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Improved ships course-keeping robust control algorithm based on backstepping and nonlinear feedback

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IMPROVED SHIPS COURSE-KEEPING ROBUST CONTROL ALGORITHM BASED ON BACKSTEPPING AND NONLINEAR FEEDBACK

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DECLARATION

I certify that all the material in this research paper that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

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ABSTRACT

Title of Dissertation: **Improved Ships Course-keeping Robust Control Algorithm Based on Backstepping and Nonlinear Feedback**

Energy efficiency and emission reduction technologies have been a significant focus of the shipping industry. Especially after a series of measures designated by IMO for reducing GHG emissions, the research and promotion of new energy efficiency and emission reduction technologies have been encouraged. Analyses the mainstream technologies in the shipping industry and research the improved course-keeping control algorithm, using it as an example to analyse the promotion and application measures of energy efficiency technologies.

To improve the shortcomings of the backstepping design of a ship course-keeping controller. The energy efficiency of the algorithm is optimised by equivalent replacement of the CLGS algorithm using nonlinear feedback driven by an inverse tangent function. The stability of the algorithm is demonstrated through formulations such as Lyapunov's theorem. The algorithm performance is analysed using simulations based on actual ship data. It is achieved a 36% reduction in average rudder angle, providing good energy efficiency compared to the algorithm before the improvement. To analyse measures to promote technologies, providing an overview of IMO and MTCC energy efficiency measures and technology promotion discusses and gives recommendations from the perspective of promoting the transformation and advancement of new technologies.

KEY WORDS: Energy Efficiency, Course-keeping Control for Ship, Robust Control, Nonlinear Feedback, Technology Promotion

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LIST OF ABBREVIATIONS

CLGS	Closed-Loop Gain Shaping
EEDI	Energy Efficiency Design Index
GloMEEP	Global Maritime Energy Efficiency Partnership
GHG	Greenhouse Gas
GMN	Global MTCCs Network
IMO	International Maritime Organization
ITCP	Integrated Technical Cooperation Plan
LDCs	Least Developed Countries
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MARPOL	The International Convention for the Prevention of Pollution from Ships
MEPC	Maritime Environment Protection Committee
MTCC	Maritime Technology Cooperation Centre of Excellence
SIDS	Small Island Developing States
UNFCCC	United Nations Framework Convention on Climate Change

CHAPTER 1: INTRODUCTION

International Maritime Organization (IMO) is concerned about developing and promoting energy efficiency and emission reduction technologies in the shipping industry. It encourages the development and adoption of innovative technologies in a series of measures that are continuously promoted. The current ship energy efficiency technologies range from ship structure, systems, operation and energy (Zong, 2013). As a core function of the autopilot system, optimisation of the ship course-keeping control can effectively reduce the energy consumption of ship navigation. The ship course-keeping algorithm has little impact on the ship structure modification and has the advantages of a short modification cycle and low cost (Zhang et al., 2019). It is of significant value as a further extension of energy efficiency and emission reduction technology.

To improve the deficiencies of the ship course-keeping controller designed by the backstepping method with added integral terms, such as insignificant robustness, complex parameter adjustment, high control energy, and steering frequency not matching the actual sailing reality. Building on previous research, using nonlinear feedback driven by an inverse tangent function is investigated to optimise the energy efficiency of algorithm(Zhang et al., 2019). The stability of the algorithm is demonstrated by formulas such as Lyapunov theorem, and the corresponding analytical equations for the design parameters before and after the algorithm improvement are provided.

Through analysis of actual ship data and verification of algorithm performance, a steering frequency that matches the realities of navigation is found. The research of the simulation structure shows that the improved algorithm is significantly robust against the disturbance of wind, wave, and rudder non-linearities, and the average rudder angle is reduced by 36% compared to the enhanced algorithm before. The improved control algorithm proposed has clear theoretical arguments for both stability and robustness and has the advantages of fewer design parameters, more straightforward structure, lower control energy, and compliance with actual ship navigation conditions.

1.1 Objective of Research

This research aims to illustrate the current state of the technology in maritime energy efficiency and emission reduction using an improved ship course-keeping algorithm as an example. In addition to this, analyse the role that the IMO plays in promoting maritime energy efficiency technology in terms of its measures to reduce marine greenhouse gas emissions and propose recommendations for the promotion of technology in the current stage of maritime energy efficiency and emission reduction.

1.2 Methodology

An extensive literature review was conducted, including information on the history related to energy efficiency and emission reduction, the energy efficiency measures are taken by the IMO, the mainstream technology of maritime energy efficiency and emission reduction, and the technology of ship course-keeping algorithm. In order to make the improved algorithm technology studied more rigorous and of more practical value, the reliability of the enhanced ship course-keeping algorithm technology is demonstrated through theoretical arguments, and simulation is used to compare and verify the advantages of the technology and the effectiveness of energy efficiency.

1.3 Structure of Dissertation

This dissertation is divided into five chapters. Chapter two provides an overview of the development of energy efficiency and emission reduction, revealing the importance of the research, the energy efficiency and emission reduction measures, and mainstream technologies for the shipping industry. Chapter three is a study of the course-keeping algorithm technology, theoretical proof of the reliability of the analysis technology, and simulation to verify the energy efficiency and emission reduction effect of the technology. The fourth chapter analyses the barriers to the promotion of energy efficiency technologies, outlines the objectives of the IMO in forming the MTCC and puts forward proposals for the improvement of energy efficiency technologies led by the MTCC. Chapter five provides a summary and conclusion of the whole paper.

CHAPTER 2: THE ENERGY EFFICIENCY AND EMISSIONS REDUCTION OF THE MARITIME

2.1 The History of Energy Conservation and Emissions Reduction

Energy is an essential primary material for the survival and development of society. While supporting the rapid growth of the economy and society, energy has also brought about a series of problems and challenges such as the deterioration of the ecological environment, tension in energy supply and demand, and resource depletion (Song et al., 2018). As environmental problems become increasingly severe worldwide, countries and organisations around the world are paying more and more attention to the issue of energy conservation. They are constantly exploring ways to reduce energy consumption, reduce pollutant emissions and improve resource efficiency, with green initiatives based on energy conservation being widely implemented worldwide (Chen, Liu, & Hua, 2012).

The theory of sustainable development, which is clearly defined in the 1980 report Our Common Future by the United Nations World Commission on Environment and Development, emphasised the coherence and sustainability of the economy, ecology, and society. The idea is to change from traditional development with high energy consumption and pollution to development that does not exceed the renewal capacity of environmental systems and to promote economic growth while emphasising the harmonisation of the exploitation and use of natural resources with environmental protection (Feng, 2016). The theory of sustainable development organically combines ecological issues with development issues to rationalise energy use, protect the ecological environment and achieve a virtuous cycle that balances economic growth and environmental protection (BenJimin, 2015).

The low-carbon economy refers to a form of economic development guided by the concept of sustainable development, through technological and institutional innovation, industrial transformation, new energy development, and other means to minimise high-carbon energy consumption and greenhouse gas (GHG) emissions and achieve a win-win situation for both economic and social development (Aykut et al., 2018). The essence is the efficient use of energy and clean energy development, and the core is through the innovation of energy technology and emission reduction technology. The development of a low-carbon economy involves the improvement and upgrading of industrial structure, management systems, and energy-saving technologies, which are consistent with the goal of energy efficiency and consumption reduction and greatly promote each other (Zheng, Liu, & Lin, 2020).

British environmental economist David Preece first proposed green development theory in the blueprint of green economy, which is a new development model aiming at ecological sustainability, harmonious coexistence between humans and nature, and harmonious development of economy and society. Later, with the continuous development of the economy and culture, the concept of green development was gradually expanded to many fields (Chen, Liu, & Hua, 2012). For the shipping sector, industrial structure optimisation based on the green concept has gradually become a key area of concern for the IMO and other organisations.

Energy efficiency is adopting all measures that are technically feasible, economically reasonable, and environmentally and socially acceptable to improve the efficiency of the use of energy resources. Therefore, energy efficiency is a broad concept covering the whole process from energy production to the end of consumption, with the possibility of reducing energy losses and consumption and improving energy use efficiency at every stage. It is guided by legislation, norms and guidelines, market regulation, and technological advances that affect saving energy at different locations.

