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Improved Concise Backstepping Control of Course Keeping for Ships Using Nonlinear Feedback Technique

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Course keeping for ships is vital for automatic navigation in marine transportation. To improve the control effect and reduce the energy output of the controller, this article proposes an improved concise backstepping controller based on a Lyapunov candidate function by introducing a nonlinear function of course error to replace the course error itself in the feedback loop. The procedure of nonlinear controller design has been reduced from two steps to one step using information from controlled plant to construct the Lyapunov candidate function. Compared with the pure backstepping control, the proposed improved algorithm reserves the nonlinear item of the system, and possesses a strong disturbance rejection ability and robustness to the mathematical model uncertainty. The algorithm given here has advantages of simplified construction method, satisfactory control effect, robustness and energy saving.

KEYWORDS

1. Course keeping for ships. 2. Nonlinear feedback. 3. Lyapunov stability. 4. Improvement.

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1. INTRODUCTION. A ship's course must be controlled to reach its destination in a fast and efficient manner. Due to the uncertainty of wind, wave, current and so on, a ship always presents a nonlinear motion (Fossen, 2002). Backstepping is a powerful tool for nonlinear control, and it is a design method of regression which combines the theories of Lyapunov stability and controller design. Making use of the characteristics of system structure, backstepping is a recursively structured Lyapunov candidate function for overall system control (Krstic and Smyshlyaev, 2008; Nejati et al., 2012; Tsai et al., 2015; Zhu et al., 2015). Lin (2007) designed a nonlinear robust adaptive controller for ship course-keeping based on backstepping by introducing an integral item to eliminate the static error. To linearize the ship motion system, the nonlinear item of the system was cancelled during the controller design. Liu et al. (2012) proposed a linear tracking controller using the

backstepping method and Lyapunov's direct method, and the linear track-keeping control effect was made satisfactory by altering the designed parameters while the environmental disturbances, such as the wind, waves and current were ignored. Considering the Lyapunov candidate function and the Hurwitz conditions, Perera and Guedes Soares (2013) proposed a control algorithm based on a second-order Nomoto model which was simulated on a ship steering system and performed successfully. Li et al. (2015) proposed a finite-time output feedback trajectory tracking control scheme for Autonomous Underwater Vehicles (AUVs), based on the proposed state feedback backstepping controller. To get a faster convergence rate and a higher tracking accuracy for trajectory tracking control for AUVs, the control scheme design procedure was complicated. At the same time, Xia et al. (2015) developed a nonlinear robust passive observer for surface ships in surge, sway and yaw. To verify the efficiency of the observer, backstepping and Lyapunov redesign techniques were utilised. Peng et al. (2014) proposed a nonlinear inverse H-infinity optimal control algorithm, which was used to transform the global optimisation into finding the Lyapunov candidate function of the closed-loop system. Simulation results demonstrated that the heading overshoot decreased, and the maximum rudder angle reduced to 25° from 29° in the case of course turning from 000° to 030° at full speed, when applied to the Dalian Maritime University training ship *Yulong*. It could be concluded that the algorithm realised the control optimisation of course keeping for ships, as well as saving energy with a relatively complex calculation process. It is difficult for researchers to design a controller considering the concepts of reserving the nonlinear item of system, a simplified construction method and energy saving when applied to a practical control system.

However, it is worth mentioning that Zhang (2010) designed a concise backstepping controller of course keeping for ships based on Lyapunov stability. This concise backstepping controller did not cancel the nonlinear item of the system and the procedure of controller design reduced from two steps to one step. Due to the experience of teaching and researching in recent years, it was found that the effect of the controller clearly improved if nonlinear feedback driven by the sine function was added (Zhang and Zhang, 2016). Combining the special backstepping construction method based on the Lyapunov candidate (Zhang, 2010) with the nonlinear feedback (Zhang and Zhang, 2016), an improved backstepping controller is acquired with theoretical proof in this article. Applying the improved concise backstepping controller to a simulation experiment of the training ship *Yulong*, the results indicate that the maximum rudder angle drops from 22° to 13°, 40.9% down, the settling time falls to 150 s from 200 s and the heading overshoot disappears. The control effect is more satisfactory and the improved concise backstepping controller has some robustness.

