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An improved control algorithm for ship course keeping based on nonlinear feedback and decoration

Xiaxiao Yao

WORLD MARITIME UNIVERSITY

Dalian, China

AN IMPROVED CONTROL ALGORITHM FOR SHIP COURSE KEEPING BASED ON NONLINEAR FEEDBACK AND DECORATION

By

YAO XIAXIAO

The People's Republic of China

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DECLARATION

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

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

Signature: Yao Xiaxiao

Date: 28th June 2018

Supervised by: Zhang Xianku
Professor
Dalian Maritime University

Assessor:

Co-assessor:

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ABSTRACT

Title of Dissertation: **An Improved Control Algorithm for Ship Course Keeping Based On Nonlinear Feedback and Decoration**

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In order to make navigation more energy-saving, this paper uses nonlinear feedback and decoration (NFAD) technique based on fuzzy PID controller. In other words, two nonlinear functions are used to process the input and output of the controller respectively and to design control algorithm of the ship course-keeping. At the same time changed from 6 s a steering to 8 s, and verified the advantages of energy saving and less equipment wear and tear. This shows that the fuzzy PID course keeping controller designed by nonlinear feed-in technology has the characteristics of energy saving and strong robustness.

KEY WORDS: feedback and decoration; fuzzy PID; course keeping; robustness.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Shipping industry has been an important mode of transportation carrying human civilization and economy since the ancient times. Ships face various dangers in the course of navigation, so how to ensure the safe, high-speed, accurate and economic navigation of ships is particularly important. The research of ship motion control provides theoretical support for navigation activities.

When a ship is sailing at sea, it will inevitably deviate from a given course due to the disturbance of ocean environment such as sea waves, sea wind and sea current. The change of ship's course has adverse effects on the seaworthiness of ships, on the safe navigation of ships and on the equipment, goods and crew of ships. In addition, in order to reach the destination quickly and save energy, the course deviation must be minimized.

In ship control, ship course control is the most basic one. No matter what kind of ship the course control must be carried out in order to complete the mission,. The course control of a ship is usually accomplished by steering the rudder. When a ship is sailing, the pilot always tries to make the ship sail in a straight line at a certain speed. This is the question to be studied in this paper. The stability of the ship's course is a sign to measure the maneuverability of a ship.

OOCL Germany, the 21,413teu container ship built by OOCL, is the world's largest ship by OOCL nowadays.

Hundreds of ports and logistics industry practitioners took part in a survey about the future of ship size, and the result is that 58% believe that in the future the largest container ship will reach 25000 teu, 17% think it will reach 28000 teu, and 25% think it will be more than 30000 teu.

It can be seen that the trend of large-scale, specialized, intelligent, rapid and modernized ships still continues. As the operation difficulty of large-scale ships increases, the economic value carried by a single ship also increases. Different from the past, ship control can't only depend on the crew's knowledge and experiences, more attention should be paid to the establishment of system science. System science consists of three parts: system theory, information theory and control theory.

1.2 COMPLEXITY OF SHIP MOVEMENTS

The ship moves at sea, and the hull is subjected to the combined action of its own power and the forces from the Marine environment, and has six degrees of freedom in three dimensions. They are: pitch, roll, heave, heave, roll, pitch and bow. Wind, wave and current cause disturbance to ships on the sea, and ships are subjected to this kind of combined interference force, generally resulting in non-linear and coupled motion.

From the perspective of effect, the additional power caused by the wind is similar to the random walk process, the wave causes the additional high frequency oscillation on the bow and other degrees of freedom, and the flow produces the kinematic deviation of the ship position. From the perspective of the motion control paddle, steering and anchor, three of which are active control devices in the ocean, they provide the ship forward thrust, transshipment gyroscopic moment and anchoring the anchor force. To reduce the roll of ships in waves, anti-roll fins were made in the 1960s, similar to the way fish use their fins to keep their left and right sides balanced. This suggests that the ship motion is actually a run on multiple input and multiple output in the uncertain environment, complex dynamic system in all kinds of meteorological, hydro-logical, channel and other external and internal conditions, such as all coordinated control equipment with different loads and speeds. Completing the specific navigation and operation plan is a difficult task, which needs drivers to have a lot of experiences and techniques for automatic control system. (Zhang, 2014, p.2)