2.2 Emission Reduction Measures for the Maritime

The shipping industry is one of the critical factors in world trade. Based on the data of Global Insight, 90% of international trade in tonnage and 70% of international trade in value are transported by ships (IHS Markit, 2020). The shipping industry is the key to the global supply chain, especially in recent years, is also a key area of concern for energy efficiency and emission reduction. The shipping industry has been steadily promoting measures related to energy efficiency and emission reduction. The United Nations Framework Convention on Climate Change (UNFCCC) was opened for signature during the United Nations Conference on Environment and Development in 1992 and entered into force in 1994, intending to maintain greenhouse gas concentrations in the atmosphere at a stable level (Goh et al., 2021). In 1997, the Kyoto Protocol was developed as a supplement to the UNFCCC, which states that international initiatives such as shipping and spaceflight, where emissions are difficult to attribute to a particular country or economy entity to limit greenhouse gas emissions and thus minimise the impact of these activities on climate change (Ahonen, 2004). The IMO is responsible for the safety of maritime navigation, and the prevention of marine pollution from ships will be responsible for promoting measures to reduce greenhouse gas emissions from shipping and will regularly report to the UNFCCC on the progress of efforts to reduce greenhouse gas emissions.

2.3 Energy Efficiency Measures of IMO

IMO began working on effective strategies to reduce greenhouse gas emissions in 1997 by amending the MARPOL Convention and adding Annex VI, which for the first time regulated atmospheric pollution by including it in the Convention. According to greenhouse gas emission studies published by IMO, international shipping accounted for 1.8% of total global anthropogenic emissions in 1996, 2.8% in 2007, 2.76% in 2012, and 2.89% in 2018 (IMO, 2020), which predicts that CO_2 emissions will increase by 90-130% of 2018 emissions by 2050. The stabilisation of CO_2 emissions from the shipping industry is due to the emission reduction measures promoted by the IMO.

In 2011, the IMO adopted a resolution to make the Ship Energy Efficiency Design Index (EEDI) and the Ship Energy Efficient Operational Indicator mandatory for the shipping industry. The regulations apply to all ships above 400 GT and achieve the effect of improving energy use of ships and reducing greenhouse gas emissions by phasing in a higher percentage of newbuilding energy efficiency compared to the baseline. From a medium to the long-term time dimension, the EEDI designated by the IMO to benchmark the energy efficiency limits of new ships has significant energy efficiency and emission reduction effect (Maritime Fundation, 2019).

In 2018, IMO approved an initial strategy to reduce GHG from ships and its successor plan from the MEPC 72. The process aims to reduce GHG emissions from shipping and to phase out GHG emissions from shipping over the century (IMO, 2019). IMO supports the sustainable development of global trade and maritime transport services by leading countries to take counterpart actions to address the impacts on states. The initial strategy identifies short-, medium- and long-term measures to reduce GHG emissions from ships in a phased manner.

Possible short-term measures are those to be finalised and agreed between 2018 and 2023 and include, inter alia (IMO, 2019): a framework for further improving existing energy efficiency; developing technical and operational energy efficiency measures for new and existing ships; establishing improvement plans for the existing fleet; speed optimisation and speed reduction; measures to address methane emissions and further measures to address volatile organic compounds; encouraging the development and updating of national action plans; continuing and strengthening technical cooperation and capacity building actions under the ITCP (Integrated Technical Cooperation Plan) framework; measures aimed at promoting global port development and activities; initiating research and development actions addressing ship propulsion, alternative low and zero-carbon fuels and innovative technologies; incentivising pioneers in the development and adoption of new technologies; developing whole life cycle GHG/carbon intensity guidelines for all fuel types; actively contribute to the work of IMO on the international community; conduct the fourth GHG emissions study and so on.

Possible medium-term measures are those to be finalised and agreed upon by MEPC between 2023 and 2030. The main include implementation plans for the effective adoption of alternative low and zero-carbon fuels; operational energy efficiency measures for new and existing ships; new or innovative mechanisms for emission reduction including market-based mechanisms; continued and enhanced technical cooperation and capacity building actions under the ITCP framework; a feedback mechanism to collate and share experiences and lessons learned in the implementation of measures (IMO, 2019).

Possible long-term measures are those finalised and agreed upon by the MEPC after 2030. The main ones include (IMO, 2020): continuing the development and availability of zero-carbon or fossil fuels; encouraging and promoting the widespread adoption of possible new or innovative emission reduction mechanisms.

Recognising that effective mechanisms for information sharing, technology transfer, capacity building, and technical cooperation can assist global participation in the promotion of energy efficiency and emission reduction measures (Harilaos, 2019), particularly in developing countries such as the least developed countries (LDCs) and small island developing states (SIDS). IMO is committed to promoting partnerships and information exchange to assist in the promotion of low carbon technologies, and through the ITCP, Global Maritime Energy Efficiency Partnership (GloMEEP), Global Maritime Technology Cooperation Centre of Excellence (MTCC) and other projects and initiatives to contribute to the achievement of energy efficiency and emission reduction strategies.

2.4 Mainstream Technologies for Marine Energy Efficiency

According to energy efficiency solutions publicised by IMO, strategies to achieve GHG reduction targets require a combination of technical, operational, and innovative solutions applicable to ships. IMO analyses the GHG reduction potential of several technologies as follows: speed optimisations have a reduction potential of up to 75%, main propulsion power units have a possibility of 5-15%, and new energy developments such as hybrid drives, pure electricity, liquefied natural gas (LNG), liquefied petroleum gas (LPG), biofuels, and other fuels have a reduction potential ranging from 35% to 100% respectively. In addition, energy management, voyage optimisations, weight management, supply chain management, and speed optimisations have the potential to reduce emissions by 1-75% in ship operations.

At present, the mainstream energy efficiency technology of ships mainly starts from four aspects: ship structure optimisations, ship system optimisations, ship operation optimisations, and energy optimisations, to reduce ship resistance, improve propulsion efficiency and cabin system efficiency (Zong, 2013), so as to achieve the purpose of reducing fuel consumption and realise energy efficiency and emission reduction of ships. The standard optimisations in ship structure optimisations include ship line optimisations, propeller optimisations, and hull coating optimisations (Lloyd's Register Marine, 2015). Ship system optimisations include main engine optimisations, waste heat recovery systems, cooling water system optimisations. Ship operation optimisations mainly include range optimisations, navigation optimisations, low-speed operation. Ship energy optimisations mainly include hybrid drive technology, LNG, LPG, biofuels, and other low carbon energy sources to replace existing fuels (Edmund et al., 2017).

The main purpose of the linear optimisation of the ship is to reduce the wave-making resistance, avoid the creation of a large number of vortices, and reduce the viscous pressure resistance (Zhao, Li, & Xiao, 2011). For new ships, the optimisation and adjustment are usually carried out by engineers based on the linear data of the parent ship, and the hydrodynamic performance of the optimised linear is analysed by modelling software. In the case of operational ships, where the dominant operating strategy is low speeds operating, many ships differ from the ideal operating conditions for which they were designed and where simple modifications for local structural adjustments can have a specific energy efficiency effect (Goh et al., 2021). An example of a simple linear improvement is the bulbous bow retrofit. Under reduced speed conditions, the bulbous bow can create a beneficial interference with the main hull and reduce wave-making resistance. The bulbous bow modification is relatively independent of the ship as a whole and does not involve the cargo and engine room areas. It takes about half a year to analyse the line shape of the ship, design, and produce the modified bulbous bow. While the ship is in the dock for modification in only about half a month, which can be carried out simultaneously as the conventional docking survey and does not affect the regular schedule of the ship. The conversion can reduce fuel consumption by 3-6%, gradually becoming the mainstream linear optimisation conversion method for ships.

Optimisation of the main engine is also a requirement under reduced speed operating, which reduces the carbon footprint of the ship while causing some damage to the main engine. Ship navigation practice shows that the most significant energy efficiency are achieved when the main engine is operated at an ultra-low load of 40% of maximum power. However, long-term ultra-low load operation can cause damage to mechanical equipment such as boiler, exhaust gas boiler, superchargers, and fuel injectors (Lind et al., 2012). Therefore, the necessary mainframe optimisation is the key to ensuring the stable operation of the equipment and achieving energy efficiency and emission reduction targets. Main engine optimisation measures are to increase the sweep up the volume, through block one turbocharger to increase the efficiency of other normally operating turbochargers. It ensures that the main engine equipment remains at the optimum temperature under ultra-low load to ensure fuel combustion efficiency.