2. NONLINEAR SHIP MODEL.

In this section, the Dalian Maritime University training ship *Yulong* is taken as an example because of its substantial sea trials, which are convenient to verify the precision of the nonlinear ship model adopted in this section. The ship's main particulars are shown in Table 1. This article adopts a response model considering a rudder servo system to represent the nonlinear ship model (Van, 1982; Zhang and Jin, 2013) shown in Figure 1, which is composed of a first order Nomoto model with a nonlinear feedback compensating item. For the purpose of making the simulation closer to marine practice, a rudder servo system is considered, which covers the rudder transport delay, angle limiter and revolution rate limiter. Rudder transport delay $T_r = 6$s, rudder angle $\delta \in [-35^{\circ}, 35^{\circ}]$, and the revolution rate of the rudder is 2.3°/s. The first order Nomoto

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Table 1. Simulation particulars for training ship *Yulong*.

Length between perpendiculars L (m)	126
Breadth (moulded) B(m)	20·8
Designed draught d(m)	8·0
Volume of displacement ∇(m^3)	14278·1
Trial speed V(kn)	15
Rudder area A_R(m^2)	18·8
Block coefficient C_b	0·681
Longitudinal centre of gravity x_G(m)	0·25

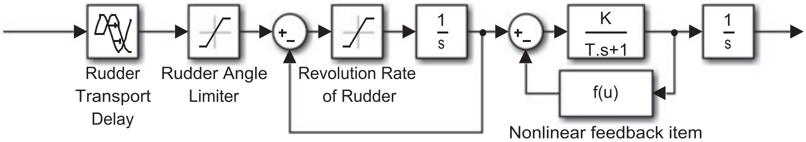

Figure 1. Nonlinear ship model considering the rudder servo system.

Table 2. Ship mathematical model parameters.

Turning ability index K(1/s)	0·48
Following index T (s)	216·58
α	9·14
β	10836·12

model from δ to yaw rate r is presented as

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

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

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

where K, T are the ship manoeuvrability indices and 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, utilising the principle illustrated in Nomoto et al. (1957) and Zhang (2012) Hence, the model parameters are listed in Table 2.

To describe the precision of the mathematical model, the concept of conformity C_{M} is formed as

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

where S_{D} and R_{D} are the simulation tactical diameter and tactical diameter of the real ship. According to the comparison of the ship turning tests with the rudder angle $\delta = -35^\circ$ shown in Figure 2 and Table 3, the horizontal S_{D} is 518·3 m, while the horizontal R_{D} is 542·2 m, so $C_{\mathrm{M\_horizontal}} = 95{\cdot}6\%$. The vertical S_{D} is 473·8 m, while the vertical R_{D} is 443·9 m, then $C_{\mathrm{M\_vertical}} = 93{\cdot}7\%$. Hence, the average conformity $\overline{C}_{\mathrm{M}}$ in the horizontal and vertical directions is 94·6%. The precision of the nonlinear mathematical model is acceptable for a ship with large inertia and nonlinearity.

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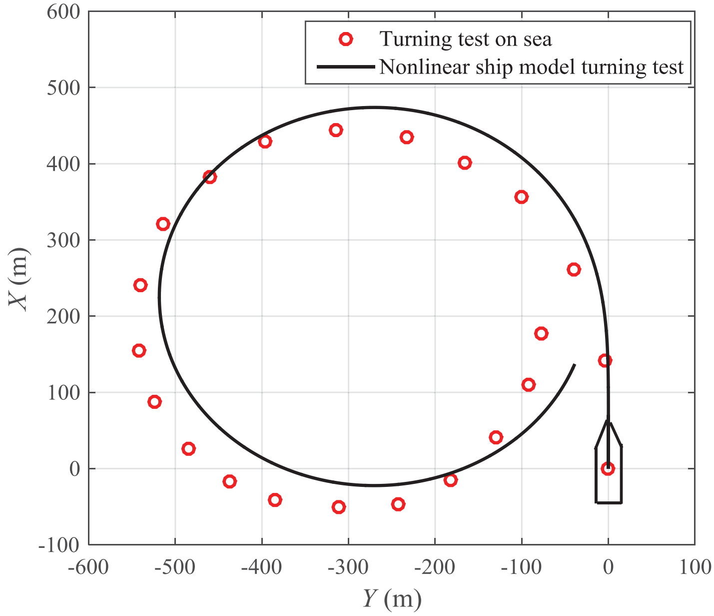

Figure 2. Comparison of the ship turning tests.

Table 3. Data comparison of the ship turning tests.