1.3 FIVE TYPES OF SHIP MOTION CONTROL

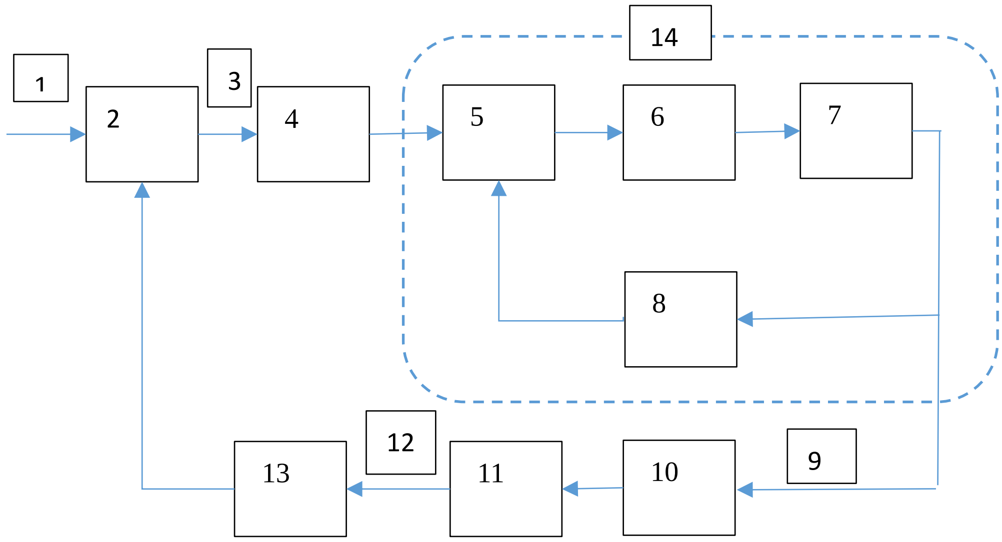
The typical manual control in the navigation of a ship is to set the speed of the propeller or the power of the main engine by the driver through the bell handle to change the speed of the ship forward or backward. The helmsman turns the steering wheel and sets the rudder Angle to rotate the rudder blade through the hydraulic servo system to maintain or change the course and track.

The automatic control of ship movement can be divided into five types: first, the automatic navigation problems of ocean navigation, including course control, track control, steering control, speed control and arrival time control, etc. Second, the navigation and automatic berthing in the port area involve the low-speed movement of ships in shallow water. The wind, waves and flow disturbance are relatively increased, the system information is increased, and the operation and control are more difficult. Third, the problem of automatic collision avoidance for navigation of crowded watercourses or ocean navigation mainly involves multiple vessel encounters, assessment of collision risk, multi-objective decision-making, optimal time and optimal range of collision avoidance, etc. Fourth, ship anti-roll control, mainly including fin anti-roll control, rudder anti-roll control and combined anti-roll control of rudder fin, etc. Fifth, Marine robot control, including underwater robot control and surface robot control. These are the five most common types for automatic control of ship movements. (Zhang,2014,p.3)

1.4 SHIP'S AUTOPILOT

The automatic steering instrument of ship is also called automatic rudder. It is a system of special importance in the control of ship motion. As early as the 1920s, the commercial automatic mechanical rudder was used for the course maintenance of merchant ships. Since then, with the development of science, technology and technology, the structure of automatic rudder has been changed greatly, and the products of electric type, electronic type and microcomputer have come out successively. GPS, the global positioning system, began offering commercial positioning services in the 1980s, making it possible for autopilot to control course.

As is said above, the ship motion is actually a run in the uncertain environment of complex dynamics system with multiple input and multiple output, which means the ship itself is a typical MIMO nonlinear systems. Uncertainties such as wind, waves and currents at sea make course control difficult. The current normal course control device for a ship is automatic navigation. The working principle of automatic rudder of ship is shown in figure 1. Automatic navigation is an important equipment in the modern ship automatic control system. A ship with good automatic rudder performance can maintain the course and achieve the desired track without constant steering, while a ship with poor performance needs frequent manual operation, which reduces the reliability and efficiency. Therefore, the research of ship course control is a very meaningful subject.



