Control algorithm of YUPENG ship autopilot based on tangent function nonlinear feedback

ZHANG Xian-ku, FENG Yong-xiao

(*Laboratory of Marine Simulation and Control, Dalian Maritime University, Dalian 116026, China*)

Abstract: Autopilot is an important navigation instrument, and it plays an important role in safe navigation. In order to further improve the performance of the autopilot, this paper adopts the first-order closed loop gain shaping algorithm (PID) to design autopilot control algorithm with robustness, and uses tangent function nonlinear feedback technology to replace the linear feedback to improve the energy saving effect of autopilot. Taking Dalian Maritime University's newly-built YUPENG ship as an example, the simulation research is carried out. The results show that the control effect is still satisfactory when the model parameters change by 25%, which suggests that the designed autopilot algorithm has good robustness. Compared with linear feedback, nonlinear feedback can save 7.9% of energy. The algorithm proposed in this paper is simple and has obvious physical meaning. At the same time, the control algorithm is also helpful for the localization of controller design.

Key words: autopilot; nonlinear feedback; tangent; YUPENG ship

CLD number: TP273 **Document code**: A

Article ID: 1674-8042(2017)01-0078-06 **doi**: 10.3969/j.issn.1674-8042.2017.01.012

0 Introduction

Dalian Maritime University is the only one subordinate college of the Department of Transportation. The school ship updates rapidly, and now there are two ships in service: YUKUNG and YUPENG. The retired ships includes HONGZHONG, YUHONG, YUYING, ZHENGHE and YULONG. YUPENG is China's second generation of the first modern multi-purpose cargo practice teaching ship. It was delivered to Dalian Maritime University on October 16, 2016. The vessel is mainly used for internship of navigational students, it can be used for transferring bulk cargo, engineering equipment and containers, and can also be used in scientific research and experiment by the students who major in traffic information engineering and control, navigation science and technology, marine engineering and environmental engineering. As a newly-built teaching and training vessel, there is few research on YUPENG. Therefore, it is necessary to design control algorithm for course-keeping. Witkowska designed a nonlinear controller based on the backstepping method[1], using genetic algorithm to optimize the parameters of the controller, whose control effect is better than that of the traditional PD controller. ZHANG Xian-ku used the essence of nonlinear feedback algorithm based on sine function[2-3], and ZHANG Guo-qing justified that the nonlinear feedback algorithm has the characteristics of energy saving and safety[4]. This paper adopts a new method, using tangent function instead of sine function to design the control algorithm of nonlinear feedback, and taking YUPENG ship as an example to verify the validity of the algorithm. At present, most of the autopilot mounted on the ship in China is produced in foreign countries. The autopilot in YUPENG is produced by a British company, Ross Royce company. It is necessary to design our own country's

Received date: 2016-12-25

Foundation items: National Nature Science Foundation of China (No. 51679024); Fundamental Research Funds for the Central University (No. 3132016315)

Corresponding author: ZHANG Xian-ku (zhangxk@dlmu.edu.cn)

autopilot, therefore the algorithm proposed in this paper has a certain practical significance.

1 YUPENG real ship test description

According to YUPENG ship integrated performance test report provided by Dalian Zhongyuan Shipping Engineering Co. Ltd, we can get the weather and sea conditions, the ship parameters and other data when YUPENG is in right turning test. The data of the turning test are obtained by the equipment on the ship, the main equipment including one set of differential global positioning system (DGPS) satellite signal receiving system, one DELL laptop, one set of the ship performance test software. The environmental data and test data are acquired when the ship is in ballast condition, as shown in Table 1.

Table 1 Turning test data in ballast condition

Parameters	Values	Parameters	Values
Wind scale	35 kn	Turning circle diameter (m)	633.36
Depth of water (m)	47	Turning circle speed (knot)	10.2
Wind direction	P175 deg.	Turning circle w-speed (deg/s)	0.76
Draft TF (m)	4.542	Time at angle 90 (s)	126
Draft TM (m)	6.313	Time at angle 180 (s)	228
Draft TA (m)	8.126	Time at angle 270 (s)	345
Max heeling angle (deg)	1deg	Time at angle 360 (s)	472
Start heading (deg)	0.24	Time at angle 540 (s)	697
End heading (deg)	168.96	Speed at angle 90 (knot)	11.42
End speed (knot)	7.75	Speed at angle 180 (knot)	9.59
Turning circle duration (s)	697	Speed at angle 270 (knot)	8.29
Transfer (m)	398.36	Speed at angle 360 (knot)	7.71
Advance (m)	686.48	Speed at angle 540 (knot)	7.75

We can get the ship's parameters in both ballast condition and full loaded condition by estimating some data.

