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Improvement of integrator backstepping control for ships with concise robust control and nonlinear decoration

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ABSTRACT

Course-keeping control through normal integrator backstepping method has defects of introducing many adjustment parameters and not considering the energy cost of actuator. In order to enhance the performance of integrator backstepping controller, a control law formed by closed-loop gain-shaping algorithm is adopted to replace the linear terms in the original control law. The energy cost is reduced by nonlinear decoration of sine function to the controller output, and the steering interval is lengthened according to the analyzation of full-scale sea trail data from training vessel Yukun. To decrease overshoot, the desired course is filtered by a first-order inertial component. Then a performance index is proposed to verify the performance of each control strategy combination. Simulation results show that the proposed controller has good robustness to the perturbation of steering mechanisms and ship model in rough sea states. At the same time, mean rudder angle is decreased by 17.3%, so energy consumption is reduced. The algorithm proposed in this paper has good theoretical analysis, satisfactory robustness with less parameters, reasonable steering frequency and remarkable energy saving effect.

1. Introduction

Course-keeping control for ships is a benchmark problem in the field of ship motion control. Many control strategies have been used to solve the problem, such as minimum variance control (Doi et al., 2010), multivariable generalized predictive control (Tao and Jin, 2012), H∞ robust control (Liu et al., 2007), neural network control (Zhou et al., 2011; Im and Van-Suong, 2018) and fuzzy control (Malecki, 2016), etc. Although the theoretical research is prosperous, in the field of application their acceptance are not that good. Apart from the delay from applying theory to engineering, the doubts on their reliability and robustness is the main reason. Complex control law usually has more parameters or higher order format, which provides more chances of failing in practical application.

Backstepping method is effective for the control of nonlinear system (Krstic et al., 1995). In Saberi et al. (1989), integral term was introduced to the method, backstepping method with integral term became a design technique for a recursive controller. Godhavn et al. (1998) first introduced backstepping method into ship motion control field. Fossen and Strand (1999) did some research on the application of backstepping method to ship motion control, and the integral term was added to improve the course control performance for ships in Roger and Fossen Thor (2004). However, their controller was complex and unable to deal with inexact mathematical models. To solve the problem, Guan et al. (2009) proposed a concise nonlinear robust controller and used close-loop gain shaping algorithm to overcome the static error. Chen and Tan (2013) introduced backstepping method into ship trajectory tracking problem with fault tolerant control to avoid failure. Zhang et al. (2015a) applied neural network in backstepping to capture vehicle uncertainties. Nevertheless, the steering frequency was not concerned in the above literatures, which could lead to a severe wear on the rudder. von Ellenrieder (2018)considered the effect of input saturation and actuator rate limits under unknown time-varying disturbances. Based on the researches above, in order to find a simpler control law and reduce rudder wearing, this research offers a new scheme.

Generally, the controller designed by backstepping is in PD format with a nonlinear damping term that cancels the nonlinearities of the mathematical model. An integral term can be introduced to the controller to eliminate the static error caused by constant wind disturbance, but this introduction brings additional parameters to be tuned.

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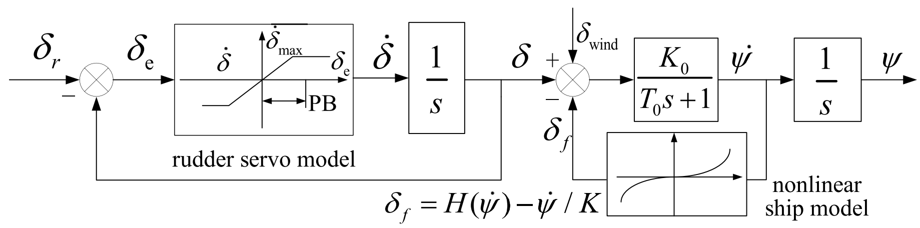

Fig. 1. Nonlinear ship motion model.

Table 1
Principle particulars of ship Yukun.

Parameters	Value
Length(LBP)	105 m
breadth	18 m
load draft	5.4 m
block coefficient	0.5595
speed	16.7kn
rudder area	11.46m^2
rudder height	4.8 m
rudder aspect ratio	1.95
propeller diameter	3.8 m
blade area ratio	0.7
displacement	5735.5m^3

The nonlinear control law designed by backstepping method usually is to cancel the nonlinearities of the system. Nevertheless, in practice the nonlinearities is unlikely to be cancelled completely (Zhang, 2012; Zhang et al., 2015b). However, if the control algorithm is robust and insensitive to the mathematical model perturbation, it is reasonable to ignore that effect.

