustness and energy saving effect when external environmental disturbances exist. However, the dashed line (non-linear feedback control) has significantly smaller overshoot and smaller average rudder angle than the solid line (backstepping control).

B. INTERNAL PARAMETER PERTURBATION REJECTION TEST

As is shown in FIGURE 1 and TABLE 2, the ship parameters K, T(K=0.21s^{-1}, T=107.76s) can be calculated when ship speed is 17.26kn under ballast condition. However, the parameters K, T are always changed because ship resistance changes when ship navigation conditions vary, i.e., speed reduction. According to the theoretical analysis and Visual Basic program verification in [25], K decreases with the ship speed reduction, while T, α, β increase with the speed reduction. To get more intuitive simulation results in this simulation, we set the external marine disturbances are the same as section V(A) and the sampling time is set for 20s [29]. Assuming that K, T vary as $K1$=K, $T1$=T (solid line), K2=0.8K, T2=T/0.8 (dash dotted line), K3=0.5K,

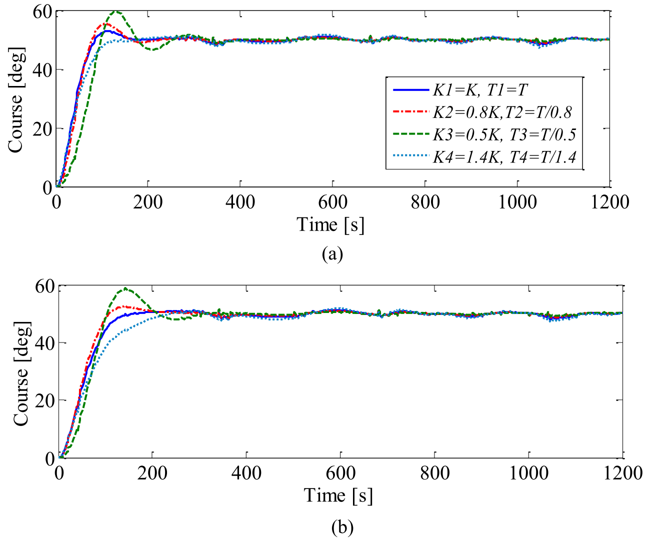

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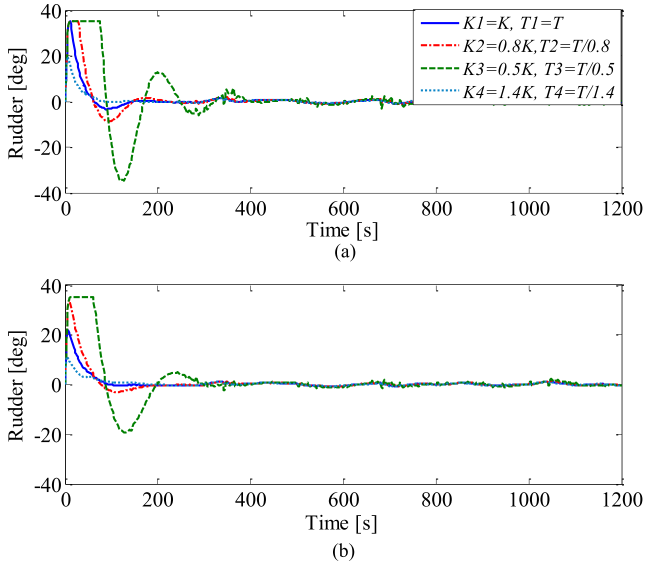
FIGURE 8. **Simulation results of control response with different control law. (a) Backsteeping. (b) Nonlinear feedback.**



(a)

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FIGURE 9. **Simulation results of control input with different control law. (a) Backstepping. (b) Nonlinear feedback.**

T3=T/0.5 (dashed line), K4=1.4K, T4=T/1.4 (dotted line), and those parameters are changed proportionally and simultaneously.

FIGURE 8 gives the comparisons of the control responses with the backstepping and nonlinear feedback. Obviously, the overshoot increases with the decrease of K value, and the nonlinear feedback has better response than backstepping, while the backstepping has smaller overshoot. In addition, course keeping control experienced around 400s period of oscillation with backstepping when $K3=0.5K$, $T3=T/0.5$, but only 310s period with nonlinear feedback. FIGURE 9 shows the comparisons of the control input with different control law. We also obviously note that the mean rudder angle increases together with K decreasing, and the nonlinear feedback method performs less control input energy than backstepping method due to the less mean rudder angle.

It can be concluded from the multiple simulation tests that the performance of the controller with nonlinear feedback is better than that of the controller with backstepping control. Under different ship parameters K, T, the backstepping control has smaller overshoot and smaller mean rudder angle. However, the course angle stabilizes with a long time when $K3=0.5K$, $T3=T/0.5$, while the steering control system acts in a long work time by using a large rudder angle which is not be accepted in the real marine practice. Generally, K decreases with the reduction of ship speed, so the robustness of nonlinear feedback method is better than that of the backsteeping method.

VII. CONCLUSION

In this note, a novel improved concise backstepping control method is proposed that the feedback error of backstepping control system between the reference input (set course) and output is modulated by an arctan function with only one regulating parameter ω. Compared with the standerd backstepping design process, the proposed concise algorithm simplifies the process from two to only one step and retains the nonlinear item of close-loop system which is useful for the existing nonlinear information. Simulation results demonstrate that the proposed method has advantages of simple design process, strong robustness and low energy consumption, which contribute to the navigation safety.

Furthermore, the same conclusions can be drawn when the arctan nonlinear feedback method is used in some other examples. Thus the design procedure is universal to some extent.

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