The result is shown in Table 2.

Table 2 Parameters of YUPENG ship in full loaded and ballast conditions

	L (m)	B (m)	T (m)	X_C (m)	Cb	Δ (t)	v (kn)	A_δ (m^2)
Full load	189.0	27.8	11.0	−1.8	0.72	30 000	17.5	38
Ballast	189.0	27.8	6.32	−4.043	0.661	22 587.6	17.26	31.67

2 Right turning simulation in ballast condition

In the turning test, due to the limitation of environment, YUPENG ship only carried out the ballast test and without full loaded test. According to the method given by Ref. [5], using VB programming to calculate parameters K, T, α and β of YUPENG ship in ballast and full loaded conditions, the results are shown in Table 3.

Table 3 Ballast and full loaded parameters

	K	T	α	β
Ballast	0.21	107.78	13.17	16 323.89
Full load	0.08	39.09	18.59	20 732.57

The simulation uses nonlinear Nomoto model, as shown in Eq. (1), to establish mathematical model of YUPENG ship, which is from the rudder angle δ to the heading angle ψ, namely

$$\dot{\psi}+\frac{K}{T}(\alpha\dot{\psi}+\beta\dot{\psi}^3)=\frac{K}{T}(\delta+\delta_{\text{wind}}), \quad (1)$$

where δ_{wind} is equivalent rudder angle, whose value can be obtained by using the method provided by ZHANG Xian-ku in Ref. [6]. The Beaufort scale and the leeway angle are acquired by using cubic interpolation method. The simulation uses simulink toolbox in Matlab, building simulation diagram, as shown in Fig. 1. The rudder servo system T_r is described by the first-order inertia system. T_r is 5 s and rudder speed is 5 °/s. The mathematical model of Eq. (1)

with wind interference is realized by programming an S function.

Simulating the right turning circle of YUPENG ship in full rudder, a comparison is made between the simulated circle and the circle of the real ship test, as shown in Fig. 2. In Fig. 2, X and Y are the coordinates of the position of YUPENG ship, and L is the length of YUPENG ship. It is calculated that the simulation of the turning circle and real ship test circle fitting is 89.52%. As far as the accuracy of the model itself is concerned, the simulation results are satisfactory.