CGSA (Closed-loop gain shaping algorithm) is a concise robust control algorithm (Zhang, 2012). The controller designed by CGSA has good robust performance, simple controller structure and concise controller design procedures, but the stability proof of CGSA controller is slightly difficult because of its constructional nature. Therefore, we can make CGSA and backstepping method complement each other.

Nonlinear feedback and nonlinear decoration are new discoveries of our team (Zhang and Zhang, 2016; Zhang et al., 2017a; Zhang et al., 2017b; Zhang et al., 2018). Suppose e is the input of the controller and u is the output of the controller. In traditional linear feedback mode, $u = f(e)e$, researches focus on finding a better nonlinear function of f to make the system more stable, accurate, energy efficient, and concise. The error e is fed back directly to the controller without any processing. Further improvement of that mode is limited after decades of development. Nonlinear feedback research focuses on changing an existing control law $u = f(e)e$ into $u = f(e)g(e)$. By improving function g, the control effect can be improved. Nonlinear decoration focuses on modifying the controller output, it changes $u = f(e)e$ into $h(u) = f(e)e$. By now, six forms of effective nonlinear feedback or decoration function have been found; they are sine function, arc tangent function, sigmoid function, power function, hyperbolic tangent function and exponential function.

In general, the adoption of the nonlinear decoration designing method cannot enhance the control performance of the system, but it can reduce the energy consumption of controlling (Zhang et al., 2018). Therefore, a concise robust integrator backstepping control methodology is proposed by combining integrator backstepping, CGSA and nonlinear decoration of sine function in this paper. In order to decrease the unreasonable steering frequency, sea trail data is analyzed and the practical range of steering frequency is explored.

Simulation results show that the proposed controller preserves the advantage of the three methods above, avoids the defects of each and has good robustness to the perturbation of steering mechanisms and ship model. Its energy saving performance is also satisfactory and the algorithm is more consistent with navigation practice.

2. The design of nonlinear robust controller for ship course keeping based on nonlinear decoration and integrator backstepping method

To guarantee the ship course ψ tracks the desired course ψ_r, let $x_1 = \psi$, $x_2 = \dot{x}_1 = r = \dot{\psi}$ and $e = \psi - \psi_r$, where e is the tracking error, the nonlinear dynamic model of the ship can be described as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = F(x_2) + bu + \Delta \\ y = x_1 \end{cases} \tag{1}$$

where $y \in R$ is the output of the system, $F(x_2) = -\frac{K_0}{T_0} H(\dot{\psi})$, $H(\dot{\psi}) = \alpha\dot{\psi} + \beta\dot{\psi}^3$, $b = \frac{K_0}{T_0}$, $u = \delta$, K_0 and T_0 are the maneuverability indices of ship, δ is the input rudder angle, α and β are nonlinear parameters. Δ is the uncertain disturbance. Generally, Δ is a bounded disturbance and its boundary is unknown, thus $\|\Delta\|_\infty \le \rho$, where ρ is an unknown constant.

For a system described as (1), the course-keeping controller design method via backstepping is as follows:

Firstly, define the error of the system as

$$\begin{cases} \dot{\xi} = z_2 \\ z_1 = x_1 - \psi_r \\ z_2 = x_2 - \sigma \end{cases} \tag{2}$$

where σ is the virtual control variable, z_1 is the course tracking error, ξ is an integral term introduced in the controller design to eliminate the static error caused by an uncertain interference term Δ.

Set the first Lyapunov function as

$$V_1 = \frac{1}{2} z_1^2$$

$$\dot{V}_1 = z_1(z_2 + \sigma - \dot{\psi}_r) \tag{3}$$

Define the virtual control parameter as

$$\sigma = -c_1 z_1 + \dot{\psi}_r \tag{4}$$

where $c_1 > 0$ is a controller design parameter. Substitute (4) into (3), we have

$$\dot{V}_1 = -c_1 z_1^2 + z_1 z_2 \tag{5}$$

Define the second Lyapunov function as

$$V_2 = V_1 + \frac{\lambda}{2}\xi^2 + \frac{1}{2} z_2^2 \tag{6}$$

where λ is a constant larger than 0.