Test state	Horizontal	Vertical
Turning test on sea (Liu, 2007)	542·2 m	443·9 m
Nonlinear ship model turning test	518·3 m	473·8 m
C_M	95·6%	93·7%
$\bar{C}_M$	94·6%	

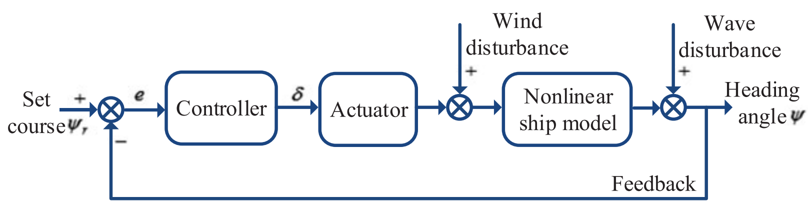

Figure 3. Diagram of the closed loop system in ship motion.

3. IMPROVED BACKSTEPPING CONTROLLER DESIGN VIA NONLINEAR FEEDBACK TECHNIQUE. Considering the uncertainty of the ship motion parameters, the nonlinear control scheme of the course keeping for ships is first designed. The ship heading angle is defined as ψ set course ψ_r course error e and yaw rate r. Figure 3 presents a diagram of the closed loop system in ship motion.

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Then a special algebraic coordinate transformation can be proposed as

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

Hence, the state space equation and output equation of the system is represented as

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

where the output of system can be defined as y, and the nonlinear function $f\,(x_2)$ can be further written as

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

where δ is the input of rudder angle and u is the designed control scheme of course keeping for ships. Assuming

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

if the controller can stabilise the state variables z_1 and z_2, the original system reaches the uniform asymptotic stability at the equilibrium point shown in Equation (8)

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

A Lyapunov function can be structured according to Zhang (2010), which is performed as

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

The differential relationship between z_1 and z_2 has been considered, which possesses a certain universality. If z_2 is stabilised on the equilibrium point of zero, z_1 is stabilised

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simultaneously. $\dot{V}_1$ contains the information of z_1 implicitly so as to ensure the proper control scheme and stabilise z_1 and z_2 simultaneously, though V_1 does not contain z_1 directly.

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

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

To make $\dot{V}_1 \leq 0$, the designed control scheme u is constructed as follows.

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

where ω, k_1 are the designed parameters of the controller, which satisfy $k_1 > 0$, $\omega \in (0, 1)$. According to the Taylor series expansion and restricting to the third order (Arunnehru and Paramasivam, 2014), Equation (13) is derived.

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

Substituting Equation (13) into Equation (12), we obtain Equation (14) by combining Equations (4)–(7) and (12).

$$\begin{aligned}
\dot{V}_1 &= z_2\left(f(x_2) + bu\right) \\
&\approx z_2\left\{f(x_2) + b\cdot\frac{1}{b}\left[f(x_2) - k_1\omega z_1 + \frac{k_1\omega^3 z_1^3}{6}\right]\right\} \\
&= 2x_2 f(x_2) - k_1\omega z_1 z_2 + \frac{k_1\omega^3 z_1^3 z_2}{6} \\
&= -2b(\alpha x_2^2 + \beta x_2^4) - k_1\omega\frac{x_1 - \psi_r}{h} h x_2 + \frac{k_1\omega^3}{6}\left(\frac{x_1 - \psi_r}{h}\right)^3 h^3 x_2 \\
&\approx -2b(\alpha x_2^2 + \beta x_2^4) - k_1\omega h x_2^2 + \frac{k_1\omega^3 h^3}{6} x_2^4 \\
&= -\left(2b\alpha + k_1\omega h\right) x_2^2 - \left(2b\beta - \frac{k_1\omega^3 h^3}{6}\right) x_2^4
\end{aligned} \tag{14}$$

where b, α, β, h are positive, h is the sample time. Noting that the first item of $\dot{V}_1$

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

and in marine practice, $\omega \in (0, 1)$, $h \leq 1\text{s}$, if taking $k_1 \leq 0.6$ then Equation (16) can be derived

$$\frac{k_1\omega^3 h^3}{6} < 0.1 \tag{16}$$

In a general way, $b \geq 5 \times 10^{-5}$, $\beta \geq 10^3$ in marine practice (Van, 1982; Zhang and Jin, 2013), therefore $2b\beta \geq 0{\cdot}1$. In this article, $b = K/T = 0{\cdot}48/216{\cdot}58 = 2{\cdot}2 \times 10^{-3}$,