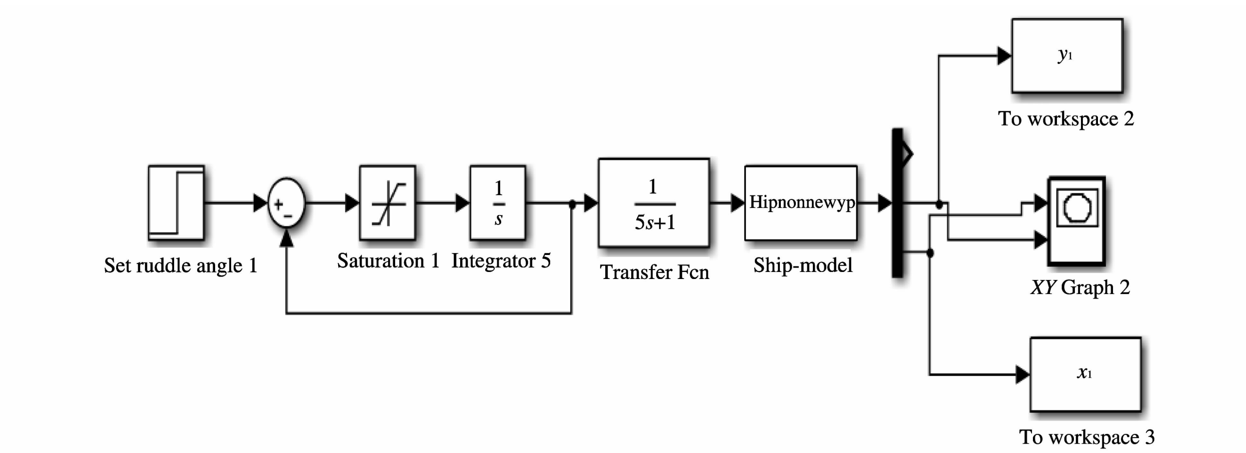

Fig. 1 YUPENG ship turning simulation

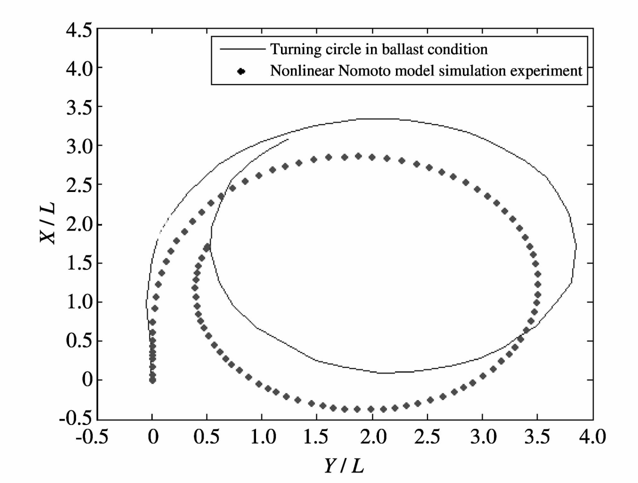

Fig. 2 Comparison of turning experiment

3 Design and verification of automatic control algorithm

3.1 Algorithm design

Autopilot is an indispensable equipment of modern ship for navigation, whose main function is to maintain or change the course of a ship automatically, reduce the workload of the crew, and avoid accidents caused by human errors. Therefore, the design of autopilot control algorithm has important significance. According to Eq. (1) of nonlinear Nomoto model, the first-order closed loop gain shaping algorithm is applied[12].

$$u=\left(\frac{1}{KT_1}+\rho+\frac{T}{KT_1}s\right)e. \tag{2}$$

Conventional linear feedback feedbacks the error (e) to the controller directly. In this paper, the nonlinear processing of e is firstly carried out. Compared with the use of sine function[2], this paper attempts to use tangent function to carry out the research. In the simulation, the interferences of the ocean waves, the random wind and the constant wind are all considered. A simple method to consider wave interference is to use white noise to drive a typical 2-order oscillation component, and then the wave transfer function is obtained under the influence of Beaufort scale of 6 as

$$h(s)=\frac{0.419\,8s}{s^2+0.363\,8s+0.367\,5}. \tag{3}$$

The sampling time of white noise is 0.5 s, and the power noise parameter is set at 0.000 01. The white noise of the ocean waves is the same as that block which is used to simulate the interference of random wind. The controller bandwidth parameter T_1 is 3 s and ρ is 2. The final diagram is shown in Fig. 3.

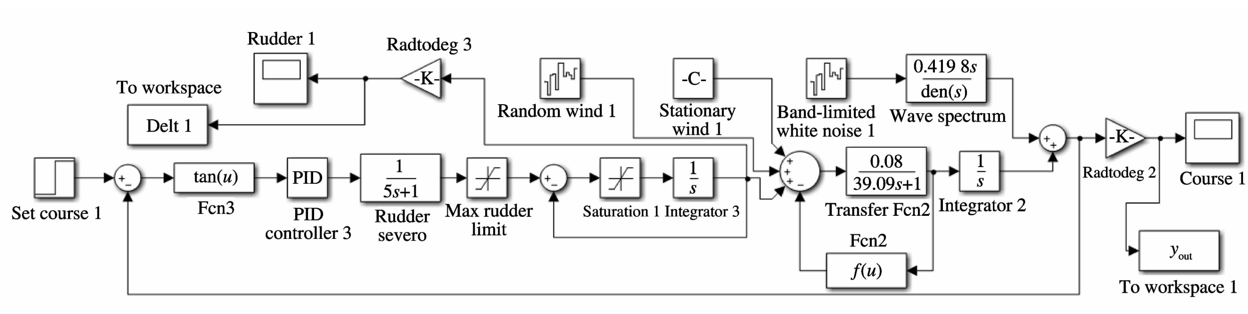

Fig. 3 Simulation block diagram of Simulink

3.2 Algorithm validation

Using the data of YUPENG ship to carry out simulation test of the control algorithms put forward in this paper. Input parameters K, T, α and β given above in Fig. 3, and YUPENG ship is in full loaded condition. The desired course input is set to 60°, and the simulation curves are shown in Figs. 4 and 5.