$$\dot{V}_2 = -c_1 z_1^2 + z_2(z_1 + \lambda\xi + \dot{z}_2) \tag{7}$$

Considering (1) and (2), it can be obtained that

$$\dot{z}_2 = -\frac{K_0}{T_0}\left(\alpha x_2 + \beta x_2^3\right) + bu + \Delta + c_1 x_2 \tag{8}$$

Assuming there is no disturbance term Δ in (8), equation (7) can be written as

$$\dot{V}_2 = -c_1 z_1^2 + z_2 \left(z_1 + \lambda \xi + a_1 x_2 + a_2 x_2^3 + bu + c_1 x_2 \right) \tag{9}$$

where $a_1 = -\frac{K_0}{T_0}\alpha$, $a_2 = -\frac{K_0}{T_0}\beta$.

Then the control law is defined as

$$u = \frac{1}{b}\left[-a_1 x_2 - a_2 x_2^3 - \lambda \xi - c_1 x_2 - z_1 - c_2 z_2 \right] \tag{10}$$

where $c_2 > 0$ is a design parameter.

Substitute (10) into (9), we can get

$$\dot{V}_2 = -c_1 z_1^2 - c_2 z_2^2 \le 0$$

According to Lyapunov stability theorem, the error z_2 can be stabilized by the control law (10) when without consideration of interference term Δ.

In order to eliminate the uncertain term Δ, control law u can be redesigned with the introduction of nonlinear damping term (Benaskeur and Desbiens, 2002).

For the system (1) and system error definition (2), the control law of the system can be defined as

$$u = \frac{1}{b}\left[-a_1 x_2 - a_2 x_2^3 - \lambda \xi - c_1 x_2 - z_1 - (c_2 + \eta) z_2 \right] \tag{11}$$

where $\eta > 0$ is a design parameter.

Substitute (11) and (8) into (7), we get

$$\dot{V}_2 = -c_1 {z_1}^2 - c_2 {z_2}^2 - \eta {z_2}^2 + z_2 \Delta$$

To achieve $\dot{V}_2 < 0$, only $z_2 \Delta \le 0$ needs to be proved.

Since the inequality (Benaskeur and Desbiens, 2002) $xy \le \eta x^2 + \frac{1}{4\eta} y^2$, we have

$$z_2 \Delta \le \eta z_2^2 + \frac{\|\Delta\|_\infty^2}{4\eta}$$

Then

$$\dot{V}_2 \le -c_1 z_1^2 - c_2 z_2^2 + \frac{\|\Delta\|_\infty^2}{4\eta} \le -c_2 z_2^2 + \frac{\|\Delta\|_\infty^2}{4\eta} \tag{12}$$

Hence $c_2 z_2^2 \ge \frac{\|\Delta\|_\infty^2}{4\eta}$ should be guaranteed.

Because $\|\Delta\|_\infty \le \rho$, when the condition $R = \left\{ z_2 : |z_2| > \frac{\rho}{2\sqrt{\eta c_2}} \right\}$ is satisfied, $\dot{V}_2$ is negative definite, z_2 asymptotically convergent to $\pm\frac{\rho}{2\sqrt{\eta c_2}}$, and the stability of the system error z_2 incorporating the uncertain disturbance can be guaranteed by the definition of the control law (11). Through deep analysis according to Benaskeur and Desbiens (2002), the condition R is easily satisfied by selecting η and c_2.

Finally, considering (1), (2), (4) and (11), the proposed control law of ship course-keeping can be expressed as

$$u = \frac{1}{b}\left\{ -(a_1 + c_1 + c_2 + \eta) x_2 - a_2 x_2^3 - (1 + c_1 c_2 + c_1 \eta)(x_1 - \psi_r) - \lambda \int [x_2 + c_1 (x_1 - \psi_r)] \mathrm{d}t \right\} \tag{13}$$

For control law (13), the tuning parameters c_1, c_2, η and λ are all required to be selected, which indicates a difficult and time-consuming procedure. Especially, the arbitrary selection of the controller tuning parameters might reduce the convergence properties of the system. Therefore, the simplification of the integrator backstepping controller is required.