$\beta = 10836{\cdot}12$, therefore $2b\beta = 25{\cdot}8$. The latter item of $\dot{V}_1$ follows that

$$-\left(2b\beta - \frac{k_1\omega^3h^3}{6}\right)x_2^4 \le 0 \tag{17}$$

Combining Equations (14), (15) and (17), we obtain

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

In summary, the system will reach uniform asymptotic stability at the equilibrium point of $x_1 = \psi_r$, $x_2 = 0$. The control scheme of Equation (12) meets the requirements and reserves the nonlinear item of the system without normal cancellation. The procedure of nonlinear controller design has been reduced from two steps to one step by choosing the simple Lyapunov candidate function rather than the conventional backstepping construction approach.

In addition, Equation (19) is formulated in Zhang (2010).

$$u = \frac{1}{b}[f(x_2) - k_1z_1] \tag{19}$$

Comparing Equation (19) with Equation (12), the sine function of z_1 with the same controller is constructed, which makes up a new mode of nonlinear feedback

4. SIMULATION STUDIES.

In this section, the Simulink toolbox is used to illustrate the effectiveness of the designed controller in a MATLAB environment. The control effects of course keeping for ships and energy saving situation are analysed in the case of standard feedback and nonlinear feedback.

4.1. *Course Keeping Control.* Taking $k_1 = 0{\cdot}001$, $\omega = 0{\cdot}6$ in the control scheme Equation (12) and $\psi_r = 050°$ in Equations (4), we can obtain results for comparison under two different control schemes, which are shown in Figure 4 and Table 4. Figure 4(a) indicates that the heading overshoot is eliminated as well as the settling time t_s drops to 150 s from 200 s under the nonlinear feedback control. Figure 4(b) shows that the maximum rudder angle δ_{max} drops to 13° from 22° while the mean rudder angle $\bar{\delta}$ falls to 2·3° from 3·6° 36·1% down. Referring to Tu (2008), energy consumption lies in the fields of steering stability, the manoeuvring times (when rudder angle exceeds 0·5°), the acting time and the revolution amplitude of the rudder blade. In Figure 4(b), the dotted line of rudder angle controlled by the nonlinear feedback is smoother than the other, which stands for a smaller revolution amplitude of rudder blade and less wear of steering gear, saving energy indirectly. Considering the cost-function

$$J = \int \delta^2 \mathrm{d}t \tag{20}$$

discretising Equation (20), Equation (21) is derived

$$J = \sum_k \delta^2(k) \tag{21}$$

The cost-function $J = 4291$ with nonlinear feedback while $J = 10764$ without nonlinear feedback, dropping by around 60.1%. Also the reduction of rudder angle means safer sailing and energy saving on account of the smaller rolling angle.

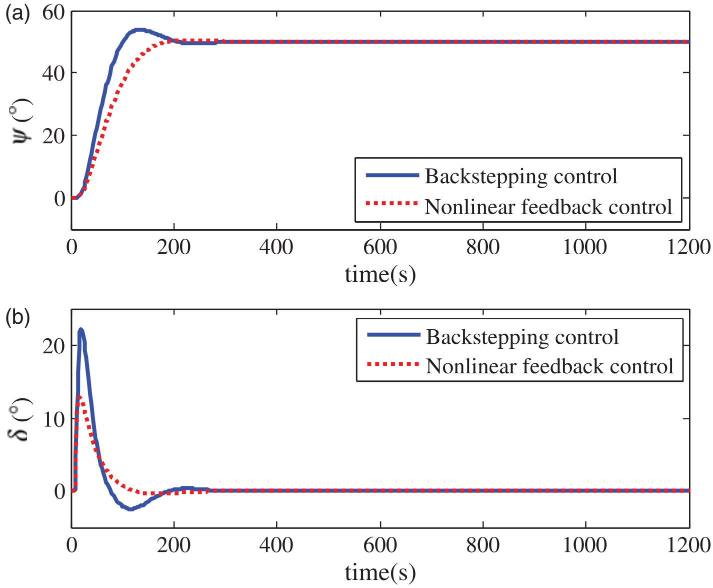

Figure 4. Comparison of the control effects: backstepping control (solid line) and nonlinear feedback control (dotted line).