The energy efficiency performance of a ship is the amount of fuel consumed under specific sailing conditions such as speed and draught. The main purpose of energy-efficient technology is to reduce fuel consumption to achieve energy efficiency and emission reduction (Aykut et al., 2018).

The above mainstream energy efficiency technologies can significantly improve the energy efficiency performance of newly built ships when detailed technology applications are considered during the ship construction design stage. Due to the changes in the external environment of ship operation, shipowners are generally cautious about energy-saving renovations with long lead time and high costs, such as ship structure optimisations, power system renovation, and system retrofits. Their willingness is influenced by factors such as policies, freight rates, and fuel prices. Willingness is usually low when there are no mandatory requirements. However, there are also optimisation methods that have a short transformation period, low impact on the ship, and low cost, which also have the potential to save energy and reduce emissions. Examples include automatic rudder optimisations, energy management, load distribution management, and other soft optimisations that require slight modification to the structure and hardware of the ship.

CHAPTER 3: CONTROLLER DESIGN BASED ON BACKSTEPPING ALGORITHM

3.1 Course-keeping Control Improve Method Analysis

Ship course-keeping control is one of the research hotspots in maritime transport to improve the safety of transportation and reduce energy consumption. Ship motion control is an effective means to achieve these aims. Due to the large inertia and hysteresis of ships, the response to rudder angle is slow and the control period is long (Yan et al., 2020). In addition, due to the interference of external environmental factors such as wind, waves, and currents, resulting in the uncertainty and non-linearity of ship motion, ship course-keeping control has become an important research direction in the field of ship motion control (Zhang & Zhang, 2016). In the course of navigation, due to the changing external environmental factors, the use of smaller rudder angle and lower steering frequency can reduce the roll amplitude of the ship, which helps to ensure the smooth and safe navigation of the ship, thus improving the safety of transportation and reducing energy consumption.

The backstepping method, which has been widely studied in recent years, is an integrated control method for uncertain nonlinear systems with good control results (Fang et al., 2018). The control law designed using the backstepping method has a PD form, eliminating the nonlinear terms in the model and allowing the system to have static differences (Benaskeur & Desbiens, 2002). Usually, the control law is proved by Lyapunov stability to ensure the stability of the system when the structure of the control law is a nonlinear function term plus a linear control law (Zhao et al., 2019). In practice, due to external environmental factors, loading, speed, and other model disturbance, the nonlinear parameters are time-varying, making it difficult to eliminate the nonlinear function term. At the same time, the robust control algorithm has the characteristic of being insensitive to the disturbance of the control model (Liu et al., 2019). In the navigation process of the ship, the disturbance of external environment factors will cause constant deviation. Adding an integral term to the control law can effectively eliminate the static difference of the system caused by constant deviation, so the use of integral improvement control law can guarantee the stability and accuracy of ship course-keeping. For the ship course-keeping control, the control law designed by the backstepping method has many adjustment parameters, too fast steering frequency, poor robustness, and high control energy consumption (Zhang et al., 2017). Through integration to improve the static difference of the control law, and the branching closed-loop gain shaping algorithm of the robust control algorithm is combined to enhance the robustness of the control law and reduce the control energy consumption by using nonlinear feedback. To address the shortcomings of the backstepping method so that the algorithms complement each other and improve the control law safer, more realistic, and energy-efficient.

The CLGS algorithm is an important branch of the robust control algorithm, which uses the four parameters of the closed-loop system: maximum singular value, the closed slope, the peak spectrum of the closed-loop, and the bandwidth frequency to construct the transfer function directly (Yan et al., 2020), avoiding the complex process of selecting the weight function and featuring a fast design process, simple structure, and good robustness. However, the control law formed by the CLGS algorithm also suffers from certain shortcomings in the theoretical proof because of the design process of direct construction. The combination of the backstepping method to design the control law has been shown by Lyapunov stability to effectively compensate for the shortcomings of the CLGS algorithm. The potent combination of the backstepping method and the CLGS algorithm can achieve a more satisfactory control effect.

Although nonlinear feedback does not significantly change the control performance of the system, it can achieve the same or even slightly better control effect with less control energy (Liang & Zhang, 2021). The design concept of nonlinear feedback optimises the control law based on the existing control law using a nonlinear function of the error to reduce energy consumption (Zhang & Zhang, 2016). Assume that the controller deviation is e, the output is u, and the control law is $f(e)$, because linear feedback generally feeds the error e directly to the input without any processing of its true value. Hence, the linear feedback control law is $u=f(e)e$. Nonlinear feedback processes the error e and feeds its nonlinear function $g(e)$ to the output, so the nonlinear feedback control law is $u=f(e)g(e)$. Using the inverse tangent function to process the error e, so that the ship can achieve the same course-keeping control effect at a smaller rudder angle (Feng & Zhang, 2018), thus effectively reducing the energy consumption of ship navigation and achieving the purpose of energy efficiency.

3.2 Construct Course-keeping Control Law

The course-keeping control optimisation is based on previous research by adding an integral term to eliminate static differences in the control law designed by the backstepping method (Zhang et al., 2019$_a$). It combined CLGS algorithm to enhance the robustness of the control law, and use nonlinear feedback to reduce control energy consumption. Combining the advantages of the backstepping method with integral terms, the robust control algorithm, and the nonlinear feedback, an improved nonlinear controller design method for ship course-keeping with stability, robustness, and energy efficiency is developed. A simulation of ship course-keeping using the nonlinear Nomoto model is conducted to verify the performance of the improved algorithm (Zhang et al., 2019b).

3.2.1 Design Controller

The objective of the course-keeping control law is to make the actual ship course follow the desired reference course, for design purposes, let the actual ship course be ψ, and the expected reference course be ψ_r, then the tracking error $e = \psi - \psi_r$, to simplify the equation format, let $x_1 = \psi$, and $x_2 = \dot{x}_1 = r = \dot{\psi}$, then the nonlinear dynamic equation for the course-keeping system is

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

In the equation, $y \in R$ is the system output, $f(x_2) = -\frac{K_0}{T_0}\left(\alpha\dot{\psi} + \beta\dot{\psi}^3\right)$, $b = \frac{K_0}{T_0}$, and $u = \delta$, where K_0, T_0 are the ship manoeuvrability indices, α and β are the nonlinear parameters, δ is the input rudder order, and Δ is the uncertain disturbance term. According to practice, Δ is usually a bounded disturbance, so let Δ be bounded but unknown, then the infinite norm of Δ is an unknown constant, denoted as $\|\Delta\|_\infty \leq \rho$.

The design of the nonlinear controller for (1) as follows.

Step 1: Define the error variables, and for the equation expression, let $z_1 = e$

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

Of which σ is the virtual control quantity and $\dot{\xi}$ is the increased integral term, which is used in the control process to eliminate the static error caused by the uncertain disturbance term Δ in (1).

Based on the above formulas, construct the first Lyapunov function as

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

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

Let virtual control quantity

$$\sigma = -c_1 z_1 + \dot{\psi}_r \quad (4)$$

Of which $c_1 > 0$ is the design parameter, and bringing (4) into (3) can get

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

Step 2: Construct the second Lyapunov function as

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

Of which $\lambda > 0$ is a constant, taking the derivative for V_2

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

Formula (1) and (2) can lead to

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

When (8) has no uncertainty disturbance term Δ, (7) can be simplified to

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

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

The feedback control law can be deduced from (9) as

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

Of which $c_2 > 0$ is the design parameter.

Bringing (10) into (9) gives $\dot{V}_2 = -c_1{z_1}^2 - c_2{z_2}^2 \le 0$. According to the Lyapunov stability theorem, the feedback control law of (10) calms the z_2 subsystem stabilisation in the absence of the uncertainty disturbance term Δ.