In practice, ψ_r can be deemed as a step function, so $\dot{\psi}_r = 0$. Let $e_1 = \psi_r - \psi = \psi_r - x_1$, then $\dot{e}_1 = -\dot{x}_1 = -\dot{\psi} = -x_2$.Then the control law (13) can be rewritten as

$$\begin{aligned} u &= \frac{1}{b}\left[\left(a_1 + c_1 + c_2 + \eta \right) \dot{e}_1 + a_2 \dot{e}_1^3 + \left(1 + c_1 c_2 + c_1 \eta \right) e_1 + \lambda \int \left(\dot{e}_1 + c_1 e_1 \right) \mathrm{d}t \right] \\ &= \frac{a_2}{b} \dot{e}_1^3 + \frac{1}{b}\left[\left(1 + c_1 c_2 + c_1 \eta + \lambda \right) e_1 + \lambda c_1 \int e_1 \mathrm{d}t + \left(a_1 + c_1 + c_2 + \eta \right) \dot{e}_1 \right] \end{aligned} \tag{14}$$

Substitute (14) into (1) and suppose $k_p = 1 + c_1 c_2 + c_1 \eta + \lambda$, $k_i = \lambda c_1$, $k_d = a_1 + c_1 + c_2 + \eta$. Then the obtained control law can be found to be composed of a nonlinear term and a linear PID controller.

$$u = \frac{a_2}{b} \dot{e}_1^3 + \frac{T_0}{K_0} v = -\beta \dot{e}_1^3 + \frac{T_0}{K_0} v \tag{15}$$

where $v = k_p e_1 + k_i \int e_1 \mathrm{d}t + k_d \dot{e}_1$.

Therefore, the control law (15) can be used directly when designing a nonlinear controller based on integrator backstepping methodology, where the linear controller part v can be replaced by other linear controllers as long as k_p, k_i and k_d are positive. In this paper, the first-order CGSA controller design scheme is used to design the linear PID controller v in (15), and the sensitivity function T of the closed-loop system is given as

$$T = 1/(T_1 s + 1) = \frac{GK}{1 + GK} \tag{16}$$

where the controller K can be easily deduced based on the selection of the bandwidth frequency of the closed-loop system $1/T_1$ and the controlled plant G.

$$K = \frac{v}{e_1} = \frac{1}{G T_1 s} \tag{17}$$

The Nomoto model can be used to design the linear part of the controller (Zhang and Jin, 2013). The standard linear Nomoto model $G = \frac{\psi}{\delta} = \frac{K_0}{T_0 s^2 + s}$ can be obtained by omitting the nonlinear term and Δ in (1) and transforming into transfer function format. To eliminate the influence of static error of the system when CGSA controller design scheme is selected, a small constant term ε could be introduced to the denominator of the transfer function of the model to represent the influence of uncertain constant disturbance to the ship. Hence, the traditional Nomoto model is expressed as

$$G = \frac{K_0}{T_0 s^2 + s + \varepsilon} \tag{18}$$

Therefore, the linear PID controller part of (15) is able to be expressed as

$$v = \frac{1}{G T_1 s} e_1 = \frac{T_0 s^2 + s + \varepsilon}{K_0 T_1 s} e_1 = \left(\frac{1}{K_0 T_1} + \frac{\varepsilon}{K_0 T_1 s} + \frac{T_0}{K_0 T_1} s \right) e_1 \tag{19}$$

So the whole expression of nonlinear control law (15) can be rewritten as

$$u = -\beta e_1^3 s^3 + \frac{T_0}{K_0} \left(\frac{1}{K_0 T_1} + \frac{\varepsilon}{K_0 T_1 s} + \frac{T_0}{K_0 T_1} s \right) e_1 \tag{20}$$

Remark:

Vessels navigating on sea will face many interferences. Wave is usually deemed as output interference, while wind is deem as input interference. For output interference, because Nomoto model itself contains an integrator, static error caused by output interference can be eliminated. But for input interference its static error cannot be eliminated.