4.2. *Energy Saving Validation.* We set a simulation experiment of sine wave course tracking to verify the energy saving of nonlinear feedback. The simulation parameters are chosen as $\psi_r = 30\sin[(2\pi/600)t]$ deg, $\psi_0 = 010°$. Control scheme u remains the same, but we take $k_1 = 0.008$ because of the sharp variation of ship set course, thus the gain coefficient k_1 needs to be larger to improve the system response rate. Figure 5(a) shows that the heading angle with nonlinear feedback control is almost capable of tracking the set course. Figure 5(b) shows that a variety of energy-consuming indices decrease, which results in falls in the value of the maximum rudder angle δ_{max} from 24° to 15° referred to in Table 4. The mean rudder angle $\bar{\delta}$ drops to 2·8° from 3·3°, 15·2% down while the cost function J falls to 13391 from 22420, 40·3% down, with the nonlinear feedback control. Hence, the control effectiveness of the nonlinear feedback control is better than the conventional backstepping control.

5. ROBUSTNESS ANALYSIS.

5.1. *External Disturbances Rejection Test.* It is clear that wind and wave disturbances exist in practical engineering, therefore these cannot be neglected when the sway motion and heading deviation of a ship are considered. Whether the designed controller behaves well or not should be verified in a higher sea state. The wind disturbance is divided into the average wind and the impulse wind. The average wind can be deemed as an equivalent rudder angle δ_{wind} (Guo, 2009) while impulse wind or gusts are considered as white noise (Kallstrom, 1982) According to Zhang and Zhang (2013a; 2013b; 2014), δ_{wind} can be calculated through an empirical formula as follows

$$\delta_{\text{wind}} = K^0 \left(\frac{V_R}{V}\right)^2 \sin\gamma_R \tag{22}$$

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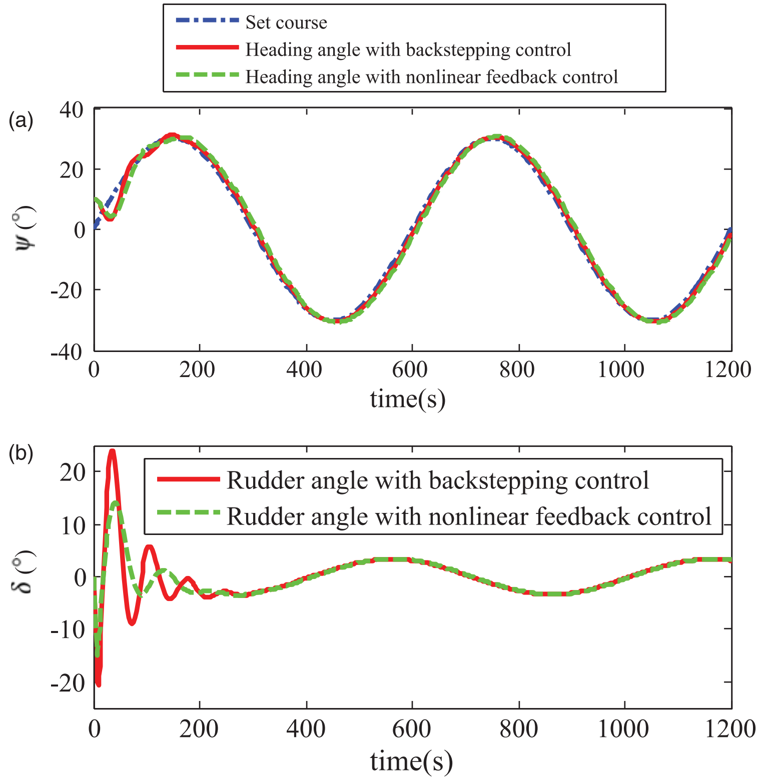

Figure 5. Simulation results of the sine wave course tracking: set course (dash dot line), backstepping control (solid line) and nonlinear feedback control (dash line).

Table 4. Comparison of the closed loop performance.

	Course keeping control				Energy saving validation		
Control method	t_s	δ_{max}	$\bar{\delta}$	J	δ_{max}	$\bar{\delta}$	J
Backstepping control	200s	22°	3·6°	10764	24°	3·3°	22420
Nonlinear feedback control	150s	13°	2·3°	4291	15°	2·8°	13391
Decline (%)	25	40·9	36·1	60·1	37·5	15·2	40·3

where K^0, V_R, V, γ_R are the leeway coefficient, relative wind speed, ship speed, and wind angle on the bow respectively. $\delta_{wind} = 3°$ when the wind scale is equal to Beaufort scale 6 and the wind bearing is 030° by computation.