1 - A given course; 2 - The signal is sent from the Angle straightener; 3 - Drift signal; 4 - Automatic steering gear; 5 – Amplifier; 6 - Electro-hydraulic servo valve; 7 - Hydraulic steering gear; 8 - Rudder Angle feedback device; 9 - Rudder Angle; 10-Ship-rudder system; 11-Electric compass; 12 – course; 13 - Rudder Angle is accepted from Angle straightener; 14 - Rudder Angle servo system

Fig.1.1 The principle chart of the autopilot

1.5 THE PURPOSE OF NONLINEAR FEEDBACK AND DECORATION

The task of linear feedback is to design a control law $u = f(e)e$, among them, $f(e)$ is the traditional control law, it can be either a linear function or a nonlinear function of the feedback error, while it does not do any processing to the error *e*, and it directly gives feedback to the input of the controller; the control law of nonlinear feedback design is $u = f(e)g(e)$, $g(e)$ is a nonlinear function of the feedback error *e*, the control law of nonlinear decoration is $h(u) = f(e)e$, $h(u)$ is the nonlinear function of the controller output *u*. Nonlinear feedback and nonlinear decoration technique can both achieve energy-saving control effect by simulation verification. Based on this, the NFAD control law is designed, $h(u) = f(e)g(e)$. This control law makes nonlinear processing of the feedback error and the output of the controller, hoping to find a more energy-efficient control algorithm, and verify the effectiveness of the control law through simulation experiments. (Feng, 2018, p, 1)

1.6 RESEARCH ACTUALITY

Study of ship course-keeping control can be seen as an a standard of ship motion control problem, make the ship course-keeping control more energy efficient, control algorithm are more likely to become the main target in the field of navigation, a new control algorithm can use the course keeping as control equipment to verify its effectiveness.

In the paper *Neuro-fuzzy system for intelligent course control of under actuated conventional ships*, NICOLAU V aiming at the under-actuated and non- holonomic motion characteristics of the ship, a kind of intelligent controller for course keeping based on fuzzy neural network was studied, and good control performance was obtained in roll rejection and course keeping.(NICOLAU V,2007,p.95-101)

It is mentioned in the article *A back steeping approach to ship course control*, based on the backstepping method, a new nonlinear controller was designed, and the genetic algorithm was used to optimize the parameters of the controller, and the control effect was better than the traditional PD controller.(WITKOWSKA A,2007,p.73-85)

In the article *Nonlinear control for ship course-keeping based on Lyapunov stability*, a nonlinear controller based on Lyapunov energy function was proposed, which had better control performance and robust performance for nonlinear ship course keeping control system.(Zhang Xianku,2010,p.140-143)

In the article *Development of an adaptive algorithm for ship motion control on a nonlinear path*, Professor Dovgobrod G M using backstepping and adaptive control strategy, a controller for ship path tracking with curved lines was designed, the closed-loop system could adjust the parameters of the controller online and compensate the uncertainty and disturbance in the model. (Dovgobrod G M, 2012, p.41-46)

In the article *Impact time and angle guidance with sliding mode control* writing by Harl N and Balakrishnan S N, an algorithm combining backstepping with sliding mode control was presented and successfully applied to ship motion control. Also mentioned in the article *Ship autopilot control based on combined backstepping and sliding-mode technique* writing by Liu Cheng, Zou Zaojian and Li Tieshan. (Harl N, 2012, p.1436-1449)(Liu Cheng, 2013, p.225-230)

In the article *Adaptive neural network control for ship steering system using filtered backstepping design*, an algorithm combining backstepping with neural network was given and achieved good control effect.(Ren Jun-sheng,2013,p.1691-1697)

In the article *Adaptive dynamic surface control with Nussbaum gain for course-keeping of ships*, an adaptive nonlinear control strategy was proposed by combining the dynamic surface control with the backstepping method with the Nussbaum gain function, and the simulation of nonlinear ship course keeping problem with parameter uncertainty was also carried out.(Du Jia-lu,2014,p.236-240)

In the article *Design of ship course-keeping autopilot using a sine function-based nonlinear feedback technique*, a nonlinear feedback ship course keeping algorithm was proposed, which used the sine function of the course deviation to drive the controller, it had the advantages of energy saving and safety.(Zhang Xianku,2016,p.246-256)

In the article *A kind of bipolar sigmoid function decorated nonlinear ship course keeping algorithm*, a new nonlinear robust algorithm was constructed by using the bipolar S function decoration technique and the linear robust control algorithm, which further reduced the control energy of the conventional linear robust control algorithm.(Zhang Xianku,2016,p.15-19)

CHAPTER 2

SHIP MOTION MODELING

2.1 INTRODUCTION

Ship motion model describes the response of the control input of the ship in the process of movement, such as rudder Angle. To understand and master the ship motion model is the precondition of ship maneuvering control condition, which is also a foundation of studying ship maneuvering performance and autopilot design.