Suppose the input signal d_i is a step interference to the plant G, y is the system output, then for controller $K(s) = \frac{d_p s^p + d_{p-1} s^{p-1} + \cdots + d_0}{c_p s^q + c_{p-1} s^{q-1} + \cdots + c_0}$, $p \le q$, the transfer function of d_i to y is

$$\frac{y}{d_i} = \frac{G}{1 + GK}$$

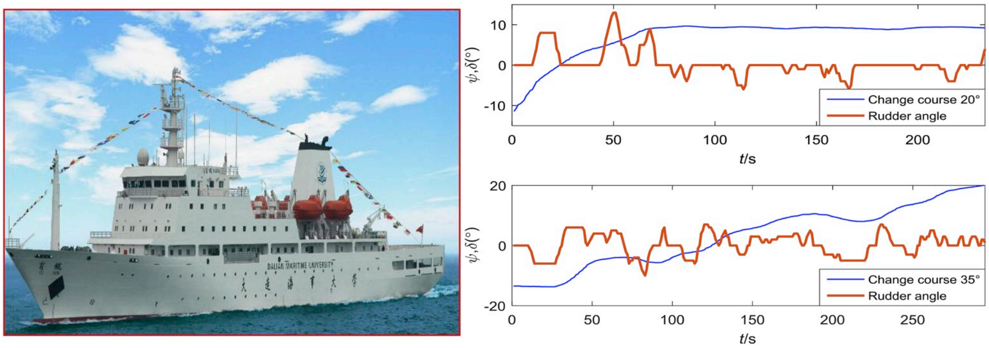

Fig. 2. Sea trail data and analysis of ship "Yukun".

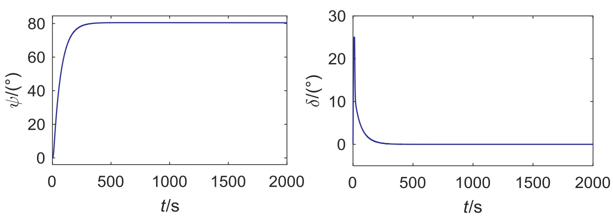

Fig. 3. Course and rudder curves without wind and wave disturbance, without nonlinear decoration and steer frequency limit.

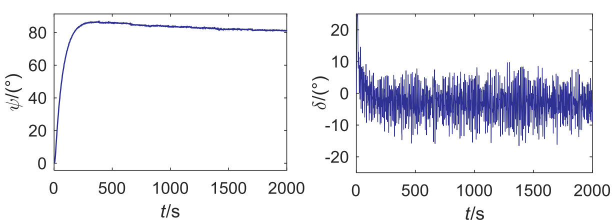

Fig. 4. Course and rudder curves under wind scale of Beaufort No.6, without nonlinear decoration and steer frequency limit.

According to final value theorem,

$$y(\infty) = \lim_{s\to 0} s\frac{G}{1+GK}\frac{d_i}{s} = \lim_{s\to 0}\frac{\frac{K_0 d_i}{s(T_0 s+1)}}{1+\frac{K_0}{s(T_0 s+1)}K} = \frac{d_i c_0}{d_0}$$

So the system static error is $\frac{d_i c_0}{d_0}$. Because $d_i \neq 0$, only when $c_0 = 0$ the static error is 0, therefore the controller needs an integral term for eliminating the input interference.

The nonlinear control law (20) is composed of a nonlinear term and a linear PID controller, which has the same structure as (14). The controller in (20) has satisfactory robustness because CGSA is a robust algorithm (Zhang, 2012). At present, only one design parameter T_1 that has definite physical meaning is to be selected rather than the original four arbitrary parameters.

According to Zhang et al. (2018), to reduce energy consumption, the original control law is nonlinear decorated by a sine function. Then the nonlinear decoration control law U can be obtained as followed.

$$U = \sin(\omega u) \tag{21}$$

where $0<\omega<1$. Because rudder angle is generally limited within 25°, the maximum absolute value of u is 0.436(rad). So ωu is small, we have $\sin(\omega u)\approx\omega u$. Stability analysis and effect analysis is demonstrated by final value theorem and closed-loop gain shaping of H_∞ robust control theory.

Control law (21) is the final format of our course-keeping controller through modified integrator backstepping methodology. The controller design procedure is definite and simple without reducing the robustness and control performance, with only two tuning parameters to be designed.

3. Simulation results and analysis

In this section, the nonlinear Nomoto model (Zhang and Jin, 2013) of training vessel Yukun is used to verify the control effect. The model consists of a rudder servo model and a nonlinear ship model (as shown in Fig. 1). Principle particulars of the ship are given in Table 1. Based on these parameters, the parameters for Nomoto model is calculated as $K_0 = 0.31\text{s}^{-1}$, $T_0 = 64.53\text{s}$, $\alpha = 8.00$, and $\beta = 4295.02$.