Step 3: According to the nonlinear damping theorem optimising the control law u as follows. The introduction of the nonlinear damping term achieves the gradual elimination of the uncertain disturbance term Δ in (8).

$$u = \frac{1}{b}[-a_1x_2 - a_2{x_2}^3 - \lambda\xi - c_1x_2 - z_1 - (c_2 + \eta)z_2] \tag{11}$$

Of which $\eta > 0$ is the design parameter.

Taking (10) and (8) into (9) can lead to $\dot{V}_2 = -c_1{z_1}^2 - c_2{z_2}^2 - \eta{z_2}^2 + z_2\Delta$. To prove that $\dot{V}_2 \le 0$, it is only necessary to prove that $z_2\Delta \le 0$. From equation $xy \le \eta x^2 + \frac{1}{4\eta}y^2$, it follows that $z_2\Delta \le \eta{z_2}^2 + \frac{{\|\Delta\|_\infty}^2}{4\eta}$. Therefore,

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

So, if proof $c_2{z_2}^2 \ge \frac{{\|\Delta\|_\infty}^2}{4\eta}$ is established, then $\dot{V}_2 \le 0$ holds.

From (1), (2), and (4) can obtain

$$\dot{z}_1 = z_2 - c_1z_1 \tag{13}$$

Solving for (13) leads to

$$z_1(t) = e^{-c_1t}\left[\int_0^t (z_2(\tau)e^{c_1\tau})\,d\tau + c_0\right] \tag{14}$$

Let the initial state $x_1(0) = 0$, and $x_2(0) = 0$, it can get $c_0 = 0$, then (14) is

$$z_1(t) = e^{-c_1t}\left[\int_0^t (z_2(\tau)e^{c_1\tau})d\tau\right] \tag{15}$$

Defined function as

$$f(z_2) = e^{-c_1 t}\left[\int_0^t (z_2(\tau)e^{c_1\tau})d\tau\right] \tag{16}$$

Then, $|z_1| = f(|z_2|)$ (17)

From (1), (2), (6), and (7) can lead to

$$V_2 = \frac{1}{2}f^2(|z_2|) + \frac{\lambda}{2}\left(\int_0^t z_2(\tau)\,d\tau\right)^2 + \frac{1}{2}|z_2|^2 \tag{18}$$

Defined function as

$$f_1(|z_2|) = \frac{1}{2}{z_2}^2 \tag{19}$$

$$f_2(|z_2|) = f^2(|z_2|) + \lambda\left(\left|\int_0^\tau z_2(\tau)d\tau\right|\right)^2 + |z_2|^2 \tag{20}$$

$$f_3(|z_2|) = c_2{z_2}^2 \tag{21}$$

Therefore

$$f_1(|z_2|) \le V_2 \le f_2(|z_2|) \tag{22}$$

To prove that $c_2{z_2}^2 \ge \frac{\|\Delta\|^2_\infty}{4\eta}$ is established, this can be expressed as proof $f_3(|z_2|) \ge \frac{{\|\Delta\|_\infty}^2}{4\eta}$, and can be converted to

$$|z_2| \ge {f_3}^{-1}\left(\frac{{\|\Delta\|_\infty}^2}{4\eta}\right) \tag{23}$$

Bringing formula (23) into (12) can be shown that in domain $R = \left\{z_2\colon |z_2| > \frac{\rho}{2\sqrt{\eta c_2}}\right\}$, $\dot{V}_2 \le 0$. Therefore, the control law (12) in R can calm the z_2 subsystem stabilisation in the presence of an uncertain disturbance term Δ.

From formula (1), (2), (4), (11) can obtain the feedback control law for the ship course-keeping as

$$u = \frac{1}{b}\{-(a_1 + c_1 + c_2 + \eta)x_2 - a_2{x_2}^3 - (1 + c_1c_2 + c_1\eta)(x_1 - \psi_r) - \lambda\int[x_2 + c_1(x_1 - \psi_r)]\,dt\} \tag{24}$$

Of which c_1, c_2, η, λ are all design parameters and greater than zero, $b = \frac{K_0}{T_0}$, $a_1 = -\frac{K_0}{T_0}\alpha$, $a_2 = -\frac{K_0}{T_0}\beta$, K_0, T_0 are ship manoeuvrability indices, and α and β are nonlinear parameters.

The control law (24) is designed based on the backstepping method, which satisfies the Lyapunov stability theorem, but four design parameters need to be set and adjusted. These design parameters complicate the control system. Because of the random nature of the parameters during the rectification process, it requires a large amount of work to achieve the expected control effect. Therefore, it is necessary to optimise the control law.

3.2.2 Improved Controller

Applying a coordinate transformation to formula (2), the expected reference course ψ_r tends to be a step signal in ship course-keeping, so that $\dot{\psi}_r = 0$. Let $e_1 = \psi_r - \psi = \psi_r - x_1$, and $\dot{e}_1 = -\dot{x}_1 = -\dot{\psi} = -x_2$, brought into (24) as

$$\begin{aligned} u &= \frac{1}{b}\left\{-(a_1 + c_1 + c_2 + \eta)x_2 - a_2 {x_2}^3 - (1 + c_1c_2 + c_1\eta)(x_1 - \psi_r) - \lambda \int [x_2 + c_1(x_1 - \psi_r)]\, dt\right\} \\ &= \frac{1}{b}\left[(a_1 + c_1 + c_2 + \eta)\dot{e}_1 + a_2 {\dot{e}_1}^3 + (1 + c_1c_2 + c_1\eta)e_1 + \lambda \int (\dot{e}_1 + c_1 e_1)\, dt\right] \\ &= \frac{1}{b}\left(a_1\dot{e}_1 + a_2{\dot{e}_1}^3\right) + \frac{1}{b}\left[(c_1 + c_2 + \eta)\dot{e}_1 + (1 + c_1c_2 + c_1\eta)e_1 + \lambda \int (\dot{e}_1 + c_1 e_1)\, dt\right] \\ &= -\frac{1}{b}\left(a_1\dot{\psi} + a_2\dot{\psi}^3\right) + \frac{1}{b}\left[(c_1 + c_2 + \eta)\dot{e}_1 + (1 + c_1c_2 + c_1\eta + \lambda)e_1 + \lambda c_1 \int e_1\, dt\right] \end{aligned} \tag{25}$$

Let $k_p = 1 + c_1c_2 + c_1\eta + \lambda$, $k_i = \lambda c_1$, $k_d = c_1 + c_2 + \eta$, then the control law (25) is a nonlinear function towards plus a PID linear controller, let the linear control law $v = k_p e_1 + k_i \int e_1 dt + k_d \dot{e}_1$, then the control law can be expressed as

$$u = -\frac{1}{b}(a_1\dot{\psi} + a_2\dot{\psi}^3) + \frac{1}{b}v = H(\dot{\psi}) + \frac{T_0}{K_0}v \tag{26}$$

For the linear control part of control law (26), other linear control algorithms can improve. The PID controller in (26) is designed using a branch of the robust control algorithm, the first order CLGS algorithm. Let the closed-loop system have a bandwidth frequency of $1/T_1$, and the closed slope is taken as *-20dB/dec*, the singular value curve of the complementary sensitivity function T is approximated by the spectral curve of the first-order inertial system with a maximum singular value of 1 (Zhang et al., 2017), denoted as

$$T = \frac{1}{(T_1 s+1)} = \frac{GK}{1+GK} \tag{27}$$

G is the controller, K is the controlled object, and s is the Laplace operator. From formula (26), (27) can lead to

$$K = \frac{v}{e_1} = \frac{1}{GT_1 s} \tag{28}$$

For ship course-keeping control, using the linear Nomoto model, which is widely used in the field of ship motion control, then the controlled object $G = \frac{K_0}{(s(T_0 s+1))}$. To eliminate the effect of static errors on the control system, a very small constant term ε is used to reproduce the effect of uncertain constant value disturbances on the ship motion, and the Nomoto model is extended as

$$G = \frac{K_0}{T_0 s^2+s+\varepsilon} \tag{29}$$

Taking (29) into (28) to obtain a linear PID control controller according to the CLGS algorithm

$$v = \frac{1}{GT_1 s} e_1 = \frac{T_0 s^2+s+\varepsilon}{K_0 T_1 s} e_1 = (\frac{1}{K_0 T_1} + \frac{\varepsilon}{K_0 T_1 s} + \frac{T_0}{K_0 T_1} s) e_1 \tag{30}$$