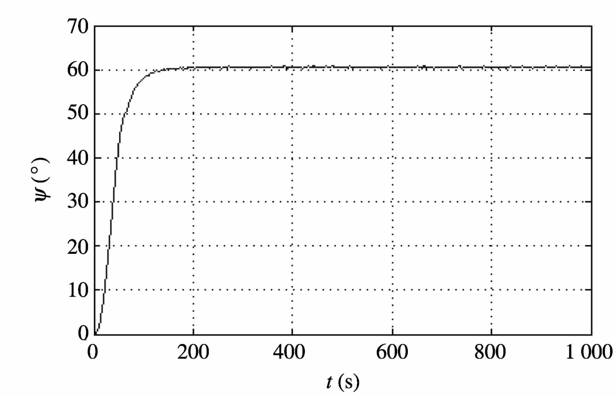

Fig. 4 Course keeping simulation

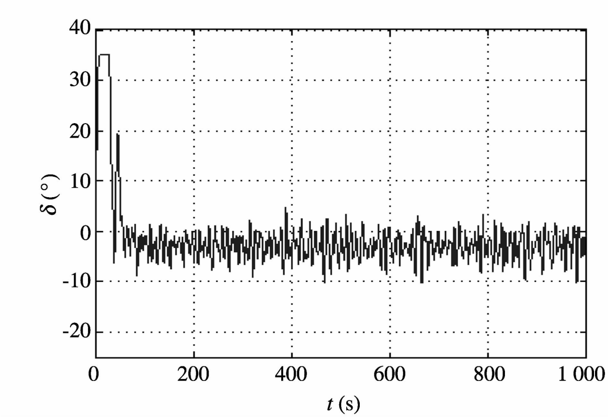

Fig. 5 Rudder angle simulation

According to Fig. 4, it can be calculated that when the nonlinear feedback autopilot control algorithm reaches the set course, keeps in a stable state and the settling time is 140 s, it can maintain the course. It does not exist overshoot phenomenon. Fig. 5 shows the usage of rudder of YUPENG ship in the process of keeping course steady. The average rudder angle in the simulation process is 4.06°, the maximum rudder angle is 35°, and the minimum rudder angle is 0°. This indicates that the algorithm can achieve the purpose of keeping course in a small rudder angle, thereby reducing the consumption of energy and having the effect of energy saving and economy. In order to verify the robustness of the system, the parameters of the Nomoto model are changed by 25%, and then the simulation test is carried out.

The simulation curve of the course and rudder angle is shown in Fig. 6.

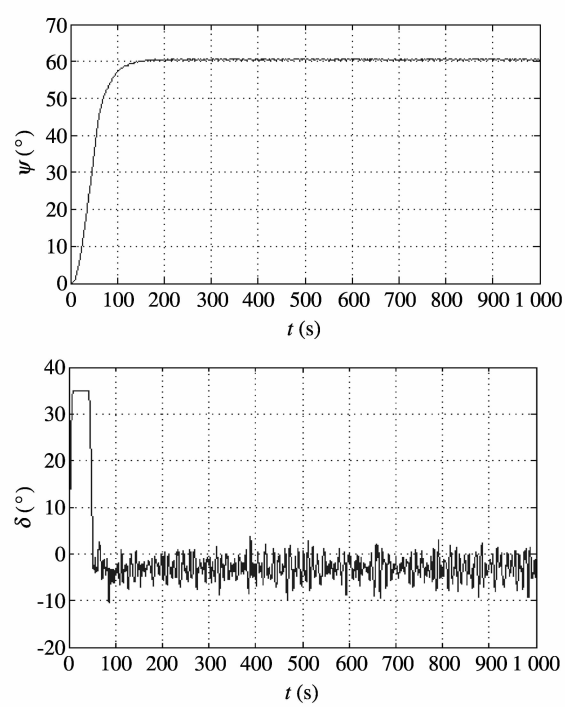

Fig. 6 Course and rudder angle simulation when model parameters change by 25%

From the figures we can see that the course curve and the rudder angle curve are very similar to that without change of parameters. This shows that the designed control algorithm has good robust performance for model perturbation. After removing tangent nonlinear feedback, there is little change in the course curve. The rudder angle simulation curve is shown in Fig. 7, with the average rudder angle of 4.41°. If the average rudder angle is used for representing the energy consumption of the ship, the use of tangent nonlinear feedback can save 7.9% of energy than the linear feedback.