The nonlinear decoration parameter ω is selected as 0.7. The spectrum of wave interference is 0.3–1.25 rad/s. In order to make the interference outside of the effective bandwidth of the closed-loop

Table 2
Comparison of different algorithms of dynamic performance and comprehensive index.

Index for methods or conditions and corresponding figure	Overshoot	Average rudder angle	Steering interval	Comprehensive performance index J	Evaluation
④, Fig. 4	8.8%	5.2°	0.5s	31.75	Commonly used algorithm in the past, high steering frequency with some overshoot.
①④, Fig. 5	10.1%	3.8°	0.5s	31.71	Nonlinear decoration leads to smaller rudder angle but larger overshoot.
①②④, Fig. 6	10.2%	4.2°	6s	14.08	Steering interval restriction enhances steering rationality.
①②③④, Fig. 7, solid line	5.9%	4.3°	6s	11.84	First-order delayed reference is capable to reduce overshoot, a satisfactory strategy.
①②, Fig. 7, dotted line	1.1%	4.2°	6s	16.09	No integrator term leads to a 4° static error. Therefore, J is enlarged.
①②(7s)③④	6.0%	4.6°	7s	11.75	For steering interval restriction, 6s and 7s roughly lead to the same performance, a satisfactory strategy.
①②(8s)③④	6.3%	4.5°	8s	12.44	Steering interval restriction larger than 7s leads to worse performance.
①②③④⑤, Fig. 8	2.5%	2.6°	6s	8.50	Good robustness to model perturbation
①②③④⑤⑥, Fig. 9	2.8%	4.3°	6s	10.32	Good robustness to disturbance

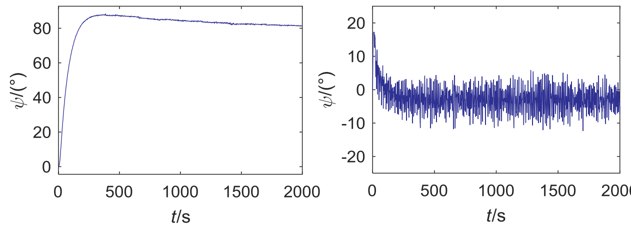

Fig. 5. Course and rudder curves under wind scale of Beaufort No.6, with nonlinear decoration, without steer frequency limit.

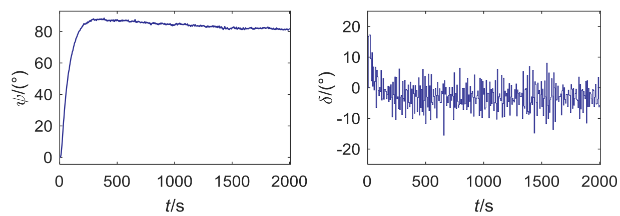

Fig. 6. Course and rudder curves under wind scale of Beaufort No.6, with nonlinear decoration and steer frequency limit.

control system, the working bandwidth frequency of the course-keeping controller should be selected as 1/3 rad/s, and thus the design parameter can be obtained as $T_1 = 3$s.

In practical ship maneuvering system, the nonlinear feature of steering servomechanism has an unneglectable influence on the course-keeping effectiveness. Hence, a single oil path steering gear hydraulic system with analog control signal is introduced in the simulations (the rudder servo model in Fig. 1). The maximum steering rate of the steer servomechanism is set as $\pm 5^\circ$/s and the maximum steering angle is set as $\pm 25^\circ$ for safe navigation.

The steering frequency is less considered when designing course keeping controller. Generally, the interval of the steering operation of the deduced controller is around 0.3s ~ 3s. Throughout the analysis of full scale experiment data of the training vessel Yukun (as shown in Fig. 2), the average manual operation rate is about 8s every time, which means the steering frequency of the traditional controller is too fast and cannot meet the practical ship maneuvering requirements. In this paper, to achieve a better control performance, the interval of steering automatic operation is set to 6s. The nonlinear characteristics of the steering servomechanisms are also taken into considerations in the following experiments.

When navigating on sea, wind and wave are important external disturbances to the ship course keeping, so their influence should be considered in the simulation. For sea wind, it can be divided into two kinds, the constant wind and the turbulent wind, where the turbulent wind can be expressed as a white noise according to Zhang (2012). The constant wind can be replaced by an equivalent leeway angle (Guo, 1999) which can be deemed as a rudder angle δ_{wind} and can be expressed as

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

where K^0 is the leeway coefficient, V_R and V are the wind speed and ship speed respectively.