Taking the improved control law (30) into (26) can lead to

$$u = H(\dot{\psi}) + \frac{T_0}{K_0} (\frac{1}{K_0 T_1} + \frac{\varepsilon}{K_0 T_1 s} + \frac{T_0}{K_0 T_1} s) e_1 \tag{31}$$

Control laws (31) and (24) are nonlinear control laws of the same structure, consisting of a nonlinear function and a linear PID controller. The controller designed by the backstepping method in the actual parameter adjustment, control law (24) of c_2 and λ is almost always equal or minimal difference, so set $\lambda = c_2$, then the control law (31) and (24) can be obtained equivalent relationship as

$$c_1 = \sqrt[3]{-\frac{q}{2} - \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}} + \sqrt[3]{-\frac{q}{2} + \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}}$$

$$c_2 = \frac{\varepsilon}{c_1 K_0 T_1}$$

$$\eta = \frac{T_0}{K_0 T_1} - c_1 - c_2$$

Of which $p = \left(\frac{1-K_0T_1}{K_0T_1}\right) - \frac{1}{3}\left(\frac{T_0}{K_0T_1}\right)^2$, $q = \frac{2}{27}\left(\frac{T_0}{K_0T_1}\right)^3 + \frac{T_0}{3K_0T_1}\left(\frac{1-K_0T_1}{K_0T_1}\right) - \frac{\varepsilon}{K_0T_1}$, $T_1 \leq \frac{1}{K_0}$.

Satisfying the above equivalence relationship, the control law (31) is equivalent to (24). However, (31) is designed using the CLGS algorithm, which has more significant robustness. In addition, the control law has been improved by reducing the setting parameter from four to one, and this parameter has physical significance. This results in a simplification of the control law, which enhances the robustness of the control law and reduces the difficulty of adjusting the controller parameters.

3.2.3 Improved the Energy Efficiency of Controller

As the control law (24) is designed using the backstepping method, the nonlinear function is challenging to eliminate in practice. In contrast, the control law (31) is optimised using a CLGS algorithm with stable robustness. Basis of a weakened nonlinear function term, the control law, is further optimised. Replacing the original linear feedback e_1 of the control law with nonlinear feedback of the inverse tangent function.

$$u = \frac{T_0}{K_0}\left(\frac{1}{K_0T_1} + \frac{\varepsilon}{K_0T_1s} + \frac{T_0}{K_0T_1}s\right)\tan^{-1}(\omega e_1) \tag{32}$$

Of which $\omega < 1$ is the design parameter.

Analyse the effect of the nonlinear feedback of the inverse tangent function on the steady-state of the system: because the error $e_1 = \psi_r - \psi$, when e_1 is small, $\tan^{-1}(\omega e_1) \approx \omega e_1$, according to the final value theorem, the (28), (29) can lead to the steady-state output of the system as

$$\psi(\infty) = \lim_{s\to 0} s\frac{GK\omega}{1+GK\omega}\frac{\psi_r}{s} = \lim_{s\to 0} s\frac{\frac{\omega}{T_1s}}{1+\frac{\omega}{T_1s}}\frac{\psi_r}{s} = \lim_{s\to 0}\frac{\omega}{T_1s+\omega}\psi_r = \psi_r \tag{33}$$

Since $\psi_r - \psi(\infty) = \psi_r - \psi_r = 0$, the controller output steady-state error is 0 when e_1 is small and the nonlinear feedback driven by the inverse tangent function has no effect on the steady-state of the system.

Analyse the effect of the nonlinear feedback of the inverse tangent function on the dynamic performance of the system: the transfer function from the input ψ_r to the output ψ is

$$\frac{\psi}{\psi_r} = \frac{GK_c\omega}{1+GK_c\omega} \tag{34}$$

Of which GK_c is the open-loop frequency characteristic of the system. According to closed-loop gain shaping theory, GK_c satisfies the requirement of high gain at low frequencies and low gain at high frequencies. In the low-frequency range, the (34) is compared with the closed-loop transfer function $\frac{GK_c}{1+GK_c}$ of a standard feedback system, and ω has little effect on the dynamic performance of the system.

Similarly, the effect on the system output: the transfer function from the input ψ_r to the rudder angle output δ of the controller is

$$\frac{\delta}{\psi_r} = \frac{GK_c\omega}{1+GK_c\omega} \tag{35}$$

The formula (35) is compared with the closed-loop transfer function $\frac{GK_c}{1+GK_c}$ for a standard feedback system (Wu, Zhang, & Yang, 2017). The ω reduces the numerator more than it affects the denominator, resulting in a relatively small controller output δ.

The control law (32) is designed by combining the backstepping method and the CLGS algorithm. It ensures the stability of the control law while having strong robustness and can effectively deal with the problem of pair elimination of nonlinear functions. At the same time, the nonlinear feedback of the inverse tangent function is used instead of the linear control feedback, which reduces the control energy while ensuring the control effect, making the ship course-keeping controller designed with this control law have the advantages of stability, robustness, and energy efficiency. In addition, when using the control law (32) to design the ship course-keeping controller, the only design parameters in the controller are ω and T_l, and T_l can be directly set as the inverse of the operating bandwidth frequency of the controller, so only one design parameter ω needs to be rectified, avoiding the complex situation of rectifying four design parameters for the original control law designed by the backstepping method, which greatly simplifies the design process of the controller.

3.3 Construct Simulation Model

Simulation modelling of ship course-keeping using the "Yukun", a trainee ship of Dalian Maritime University, as a prototype. The ship parameters are shown in table 1.

Table 1 Detailed parameters of the Yukun

Parameters	**Value**
Length [$\boldsymbol{m}$]	105
Breadth [$\boldsymbol{m}$]	18
Load draft [$\boldsymbol{m}$]	5.4
Rudder height [$\boldsymbol{m}$]	4.8
Rudder area [$\boldsymbol{m^2}$]	11.46
Displacement [$\boldsymbol{m^3}$]	5735.5
Speed [$\boldsymbol{kn}$]	16.7
Propeller diameter [$\boldsymbol{m}$]	3.8
Blade area ratio	0.7
Rudder aspect ratio	1.95
Block coefficient	0.5595

From the parameters in Table 1, the parameters in the Nomoto model are $K_0=0.31s^{-1}$, $T_0=64.53\ s$, $\alpha=8.00$, $\beta=4295.02$. The nonlinear feedback design parameter is adjusted to $\omega = 0.6$, and the effective operating bandwidth frequency of the ship course-keeping controller is set to 1/3 rad/s. The design parameter T_1=3s, because the wave spectrum is 0.3~1.25 rad/s, using this operating bandwidth can effectively suppress the wave spectrum outside the operating bandwidth of the controller.

In ship course-keeping control, apart from the Nomoto model, two other factors have a non-negligible effect on the control performance: the rudder servo system and the other is wind and wave disturbance. The rudder speed, rudder angle, and steering frequency in the rudder servo system are three nonlinear factors that significantly influence the course-keeping control. Therefore, in the simulation, a single oil circuit is added to simulate the rudder servo system with control variables. The maximum rudder speed is set to ± 5°/s concerning the actual parameters of the Yukun. The rudder angle is limited to ± 25∘ based on the safety of navigation. The analysis of the actual sailing steering frequency of the Yukun shows that the average manual steering frequency is 8s, while considering that manual steering has a certain lag in the actual course-keeping, the steering frequency is set to 6s in order to improve the control effect. The above three nonlinear factors are determined, which can effectively ensure realistic control performance.

In addition, external environmental disturbances are a vital factor in ship yawing. For wind disturbances, the wind is split into pulsating and average winds for simulation. The pulsating wind is simulated using the white noise substitution method proposed by Astrom and Kallstrom. The average wind can be represented in nautical terms by the equivalent of leeway angle of the ship, which in the simulation is converted to the corresponding rudder angle δ_{wind}, it can be expressed as

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

Of which K^0 is the leeway differential coefficient, V is the speed of ships, V_R is the wind speed and γ is the windward angle.