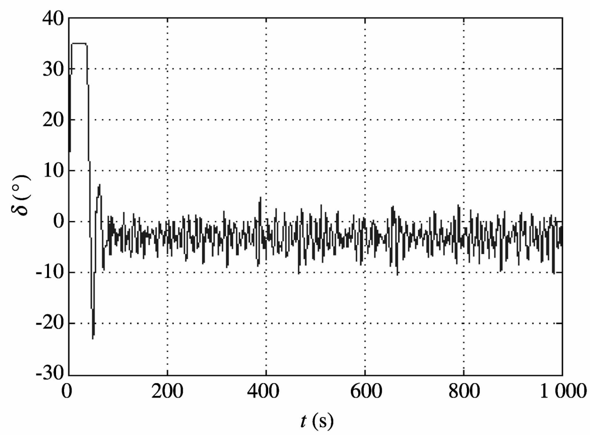

Fig. 7 Rudder angle simulation without tangent feedback

4 Conclusion

Autopilot is an important tool for modern ship and has a variety of control algorithms. At present, most domestic ships use imported autopilot, which not only increases the shipbuilding cost, but also makes China limited to other countries in this technology. This paper carried out a research for the newly-built vessel and made a simulation for right turning cycle. The simulation results verifies the control algorithm has good performance of control and robustness. The autopilot control algorithm based on tangent nonlinear feedback used in this paper will make a little effort to realize the localization of autopilot. At the same time, the algorithm has certain engineering application value and can be used in the design of controller.

References

[1] Itkowska A, Tomera M, Smierzchalski R. A backstepping approach to shipcarnput course control. International Journal of Applied Mathematics and Computer Science, 2007, 17(1): 73-85.

[2] ZHANG Xian-ku. Control algorithm for autopilot driven by sine of course deviation. Navigation of China, 2011, 34 (1): 1-4.

[3] ZHANG Xian-ku. Robust control of longitudinal motion for hydrofoils based on nonlinear feedback. Navigation of China, 2016, 39(1): 60-63.

[4] ZHANG Guo-qing, ZHANG xian-ku. Comparative studies of course-keeping algorithm based on intrinsic nonlinear feedback. Journal of Dalian Maritime University, 2012, 38 (1): 1-4.

[5] ZHANG Xian-ku, JIN Yi-cheng. Modeling and digital simulation of control system. Dalian: Dalian Maritime University Press, 2013.

[6] ZHANG Xian-ku, CHEN Xiu-jia, LU Yu. Mathematical model of target ship in marine simulator. Shipbuilding of china, 2014, 3(55): 125-130.

[7] ZHANG Xian-ku, WANG Li-jun. Nonlinear suppression algorithm of ship steering gear based on closed loop gain shaping. Shipbuilding of China 2013, 54(4): 94-99.

[8] SHAN Xiong-fei, LI wei. Turning motion analysis on the ship of "Yukun" under the influence of wind and current. Journal of Dalian Maritime University, 2014, 40(3): 21-27.

[9] FENG Yi-wei, GUO Ge. Network-based controller design for ship course control. Journal of Lanzhou University of Technology, 2010, 36(5): 73-78.

[10] JIA Xin-le, YANG Yan-sheng. Mathematical model of ship motion. Dalian: Dalian Maritime University Press, 1999.

[11] LI Zong-bo. Research on the problem of the speed decrease during the course of the ship steering. Master's theses. Dalian: Dalian Maritime University, 2008.

[12] ZHANG Xian-ku. Concise robust control for ship motion. Beijing: Science Press, 2012.

基于正切函数非线性反馈的“育鹏”轮自动舵控制算法

张显库，冯永孝

（大连海事大学 航海动态仿真和控制实验室，辽宁 大连 116026）

摘　要： 自动舵是重要的航海仪器，对于船舶的安全航行有着重要作用。为了进一步改善自动舵的性能，本研究采用一阶闭环增益成形算法(PID)设计了具有鲁棒性的自动舵控制算法，并用正切函数非线性反馈技术代替线性反馈以提升自动舵的节能效果。以大连海事大学新交付使用的“育鹏”轮为例，开展仿真研究。结果表明模型参数改变 25％控制效果良好，说明设计的自动舵算法具有良好的鲁棒性，与线性反馈相比，非线性反馈能节能 7.9％。本文所提算法简单，物理意义明显，同时该控制算法也有助于船舶控制器设计的国产化。

关键词： 自动舵；非线性反馈；正切；“育鹏”轮

引用格式： ZHANG Xian-ku，FENG Yong-xiao. Control algorithm of YUPENG ship autopilot based on tangent function nonlinear feedback. Journal of Measurement Science and Instrumentation，2017，8(1)：78-83. [doi：10.3969/j.issn.1674-8042.2017.01.012]