With the development of shipping industry, the port is becoming busier and more demanding for the operation performance of various ships. For dynamic positioning ships such as offshore oil exploitation and geological exploration, the control precision of course and track is higher, which requires us to establish a more accurate mathematical model.

2.2 A MATHEMATICAL MODEL OF THE MOVEMENT OF A SHIP

At present, the ship control motion equation elaborated by professor Zhang Xianku in book *Ship modeling and control* (2014,pp.10-29)is the most authoritative in terms of ship controller, so this paper also establishes the motion equation based on this.

Ship maneuverability is the study of the ship's motion under the control of the control devices. The main content of building the ship motion model is to analyze the force acting on the ship, and to build the mathematical model of the ship operation motion, so as to serve as the basis for studying various control algorithms of the ship operation movement.

2.2.1 EXPRESSION OF SHIP PLANE MOTION

As shown in figure 2, the plane motion of a ship as it maintains course or turns back by steering, due to the use of the spatial fixed coordinates ($O-x_0y_0z_0$) and the dynamic coordinates G-xyz fixed to the hull with the center of gravity G as the origin, the equations of motion of the ship are of course in different forms.

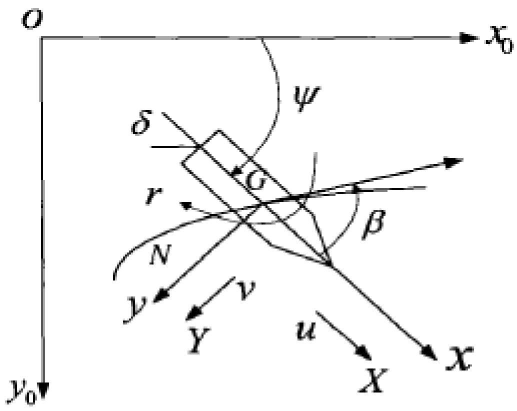


Fig.2.1 Coordinate system for the motion of a ship's plane

Adopt fixed space coordinates, can decompose the planar motion of the ship into the center of gravity G along the X_0 axis direction, the linear motion along the Y_0 direction and around through the center of gravity G along the Z_0 axis nutation, and use the following movement type:

$$\begin{cases} m\ddot{x}_0 = X_0 \\ m\ddot{y}_0 = Y_0 \\ I_{zz}\ddot{\psi} = N \end{cases} \tag{1}$$

$m - Quality\ of\ ship$
$X_0, Y_0 - The\ linear\ acceleration\ of\ the\ ship\ along\ the\ x\ and\ y\ axes$
$I_{zz} - The\ moment\ of\ inertia\ of\ a\ ship\ around\ the\ Z_0\ axis\ of\ G$
$\psi - Acceleration\ from\ ship's\ turning\ point$
$N - For\ the\ moment\ of\ rotation\ through\ the\ Z_0\ axis\ of\ G$

In addition, it can be seen from figure 2 that there is the following relation between the physical quantities of the space fixed coordinate ($O - x_0 y_0 z_0$) and the coordinates G-xyz fixed on the hull:

$$\begin{cases} X_0 = X\cos\psi - Y\sin\psi \\ Y_0 = X\sin\psi + Y\cos\psi \end{cases} \tag{2}$$

$$\begin{cases} x_0 = u\cos\psi + (-v)\sin\psi \\ y_0 = u\sin\psi - (-v)\cos\psi \end{cases} \tag{3}$$

Here, for the formula (1) type transformation is fixed on the expression of the coordinates of the hull will first type formula (3) on both sides of the differential time, $\ddot{x}_0, \ddot{y}_0$ are obtained by $\dot{x}_0, \dot{y}_0$ with the type (2) with substitution type (1) and arrange them later, can get the ship plane motion for hull fixed coordinate movement type:

$$\begin{cases} \text{For ships advancing}: m(u - v\psi) = X \\ \text{For transverse shift}: m(v + u\psi) = Y \\ \text{For turning the ship}: I_{zz}\psi = N \end{cases} \quad (4)$$