For wave disturbance, a typical second-order oscillation driven by white noise is used to complete the simulation, in which the wind is set at level 6 for the control performance study, the transfer function of the wave model is

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

3.4 Improve Method Performance Analysis

It is assumed that the ship is sailing in a no wind and wave disturbance situation and that the ship expects a reference course $\psi_r = 80°$. As the ship is in the no wind and wave disturbance situation, the constant term ε in the Nomoto model, representing the uncertain constant value disturbance, is set to 0.0001. The simulation results are shown in Figure 1. It can be seen from the figure that the ship course-keeping controller designed based on the improved algorithm in the no disturbance situation has no overshoot and the control effect is ideal.

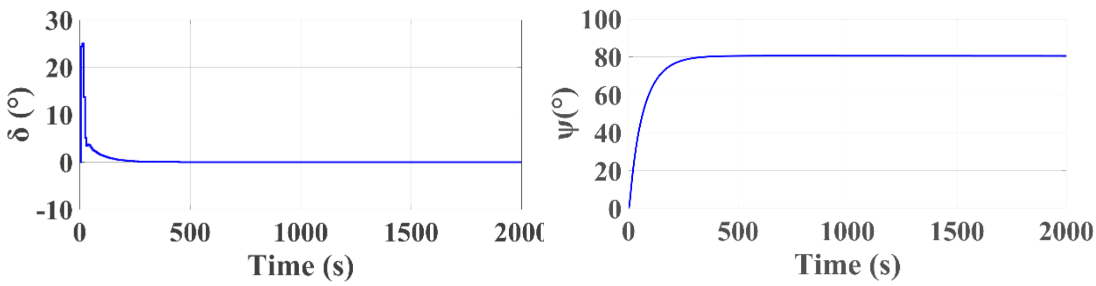

Figure 1 Rudder angle and course angle curves without wind and wave disturbance, with nonlinear trim and steering frequency limits

The ship is assumed to be in a strong wind with a wind direction of 50◦ equivalent to a leeway angle of 3◦when the ship is significantly disturbed. The constant term ε, which represents the uncertain constant disturbance, is set to a slightly larger value of 0.001. Analysing the performance of the algorithm, the control effect of the controller designed by the improved algorithm and the PID linear controller were compared in this situation. The simulation results of the PID linear controller are shown in Figure 2. Due to the effect of the disturbance, the ship course-keeping control produced an overshoot of 9.4%, and the average rudder angle of steering is 6.6◦.

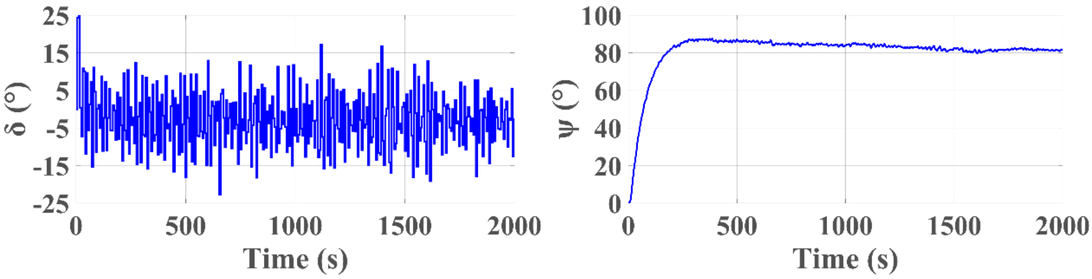

Figure 2 Rudder angle and course angle curves with wind and wave disturbance, steering frequency limitation, and no nonlinear modifications

The simulation results of the controller designed by the improved algorithm are shown in Figure 3, which shows that due to the influence of disturbances, the ship course-keeping control produces an overshoot of 10.5%, and the average rudder angle of steering is 4.2◦. In the presence of significant disturbances, the improved controller overshoots slightly. However, the average rudder angle is significantly reduced, showing good robustness, which shows that the improved algorithm has qualified control performance. The above data can initially show that the improved ship course-keeping control algorithm has certain advantages. However, the implementation of the algorithm needs to be quantified in detail using metrics.

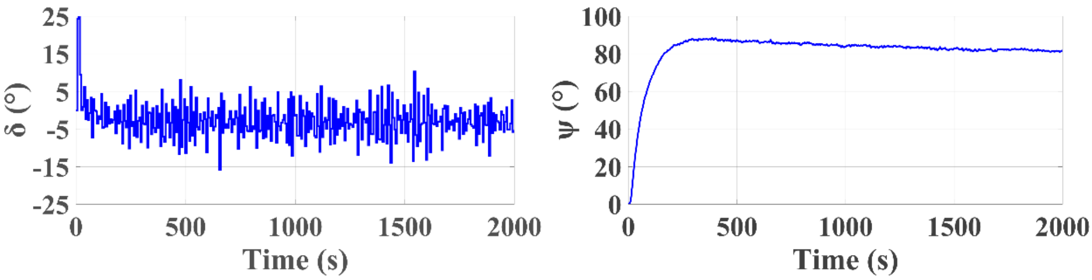

Figure 3 Rudder angle and course angle curves with wind and wave disturbance, steering frequency

limitation, and nonlinear feedback

For ship course-keeping, the key control indexes are ship course error $\varDelta\psi$, steering frequency $\delta_{n,}$ and rudder angle δ. Among them, rudder angle, and course error reflect the effect of course-keeping, rudder angle reflects the size of control energy, and steering frequency confirms that the algorithm meets the actual navigation situation. The performance indicator J of the algorithm is obtained by calculating the average value of the above three indexes over a certain period, which is used to comprehensively evaluate the performance of algorithm.

$$J = \frac{1}{T_o}\int_0^{T_o}(|\varDelta\psi| + |\delta|)dt + \frac{\delta_n}{T_o}\times 10 + e^{\frac{\varDelta}{3}} \quad (36)$$

Of which T_o is the total course-keeping time, $\varDelta\psi$ is the course error, δ is the rudder angle, $\varDelta$ is the steering frequency, and Δ is the static error. The comprehensive performance of the algorithm is shown in Table 2

Serial Number	**Feedback Type**	**Steering Frequency**	**Overshoot**	**Average Rudder Angle**
1	Liner Feedback	0.5s	9.1%	4.7°
2	Liner Feedback	6s	9.4%	6.6°
3	Non-liner Feedback	0.5s	10.3%	3.7°
4	Non-liner Feedback	4s	11.1%	3.8°
5	Non-liner Feedback	5s	11.1%	4.0°
6	Non-liner Feedback	6s	10.5%	4.2°
7	Non-liner Feedback	7s	10.6%	4.3°
8	Non-liner Feedback	8s	10.9%	4.2°
9	Non-liner Feedback	9 s	11.5%	4.5°
10	Non-liner Feedback	10s	13.6%	4.7°

Table 2 Algorithm structure and performance indicators

Algorithm 1 uses linear feedback and does not limit the steering frequency as a reference algorithm to compare and judge the comprehensive performance of the improved algorithm. Algorithm 1 has a steering frequency of 0.5 seconds each time. Due to the large inertia and lag of the ship, the frequent steering times do not correspond to the actual sailing conditions and increase the stress on the rudder servo system. Algorithm 3 uses nonlinear feedback with an inverse tangent function instead of the linear feedback of Algorithm 1. In the case of unrestricted steering frequency, compared to Algorithm 1, the overshoot of the controller increases by 1.2%, and the average rudder angle decreases by 21%. As shown in Figure 4, the rudder angle was significantly reduced. Although the practical application of the controller without limiting the rudder angle frequency is of low value, it has been theoretically demonstrated that nonlinear feedback can significantly reduce the control energy and that a lower rudder angle can be used to achieve an approximately equivalent control effect in the ship course-keeping control through nonlinear feedback.