For wave disturbance, a simplified transfer function model shown in Equation (23) is capable of simulating it under the Beaufort scale 6, which is a second-order oscillating system driven by a Gaussian white noise (Zhang et al., 2014)

$$\psi_H = \frac{0.4198s}{s^2 + 0.3638s + 0.3675} w_H \tag{23}$$

where w_H, s, ψ_H are the Gaussian white noise, Laplace operator and high frequency wave disturbance. As shown in Figure 3, ψ_H directly acts on the ship heading angle ψ.

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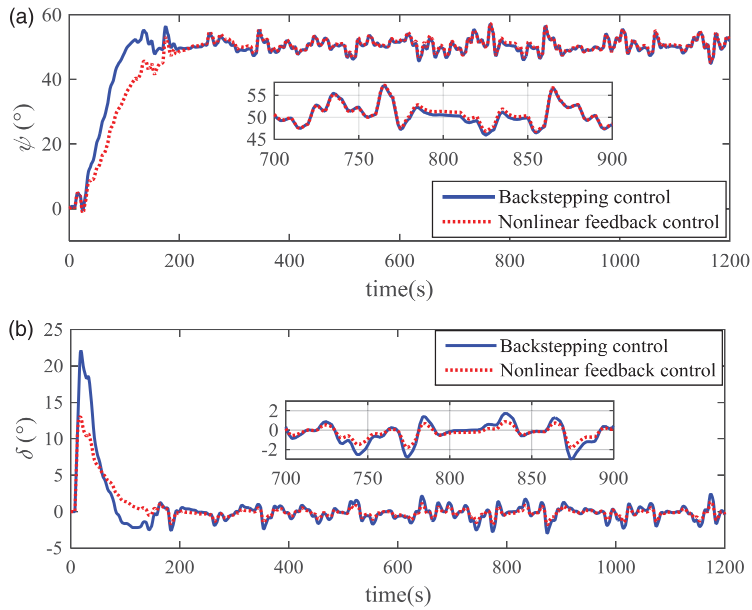

Figure 6. Comparison of the control effects with the wind and wave disturbances: backstepping control (solid line) and nonlinear feedback control (dotted line).

Suppose the Gaussian noise power w_H is 0·001 and the sample time equals 10 s, the same as that in the simulation of impulse wind. The curves of the heading angle and rudder angle of ship are given in Figure 6 under the different control schemes. The curves indicate that the two control schemes achieve a good performance in course keeping control with wind and wave disturbances. However, the dotted one with nonlinear feedback control possesses less overshoot and smaller mean rudder angle than with backstepping control.

5.2. *Internal Parameter Perturbation Rejection Test.* The ship manoeuvrability indices K, $T(K = 0{\cdot}48s^{-1}$, $T = 216{\cdot}58$s) in Figure 1 and Table 2 are calculated when ship speed is 15 knots. However, the ship speed usually reduces because of the fouling on the bottom surface of the hull and external disturbances. Based on the theoretical analysis and Visual Basic program validation, K decreases while T, α, β increase proportionally along with the reduction of ship speed (Zhang, 2012). Assume the external disturbances remain unchanged, the sample time equals 200 s for the sake of a more visual simulation (Lei and Guo, 2015). Suppose that K, T vary in a series of $K1 = K$, $T1 = T$(solid line) $K2 = 0{\cdot}7K$, $T2 = T/0.7$(dash line) $K3 = 0{\cdot}5K$, $T3 = T/0{\cdot}5$(dotted line) $K4 = 1{\cdot}5K$, $T4 = T/1{\cdot}5$(dash dot line) (Figures 7 and 8). α, β change simultaneously.

It can be concluded from Figures 7 and 8 that the overshoot and mean rudder angle increase together when K decreases. Meanwhile the controller with nonlinear feedback performs better than that with backstepping control, which possesses less overshoot and smaller mean rudder angle. The multiple simulation tests show that the heading angle stabilises after long oscilation when $K5 = 0{\cdot}3K$, $T5 = T/0{\cdot}3$. However the ship steering system is acting over a long time to hold a large rudder angle which is accepted in marine practice. Although the settling time extends when K increases, mean rudder angle also