For sea wave, a typical second order oscillation component driven by white noise is adopted to describe the sea waves model (Yang et al., 2016). The transfer function of sea wave model of wind scale of Beaufort No.6 can be expressed as

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

Desired course is set as 80°, when without wind ($\varepsilon = 0.0001$), simulation result is shown in Fig. 3. Obviously, in nominal condition the controlled system has a short rising time without any overshoot, and the steering operation is reasonable. When the wind scale is Beaufort No.6, wind direction set as 50°, the calculated leeway is 3°, then the interval of the steering operation is set as 6s, simulation result ($\varepsilon = 0.001$) is shown in Fig. 4. It can be seen that the controlling effect becomes worse with an 8.8% overshoot and the average steering angle is 5.2°. Because the controller is designed based on nominal model, with perturbation on rudder servo system, wind scale of Beaufort No. 6 wind and wave disturbance, this slight performance deterioration is acceptable. It indicates the robustness of the proposed controller is satisfactory.

To evaluate the control performance of different strategies, a comprehensive performance evaluation index (CPEI) J is defined in (22). The assessment of the different algorithms are shown in Table 2.

$$J = \frac{1}{T_o}\int_0^{T_o} (|\Delta\psi| + |\delta|)\mathrm{d}t + \delta_n/T_0 \times 10 + \exp\left(|e_n|/3\right) \tag{22}$$

where T_0 is the total time, $\Delta\psi$ is the course error, δ is the rudder angle, δ_n/T_0 is the steering frequency, e_n is the static error. We can see J is formed by 4 terms. For each term, when its contribution to J is 10, separately means: average course error is 10°, average absolute rudder angle is 10°, average steering interval is 1s, static error is 7°. So generally J is less than 40.

With the same condition as Fig. 4, this time we introduce a nonlinear decoration element into this system, simulation result is shown in Fig. 5. The overshoot is enlarged to 10.1%, but the mean rudder angle is decreased to 3.8°. Therefore, energy consumption is reduced through nonlinear decoration. Both the two strategy do not consider steering frequency, so the CPEI of them is large.

Still the same condition as Fig. 4, this time besides nonlinear decoration, we introduce a zero-order hold element with time 6s into this system. Simulation result is shown in Fig. 6. It is obvious that the steering frequency is much lower and now CPEI becomes much smaller. However, the overshoot problem is not solved.

The overshoot is mainly caused by two reasons. One is the wind interference, the other is the integrator term. Detecting and tackling

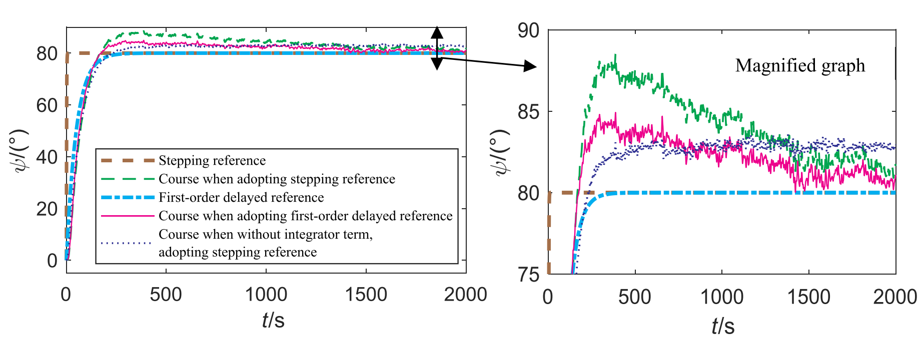

Fig. 7. Comparison of course for different reference under wind scale of Beaufort No.6, with nonlinear decoration and steer frequency limit of 6s once.

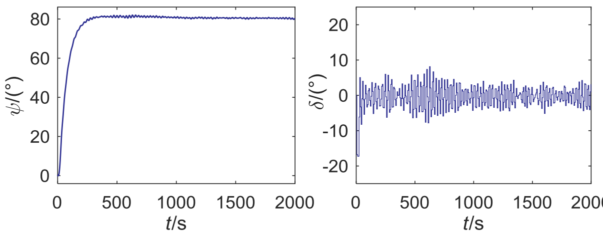

Fig. 8. Course and rudder curves under wind scale of Beaufort No.6, Norrbin model, with nonlinear decoration, without steer frequency limit.