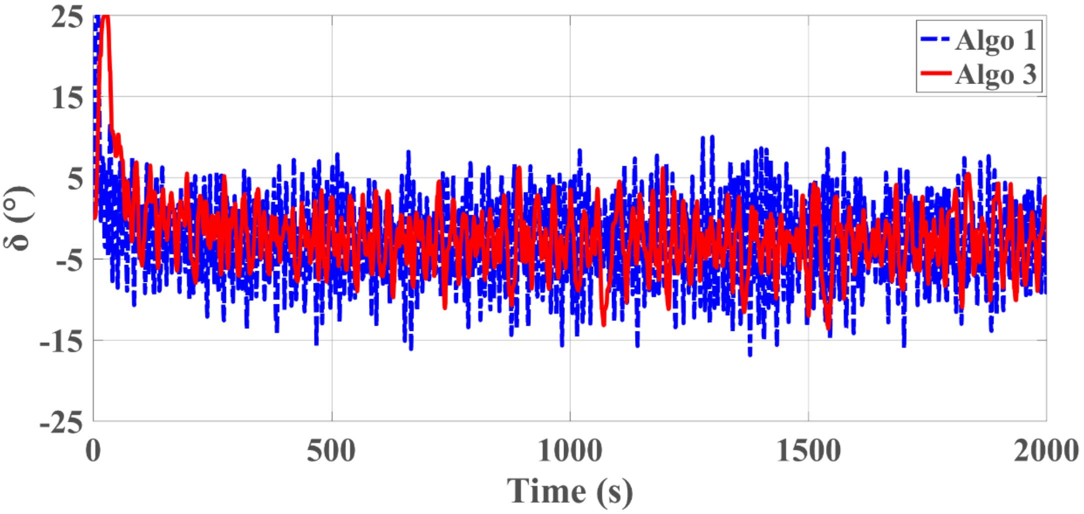

Figure 4 Comparison of the average rudder angle curves of the linear feedback algorithm and the

nonlinear feedback algorithm without restricted steering frequency

As the manual steering frequency of Yukun is 8 seconds each time, the above study presumes 6s as the steering frequency, and Algorithms 4-10 test the control effect under different rudder frequencies to analyse and obtain a more reasonable steering frequency. Based on the data in Table 2, it can be concluded that the comprehensive performance of the controller is optimal when the steering frequency is 6s, which verifies that using 6s as the steering frequency for ship course-keeping control can achieve better control results.

In Algorithm 2, the steering frequency is limited to 6 seconds each time, and other conditions are the same as in Algorithm 1. The overshoot of the controller increases by 0.3%, and the average rudder angle increases by 40%. From Figure 5, it can be seen that a lower steering frequency will significantly increase the average rudder angle.

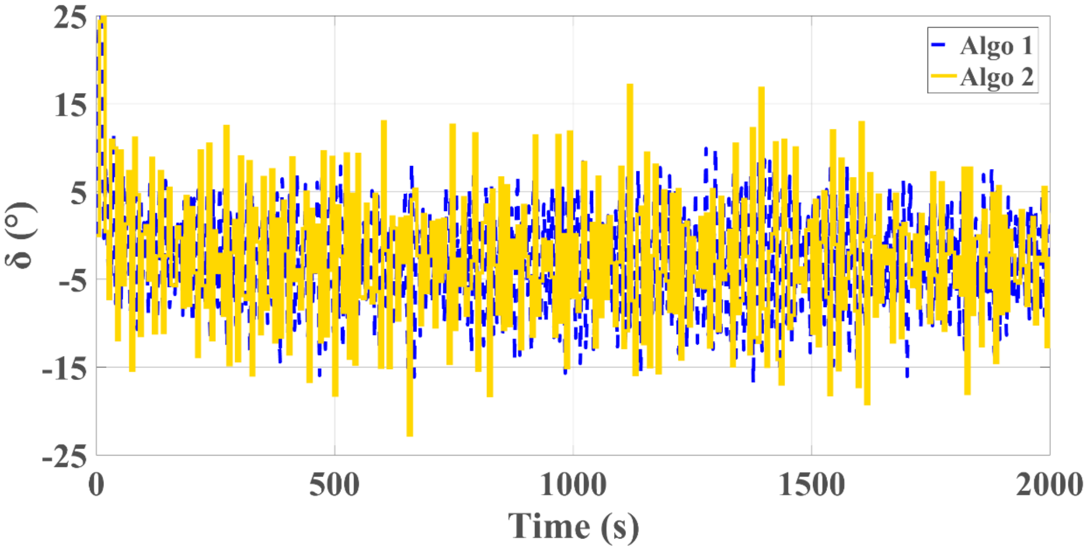

Figure 5 Comparison of the average rudder angle curves of the linear feedback algorithm with and without steering frequency limitation

Algorithm 6 limits the steering frequency to 6 seconds each time based on Algorithm 3. The indexes in Table 2 show that Algorithm 6 increases the overshoot by 0.2% and the average rudder angle by 13% compared to Algorithm 3. It can be seen from Figure 6 that the increase in the average rudder angle is not significant after limiting the steering frequency. Comparing the increase in mean rudder angle between the algorithm with linear feedback and the algorithm with nonlinear feedback, it is clear from Figure 5 and Figure 6 that the algorithm with nonlinear feedback has a significantly lower increase than the algorithm with linear feedback, which indicates that Algorithm 6 has relatively good robustness.

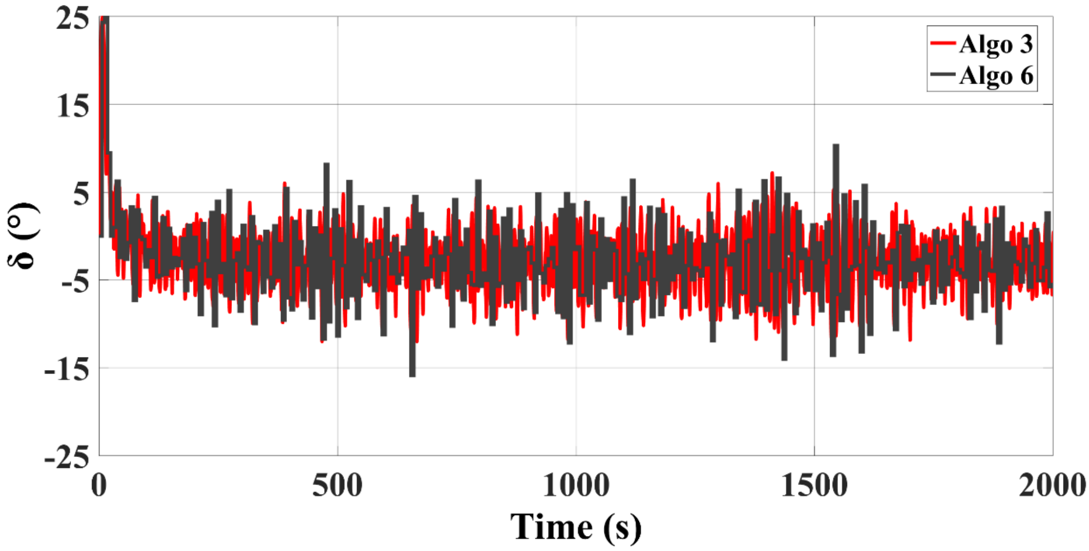

Figure 6 Comparison of the average rudder angle curves of the nonlinear feedback algorithm with and without steering frequency limitation

Algorithm 6 increases the controller overshoot by 1.1% and reduces the average rudder angle by 36% compared to Algorithm 2 with the same constraints. As Figure 7 shows, Algorithm 6 has a more significant energy efficiency effect in line with practical applications.