This is Eider's equation of motion

2.2.2 LINEAR MATHEMATICAL MODEL OF SHIP PLANE MOTION

When the origin of the attached coordinate system is not set at the center of mass C, $X_C \neq 0$. Since the angular velocity $r = \dot{\psi}$ at the head of rotation and angular acceleration $\dot{r} = \ddot{\psi}$, the simplest form of basic equation of ship plane motion can be obtained for formula (4) slight change:

$$\begin{cases} m(u - vr - x_c r^2) = X \\ m(v + ur + x_c r) = Y \\ I_{zz} r + m x_c (v + ur) = N \end{cases} \quad (5)$$

Type formula (5) represent the three force equilibrium on the left is the inertia force and moment of hull itself, a fluid on hull motion reaction on the right, actually including the fluid inertia force and moment as well as Bourgogne force and moment. Type formula (5) is nonlinear in nature, the left side show up ur, vr, such as nonlinear term, especially for the right X, Y, N will be multi-variable non-linear functions and movement and control variables of complex structures.

2.2.2.1 LINEARIZATION OF SHIP PLANE MOTION MATHEMATICAL MODEL

In order to linearize the mathematical model of ship plane motion, only the first order small quantity is retained when the hydrodynamic X,Y and N are expanded into Taylor series；At the same time, the left end of the basic equation of ship motion is also linearized, so that the linear mathematical model of plane motion can be obtained：

$$\begin{bmatrix}(m-X_{\dot{u}}) & 0 & 0\\ 0 & (m-Y_{\dot{v}}) & (mx_c-Y_{\dot{r}})\\ 0 & (mx_c-N_{\dot{v}}) & (I_{zz}-N_{\dot{r}})\end{bmatrix}\begin{bmatrix}\vartriangle\dot{u}\\ \dot{v}\\ \dot{r}\end{bmatrix}=\begin{bmatrix}X_u & 0 & 0\\ 0 & Y_v & (Y_r-mu_0)\\ 0 & N_v & (N_r-mx_cu_0)\end{bmatrix}\begin{bmatrix}\vartriangle u\\ v\\ r\end{bmatrix}+\begin{bmatrix}0\\ Y_\delta\\ N_\delta\end{bmatrix}\delta$$

(6)

2.2.2.2 FORWARD MOTION IS DECOUPLED FROM THE MOTION OF DRIFT AND HEAD TURNING

Formula (6) shows that, under the premise of linearization, the forward motion is independent of the other two degrees of freedom. From the perspective of speed control, the motion at this degree of freedom can be considered separately； There is a strong disaster combination between the movement of horizontal drift and head turning. The movement at these two degrees of freedom is closely related to the control of the ship's course and track：

$$(m-X_{\dot{u}})\dot{u}=X_u\vartriangle u \tag{7}$$

$$\begin{bmatrix}(m-Y_{\dot{v}}) & (mx_c-Y_{\dot{r}})\\ (mx_c-N_{\dot{v}}) & (I_{zz}-N_{\dot{r}})\end{bmatrix}\begin{bmatrix}\dot{v}\\ \dot{r}\end{bmatrix}=\begin{bmatrix}Y_v & (Y_r-mu_0)\\ N_v & (N_r-mx_cu_0)\end{bmatrix}\begin{bmatrix}v\\ r\end{bmatrix}+\begin{bmatrix}Y_\delta\\ N_\delta\end{bmatrix}\delta \tag{8}$$

2.2.2.3 ESTIMATION FORMULA OF HYDRODYNAMIC DERIVATIVE

Ship linear mathematical model of further deduction mainly involves ten hydrodynamic derivatives, $Y_v, Y_r, N_v, N_r, Y_{\dot{v}}, Y_{\dot{r}}, N_{\dot{v}}, N_{\dot{r}}, Y_\delta, N_\delta$, the first four known as "derivative" speed, five to eight become derivative "acceleration", the last two known as the "rudder force and steering torque derivative”. Due to the ship (including the oar and rudder) the complexity of geometric shape, theory of fluid mechanics method is applied to calculate the hydrodynamic derivatives is impossible, so they must rely on to determine the model experiment. Clarke (1982,pp,45-68) compiled a large number of ship model test data and gave a regression formula for 10 linear hydrodynamic derivatives, which were summarized as follows:

$$
\begin{cases}
Y_{\dot{v}}' = -\left[1 + 0.16C_b B/T - 5.1(B/L)^2\right] * \pi(T/L)^2 \\
Y_{\dot{r}}' = -\left[0.67B/L - 0.0033(B/L)^2\right] * \pi(T/L)^2 \\
N_{\dot{v}}' = -\left[1.1B/L - 0.041B/T\right] * \pi(T/L)^2 \\
N_{\dot{r}}' = -\left[1/12 + 0.017C_b B/T - 0.33B/L\right] * \pi(T/L)^2 \\
Y_v' = -\left[1 + 0.40C_b B/T\right] * \pi(T/L)^2 \\
Y_r' = -\left[-1/2 + 2.2B/L - 0.080B/T\right] * \pi(T/L)^2 \\
N_v' = -\left[1/2 + 2.4T/L\right] * \pi(T/L)^2 \\
N_r' = -\left[1/4 + 0.039B/T - 0.56B/L\right] * \pi(T/L)^2 \\
Y_\delta' = 3.0A_\delta / L^2 \\
N_\delta' = -(1/2)Y_\delta'
\end{cases} \tag{9}
$$

In the above equation, B, T, C_b, A_δ refers to the ship's width, draft, square coefficient and rudder area respectively. In the above equation, Y_v', Y_r', N_v', N_r' are the hydrodynamic derivatives of the ship itself. In practical application, some modifications should be made to these hydrodynamic derivatives:

$$
\begin{cases}
\triangle Y_v' = -0.30Y_\delta' \\
\triangle Y_r' = -0.5\triangle Y_v' \\
\triangle N_v' = -0.5\triangle Y_v' \\
\triangle N_r' = 0.25\triangle Y_v'
\end{cases} \tag{10}
$$

2.2.2.4 MATHEMATICAL MODEL OF SHIP PLANE MOTION IN STATE SPACE TYPE

State space model of the ship surface movement mathematic model is the basis of ship motion controller design, and it can make a multi-level modeling scheme with different dimension of the model is used in the design for different purposes and accuracy requirements.

2.2.2.5 LINEAR MODEL OF TWO - DEGREE - FREEDOM STATE - SPACE SHIPS

In the first row of equation (8), divide both ends by $0.5\rho L^3$, and in the second row, divide both ends by $0.5\rho L^4$ and turn into the infinitely rigid hydrodynamic derivative, then:

$$\begin{bmatrix} (m^{'}-Y_{\dot{v}}^{'}) & L(m^{'}x_c^{'}-Y_{\dot{r}}^{'}) \\ (m^{'}x_c^{'}-N_{\dot{v}}^{'}) & L(I_{zz}^{'}-N_{\dot{r}}^{'}) \end{bmatrix}\begin{bmatrix} \dot{v} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{V}{L}Y_v^{'} & V(Y_r^{'}-m^{'}) \\ \frac{V}{L}N_v^{'} & V(N_r^{'}-m^{'}x_c^{'}) \end{bmatrix}\begin{bmatrix} v \\ r \end{bmatrix} + \begin{bmatrix} \frac{V^2}{L}Y_\delta^{'} \\ \frac{V^2}{L}N_\delta^{'} \end{bmatrix}\delta \quad (11)$$

When equation (11) is converted into the standard state space form, the following equation can be obtained:

$$X_{(2)} = A_{(2)}X_{(2)} + B_{(2)}\delta \quad (12)$$

In which that：

$$A_{(2)} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, B_{(2)} = \begin{bmatrix} b_{11} \\ b_{21} \end{bmatrix} \quad (13)$$

And:

$$\begin{cases} S_1 = \left[(I_{zz}^{'}-N_{\dot{r}}^{'})(m^{'}-Y_{\dot{v}}^{'})-(m^{'}x_c^{'}-N_{\dot{v}}^{'})(m^{'}x_c^{'}-Y_{\dot{r}}^{'})\right]L \\ a_{11} = \left[(I_{zz}^{'}-N_{\dot{r}}^{'})Y_v^{'}-(m^{'}x_c^{'}-Y_{\dot{r}}^{'})N_v^{'}\right]V/S_1 \\ a_{12} = \left[(I_{zz}^{'}-N_{\dot{r}}^{'})(Y_r^{'}-m^{'})-(m^{'}x_c^{'}-Y_{\dot{r}}^{'})(N_r^{'}-m^{'}x_c^{'})\right]LV/S_1 \\ a_{21} = \left[-(m^{'}x_c^{'}-N_{\dot{v}}^{'})Y_v^{'}+(m^{'}-Y_v^{'})N_v^{'}\right]V/L/S_1 \\ a_{22} = \left[-(m^{'}x_c^{'}-N_{\dot{v}}^{'})(Y_r^{'}-m^{'})+(m^{'}-Y_{\dot{v}}^{'})(N_r^{'}-m^{'}x_c^{'})\right]V/S_1 \\ b_{11} = \left[(I_{zz}^{'}-N_{\dot{r}}^{'})Y_\delta^{'}-(m^{'}x_c^{'}-Y_{\dot{r}}^{'})N_\delta^{'}\right]V^2/S_1 \\ b_{21} = \left[-(m^{'}x_c^{'}-N_{\dot{v}}^{'})Y_\delta^{'}+(m^{'}-Y_{\dot{v}}^{'})N_\delta^{'}\right]V^2/L/S_1 \\ m^{'} = m/(0.5\rho L^3), x_c^{'} = x_c/L, I_{zz}^{'} = m/(8\rho L^3) \end{cases} \quad (14)$$

2.2.2.6 LINEAR MATHEMATICAL MODEL OF THREE - DEGREE - FREEDOM STATE - SPACE SHIPS

On the basis of (12), a state variable course deviation $\triangle\psi$ is added to facilitate the study of the problem, so that the state vector becomes $X_{(3)} = \left[v \quad r \quad \triangle\psi\right]^T$. Since $\triangle\dot{\psi} = \mathrm{r}$, it can be obtained:

In which that:

$$X_{(3)} = A_{(3)} X_{(3)} + B_{(3)}\delta \tag{15}$$

$$A_{(3)} = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ 0 & 1 & 0 \end{bmatrix}, B_{(3)} = \begin{bmatrix} b_{11} \\ b_{21} \\ 0 \end{bmatrix} \tag{16}$$

2.2.3 TRANSFER FUNCTION MODEL OF SHIP MOTION

Transfer function model of ship motion mathematical model in classical control theory and intelligent control realm to analyze the dynamic behavior of the ship motion, and can be used as the basis of design course, track controller.

1) Third order transfer function model

For ship course control, the state space mathematical model of three degrees of freedom formula (16) plus the output equation is adopted:

$$\psi_m = CX_{(3)} \tag{17}$$

Where ψ_{m} is the measuring direction and C=[0, 0, 1], the state space mathematical model is converted into the form of transfer function, which is:

$$G_{\psi\delta}(s) = C\left[sI - X_{(3)}\right]^{-1} B_{(3)} = \frac{K_0(T_3 s + 1)}{s(T_1 s + 1)(T_2 s + 1)} \tag{18}$$

This is a third-order system with two non-zero poles and one zero point, and there are:

$$\frac{1}{T_1T_2}=a_{11}a_{22}-a_{12}a_{21},\frac{T_1+T_2}{T_1T_2}=-(a_{11}+a_{22})$$
$$\frac{1}{T_3}=\frac{1}{b_{21}}(b_{11}a_{21}-b_{21}a_{11}),\frac{K_0T_3}{T_1T_2}=b_{21} \quad (19)$$

2) Second order transfer function model(Nomoto model)

Professor Nomoto K (1957, pp, 188-194) did a good job about the third order ship type formula (18) simply, make it to the second order, the starting point of argument is that for ship the large inertia of the vehicle, its dynamic characteristic in low frequency band is important, therefore, in the type formula (18) to $s=jw\to 0$, and use two known as the approximate relationship: When $x\to 0,1/(1+x)\approx 1-x,(1-x)\approx 1/(1+x)$ is obtained, the famous Nomoto model is derived:

$$G(s)=\frac{K_0}{s(T_0s+1)} \quad (20)$$

Where, the gain coefficient K_0 is the same as the third-order model, the time constant $T_0=T_1+T_2-T_3$, or is solved directly from the following equation:

$$K_0=\frac{b_{11}a_{21}-b_{21}a_{11}}{a_{11}a_{22}-a_{12}a_{21}},T_0=-\frac{a_{11}+a_{22}}{a_{11}a_{22}-a_{12}a_{21}}-\frac{b_{21}}{b_{11}a_{21}-b_{21}a_{11}} \quad (21)$$

Equation (20) is widely used in the controller design of automatic rudder of ship. Ship motion controller design which carried out with Nomoto model has two advantages: one is in low frequency range, its spectrum and high frequency model of spectrum are very close. Secondly, the design of the controller order time is low and easy to implement.