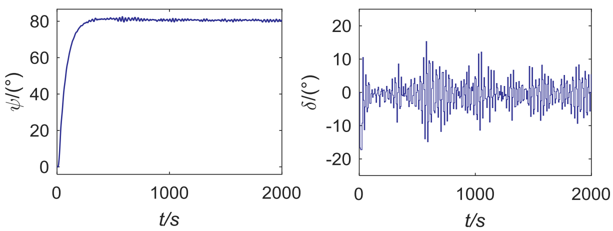

Fig. 9. Course and rudder curves for Norrbin model, under wind scale of Beaufort No.8, with nonlinear decoration, without steer frequency limit.

interference is relatively tough, but it is easy to eliminate the negative effect of integrator term. Overshoot caused by integrator term is because initially the difference between desired value and output value is too large. Therefore, it is reasonable to decrease this difference by adding a first-order inertial component to the desired course and this is equivalent to using the second order CGSA controller (Zhang, 2012). Inertia is the inherent property of ships, thus for a specific ship, its rise time for changing course must be larger than a certain value. This is why delaying the desired course properly does not affect rising time. With the same condition as Fig. 6 and additionally add this method, we can get the solid line in Fig. 7. The overshoot becomes 5.9%, which is 42.2% less than before. This is the proposed control strategy in this paper.

Fig. 7 also illustrates that there will be a 4° static error if integrator term is not applied. Therefore the integrator term is necessary.

In order to further verify the robustness of the proposed controller, the simplified nonlinear ship motion model shown in (1) is replaced by a complicated Norrbin nonlinear mathematical model. Details of Norrbin model can be got in Claes et al., (1977) or Zhang and Jin (2013). The model of rudder servomechanisms with 5s delay and the nonlinear model of wind and wave are also taken into consideration for wind scale of Beaufort No.6 and 8 with wind direction 50°. The maximum rudder speed and the maximum rudder angle of the steer servomechanism (Fig. 1) remain the same as the above descriptions. Control strategy and other parameters are set the same as in Fig. 6.

Simulation results are shown in Fig. 8, Fig. 9 and Table 2. With model perturbation, the control performance and energy saving performance are still satisfactory. Under wind scale of Beaufort No.6, the control effect and energy saving performance of the complex nonlinear model are even better than the simple nonlinear model. One reasonable explanation is that since the rudder angle to balance leeway in the simple nonlinear model is concluded from navigation practice, the value of it may be too large (or the theoretical result is small). Comparing the simulation curves of the two, both the trend of overshoot and the rise time are the same, so we can say the designed controller is robust and is suitable for ship controlling under rough sea condition.

In order to integrate the experiments above and express them clearer. Table 2 is given with some indexes to express different methods or conditions, they are:

①: use nonlinear decoration, ②: use steering interval restriction, ③: change step reference into first-order delayed reference, ④: adopting integrator term, ⑤: change simplified nonlinear model into nonlinear Norrbin model, ⑥: change of Beaufort wind scale from No.6 to No.8.

The second row (④, Fig. 4) is the classical integral backstepping method (with parameter selected by CGSA), the rows thereafter demonstrate the improvements and perturbation tests of the improved method.

4. Conclusions

In this paper, a concise robust integrator backstepping control methodology with nonlinear sine function decorated closed-loop gain shaping algorithm is proposed. It is found that the essence of the traditional integrator backstepping controller design methodology is composed of a linear PID controller and a nonlinear term of the model. Hence, the CGSA controller design scheme, which is a concise robust control algorithm and insensitive to the perturbation of model, is used to design the linear controller. Then, the control performance is improved by nonlinear decoration of sine function, steering interval restriction and first-order delayed reference. The stability of the proposed nonlinear robust control law is proved based on Lyapunov theorem and the robustness is verified through simulation. The controller design procedure is definite and simple without reducing the robustness and control performance. Only two tuning parameters (ω and T_1) are required to be selected, and T_1 can be determined according to the system bandwidth.

The energy consumption of the proposed control strategy (Fig. 7, solid line) is reduced because the mean rudder angle is 17.3% lower than traditional control scheme (Fig. 4) and the overshoot is 33.0% smaller. The controller design concept proposed in this paper has a good theoretical analysis, satisfying robustness with less parameters, reasonable steering operation frequency and remarkable energy saving effect.

Conflicts of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oceaneng.2019.106349.

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