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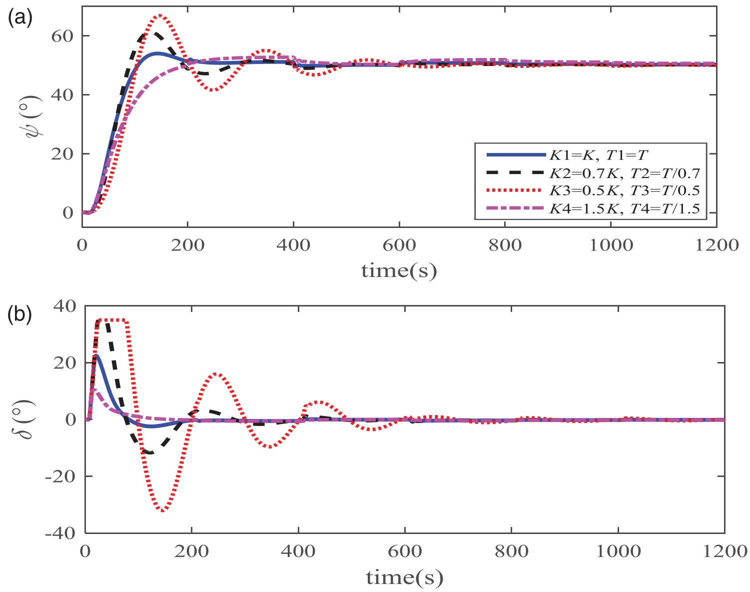

Figure 7. Simulation results with backstepping control.

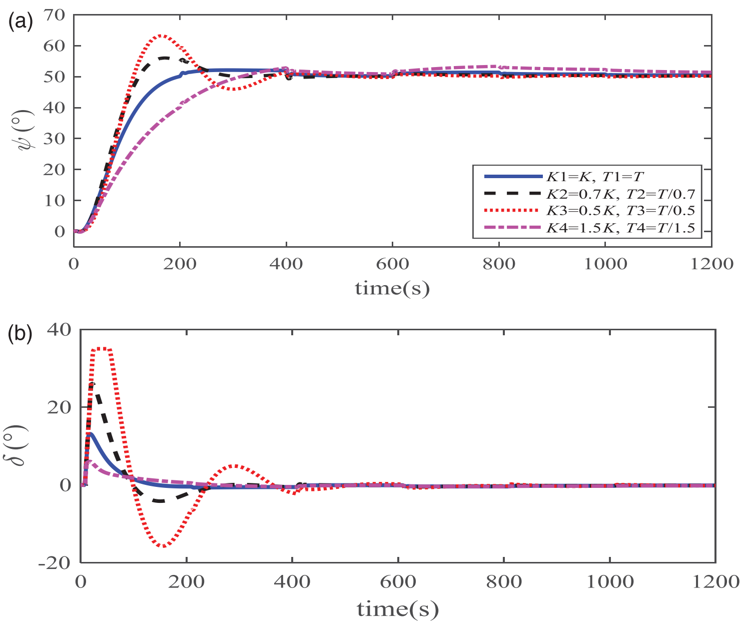

Figure 8. Simulation results with nonlinear feedback control.

reduces. Since K tends to decrease with reduction of ship speed, the robustness of nonlinear feedback control is stronger than with backstepping control.

5.3. *The Effectiveness of the Improved Control Algorithm on a Complex Mathematical Model.* As mentioned above, the improved concise backstepping control algorithm is

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Table 5. The non-dimensional hydrodynamic coefficients for the vessel *Yulong*.

The structure of hydrodynamic force (or moment)

$X: u^2, v^2, vr, r^2$

$Y: v, r, v^2, vr, r^2$

$N: v, r, r^2, v^2 r, vr^2$

The hydrodynamic coefficients normalised using the Prime-system I

$X'_{uu} = -0{\cdot}00008$	$Y'_v = -0{\cdot}3569$	$N'_v = -0{\cdot}1270$
$X'_{vv} = -0{\cdot}0285$	$Y'_r = 0{\cdot}0997$	$N'_r = -0{\cdot}0524$
$X'_{vr} = -0{\cdot}0635$	$Y'_{vv} = -0{\cdot}7238$	$N'_{rr} = -0{\cdot}0242$
$X'_{rr} = 0{\cdot}0047$	$Y'_{vr} = -0{\cdot}2221$	$N'_{vvr} = -0{\cdot}0823$
	$Y'_{rr} = -0{\cdot}0501$	$N'_{vrr} = 0{\cdot}0563$

tested on a Nomoto model with a nonlinear item, and the effectiveness of the algorithm has been affirmed. In this section, the above-mentioned improved control algorithm is exerted on the controlling of a more complex nonlinear mathematical model Equation (24) of ship dynamics, which can denote a situation similar to the motion of a full scale ship (Fossen, 2011). To some extent, if the improved control algorithm still works, its robustness is further proven.