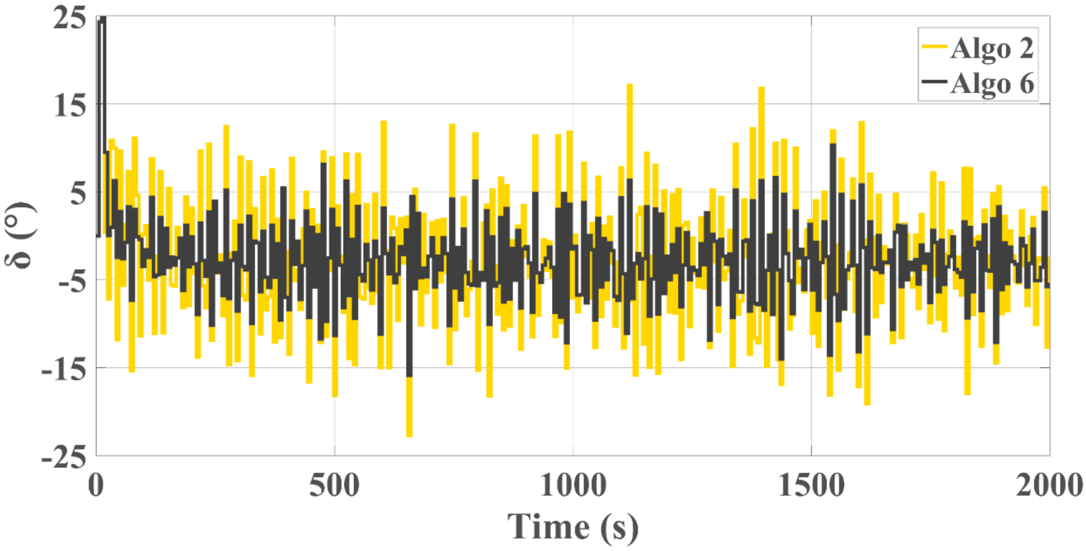

Figure 7 Comparison of the average rudder angle curves of the linear feedback algorithm and the nonlinear feedback algorithm at a steering frequency of 6s

Comparing the dynamic performance of Algorithm 2 with that of Algorithm 6, where the overshoot is 9.4% for Algorithm 2 and 10.5% for Algorithm 6. Figure 8 shows that the trend of overshoot, rise time, peak time, and other dynamic performance indicators of Algorithm 2 and 6 are almost the same, indicating that the nonlinear feedback has almost no effect on algorithm performance.

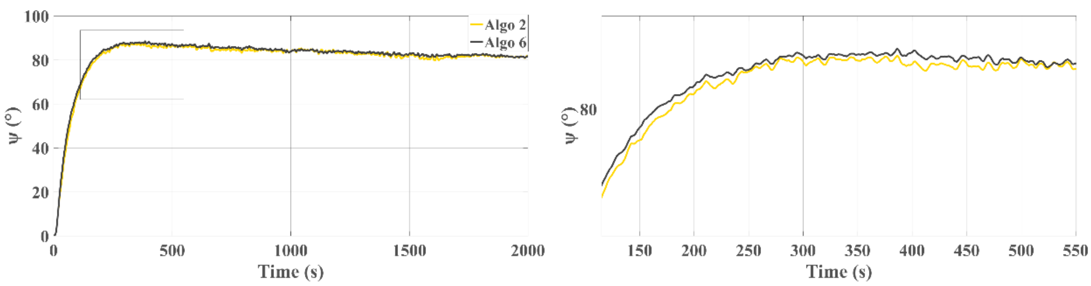

Figure 8 Course angle curves for linear and nonlinear feedback algorithms at a steering frequency of 6s

CHAPTER 4: ENERGY EFFICIENCY TECHNOLOGY PROMOTION POLICY

4.1 Barriers to Energy Efficiency Technology Promotion

Energy-efficient course-keeping control algorithms are used as a technical approach to energy efficiency and emission reduction. However, it has been theoretically proven that optimisation of the autopilot control system can significantly reduce fuel consumption during the navigation. The next step requires quantitative research of the effect of the optimised course-keeping control on energy efficiency during actual navigation.

Researchers around the world already have a deep accumulation of theoretical research, but the process of moving from academic research to practical application can be slow due to the resource constraints of the researcher or research institution. For example, Dalian Maritime University has two practice ships used for student internships and researchers with actual ship test. Due to the tight schedule of the practice ships, it is challenging to arrange long-term, multi-trip data collection and technical verification work, so there is a considerable lag in translating relevant research into practical applications.

4.2 Global Maritime Technology Cooperation Centres

The initial strategy of IMO for energy efficiency and emission reduction includes short-term measures to promote the research, development, and dissemination of technical measures for energy efficiency and emission reduction. It demonstrates that the IMO has a high level of attention in technologies related to energy efficiency and emission reduction on ships and has a strong heritage and commitment to maritime technology promotion. The Marine Environment Division and the Technical Cooperation Division of IMO have technology promotion-related activities, the most relevant of establishing the MTCC Network in 2016 with funding from the European Union. There are currently five regional maritime technology cooperation centres in Asia, Africa, Latin America, the Caribbean, and the Pacific. The five centres work together under the guidance of IMO to promote and apply energy efficiency and emission reduction technologies to improve energy efficiency and reduce carbon emissions in the shipping industry.

The MTCC offers further possibilities for the broader application of maritime energy efficiency technologies. In 2020, the MTCC completed the automatic data collection of ship fuel consumption. This baseline data collection validated the availability and reliability of the ship fuel oil consumption data collection method. For the application validation of optimised course-keeping control algorithms for automatic rudders only, the results of this research provide a strong base data collection capability to quantify the energy efficiency of optimised course-keeping. Although the main target of the Global MTCCs Network (GMN) support is LDCs and SIDS, GMN is also a positive contribution to the validation and diffusion of new technologies for energy efficiency and emission reduction. The association of researchers or research institutions with MTCC will potentially shorten the time for applying and diffusion of skilled technologies and reduce carbon emissions from ships through the application of new technologies.

4.3 Recommendation for MTCC to Promote Technology

Although IMO may currently encourage and promote the research, development, promotion, and application of maritime energy efficiency and emission reduction technologies only in short-term measures, the rise and application of actual technologies is a long-term process. IMO is a reasonable strategic plan to shift the focus to medium gradually- and long-term measures to ensure that the research, development, promotion, and updating of energy efficiency and emission reduction technologies are already in a virtuous cycle. And a virtuous cycle of technology promotion requires reasonable review, supervision, support, and incentives.

The GMN is currently funded by the European Union, with the IMO forming a Project Steering Committee to provide overall oversight and the Project Coordination Unit to coordinate the daily management of the project with the five technology cooperation centres and other stakeholders around the world. The purpose of the five centres is to facilitate support for the target countries in their regions. By reaching out to local technology and research institutions in an open manner, they can reduce the research and dissemination of new energy efficiency technologies while supporting the states in the area.

Therefore, it is recommended that the MTCC consider an open call for research into applied technologies for energy efficiency on ships and provide assistance, where possible, for theoretically rigorous technologies but lack practical application validation. Such as an optimised autopilot control system for ship course-keeping control and conduct fuel consumption statistics for different ship types and multiple voyages to comprehensively analyses the energy efficiency of the improved control system. The MTCC audits and verifies the energy efficiency technology, which is more efficient when it is further applied on a global scale. Therefore, when the MTCC is not only an organisation that supports the states in each region, but also a platform for the promotion of maritime energy efficiency technologies. It can further promote the development of global maritime energy efficiency technologies, reduce the carbon emissions of the global shipping industry, and further the goal of greening shipping and the planet.

CHAPTER 5: SUMMARY AND CONCLUSION

A nonlinear ship course-keeping algorithm based on the design of the backstepping method with increasing integral terms is proposed, and the algorithm is improved by combining a CLGS algorithm with nonlinear feedback. As the backstepping control law with increased integral term consists of a linear and a nonlinear part, the stability of the algorithm is proved according to the Lyapunov theorem. A CLGS algorithm is used to replace the original control law equivalently, and the robustness of the CLGS algorithm is exploited by neglecting the nonlinear part of the original control law and adding the nonlinear feedback driven by the inverse tangent function for optimisation. The improved algorithm has both stability and robustness. According to the improved algorithm, the ship course-keeping controller has a simple structure and reduces the number of design parameters to be rectified from four before the improvement to one. At the same time, ensuring the control performance, overcoming the drawback of using the backstepping method to design the controller structure is too complicated.

Through actual ship data collection and expert interviews, combined with algorithm performance analysis, it was verified that better course-keeping control was achieved at a steering frequency of 6s. Simulation analysis shows that the improved algorithm has good robustness when the ship is subjected to wind, wave, rudder, and non-linearities factors and reduces the average rudder angle by 36% compared to the traditional linear control method, significantly reducing the control energy. The improved control algorithm has a clear theoretical justification and a simple control structure. In addition, the algorithm significantly reduces the control energy of the ship course-keeping and achieves a good control effect with a lower rudder angle and steering frequency. The control effect of the algorithm is in line with the concept of green ship and ship operation, which helps to reduce the fuel consumption of the ship and reduce the carbon emission of the shipping industry.

The IMO, MTCC and States and their research institutes are working together to promote energy efficiency technologies for ships. It will improve energy efficiency and reduce GHG emissions.

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