$$\begin{cases} (m+m_x)\,\dot{u} - \left(m+m_y\right) vr - mx_G r^2 = X_H + X_P + X_R \\ \left(m+m_y\right) \dot{v} + (m+m_x)\,ur + mx_G r^2 = Y_H + Y_P + Y_R \\ (I_{zz}+J_{zz})\,\dot{r} + mx_G\,(\dot{v}+ur) = N_H + N_P + N_R \\ \dot{\psi} = r \end{cases} \tag{24}$$

where u, v, r, ψ express the linear velocities, angular velocity and heading angle respectively; m and I_{zz} are the ship's mass and mass moment of inertia; m_x, m_y, J_{zz} are the added mass and added moment of inertia. $X_H, Y_H, N_H, X_P, Y_P, N_P, X_R, Y_R, N_R$ are the hydrodynamic forces and the corresponding moments acting on the ship's hull, propeller and rudder. The related non-dimensional hydrodynamic coefficients for the training vessel *Yulong* are listed in Table 5. More details about the nonlinear mathematical model Equation (24) can be found in Jia and Yang (1999) and Fossen (2011).

We assume the external disturbances remain unchanged, and take $k_1 = 0{\cdot}001$, $\omega = 0{\cdot}6$ in control scheme Equation (12), $\psi_r = 050^\circ$ in Equations (4) and then we can get the comparison results under two different control schemes, which are shown in Figure 9. Based on the mathematical model of ship dynamics, both control schemes achieve a good course keeping performance with wind and wave disturbances. However, the nonlinear feedback control possesses less overshoot and smaller mean rudder angle than the solid one. This means that the control energy is reduced with the introduction of nonlinear feedback.

6. CONCLUSIONS.

In this article, an improved concise backstepping control algorithm is proposed to solve the problem of course keeping for ships by virtue of the two regulating parameters: gain coefficient k_1 and angular frequency ω. The procedure of nonlinear controller design has been reduced from two steps to one step by choosing the simple Lyapunov candidate function rather than the conventional backstepping construction approach. Meanwhile the final controller does not cancel the nonlinear item of the system since the existing nonlinear information of the system has been utilised. The control energy is reduced with the introduction of sine function feedback, while the simulation

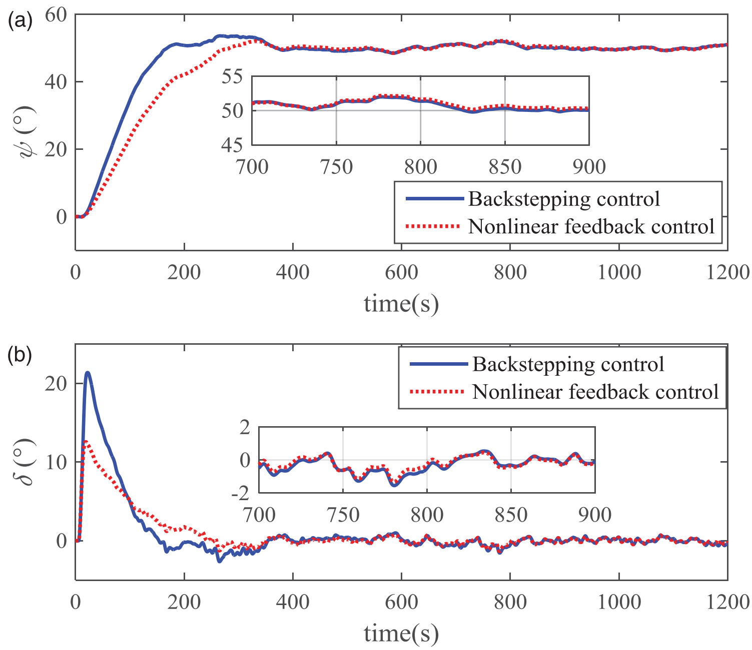

Figure 9. Comparison results of complex nonlinear mathematical model.

results validate the strong ability of the proposed improved algorithm with disturbance rejection and robustness to the nonlinear mathematical model. Furthermore, the procedure of nonlinear controller design is to some extent universal by taking full advantage of the systematic nonlinear information and structural characteristics. This work cannot deal with every detail of the control task, e.g., the proposed algorithm may not obtain its targets because of the saturation of control actions, and this will be addressed in future research.

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