In the design of automatic rudder of ship's course, the model of ship's course control system generally adopts the wild model, that is, equation (20) converts it into the time domain form:

$$T_0\ddot{\psi}+\dot{\psi}=K_0\delta \quad (22)$$

Where, K_0,T_0 can be directly used to evaluate the ship's operating characteristics, it is called the maneuverability index, and generally expressed as $T_0=T'L/v,K_0=K'v/L.T'$, K' as the dimensionless coefficient of the model.

Eight ship parameters need to be known to solve the mathematics of ship motion, which namely speed (V), length between perpendiculars (L), ship wide (B), full draft (T), block coefficient (C_b), displacement (∇), center of gravity away from the center distance (X_C), rudder area (A_δ)

2.3 MATHEMATICAL MODEL OF INTERFERENCE

Navigation of ships in the sea is often disturbed by wind, wave and current, so the study of ship's navigation performance on waves has attracted more and more attention. In order to develop a good ship motion controller, the influence of various environmental disturbances on the control effect must also be considered in the development of the controller. Therefore, the environmental interference model of ship motion controller is an important part in the development of ship motion controller.

2.3.1 SEA BREEZE

The influence of sea wind on the movement of ships, in addition to the corresponding force and torque generated by waves, will directly affect the buildings of ships above the waterline surface, result in the corresponding force and torque. The influence caused by sea wind can be considered in two parts, which are, constant sea wind and variable sea wind.

For the automatic rudder system, the additional disturbance force and moment caused by the constant sea wind on the ship building above the water line are:

$$\begin{cases} X_W = \frac{1}{2}\rho_a A_X V_W^2 C_{X_W}(\varphi_W) \\ Y_W = \frac{1}{2}\rho_a A_Y V_W^2 C_{Y_W}(\varphi_W) \\ N_W = \frac{1}{2}\rho_a A_Y L_S V_W^2 C_{N_W}(\varphi_W) \end{cases} \quad (23)$$

$\rho_a - Air\ density$

$A_X - The\ projected\ area\ of\ a\ ship\ below\ the\ waterline$

$A_Y - Lateral\ projection\ area\ of\ a\ ship\ above\ water\ line$

$L_S - Length\ of\ ship's\ waterline$

$V_W - The\ relative\ wind\ speed$

$\varphi_W - The\ wind\ Angle$

$C_{X_W}(\varphi_W), C_{Y_W}(\varphi_W), C_{N_W}(\varphi_W) - relative\ wind\ speed\ and\ the\ wind\ moment$

Coefficient of large ships, the sea wind variation of the OZ axis torque caused by some factors can be regarded as the white noise with the mean value of zero and the variance is

$$\begin{aligned} &\sigma_N = \rho_a V_r S_W L_S \sigma \left| C_{N_W} \right| \\ &\sigma = 0.2 V_T \end{aligned} \quad (24)$$

2.3.2 CURRENT

The effect of ocean current on ship motion can be equivalent to the additional disturbance force and torque caused by the change of ship relative velocity relative to sea water. Generally speaking, in a short period of time, the current can be considered constant, that is, its flow Vc= is constant. For the course motion of the ship, the existence of the current will cause an additional disturbance force and torque around the OZ axis, which can be expressed as:

$$\begin{cases} X_C = \dfrac{1}{2}\rho A_{FW} V_C^2 C_{X_C}(\beta) \\ Y_C = \dfrac{1}{2}\rho A_{SW} V_C^2 C_{Y_C}(\beta) \\ N_C = \dfrac{1}{2}\rho A_{SW} L_S V_C^2 C_{N_C}(\beta) \end{cases}$$

$$\begin{aligned} &\rho - Density\ of\ sea\ water \\ &A_{FW} - The\ area\ of\ a\ ship\ under\ the\ waterline \\ &A_{SW} - The\ projected\ area\ of\ the\ ship's\ side\ below\ the\ waterline \\ &V_C - The\ velocity \\ &L_S - Length\ of\ ship's\ waterline \\ &\beta - Inlet\ Angle\ of\ current\ \left(drift\ Angle\right) \\ &C_{X_C}(\beta), C_{Y_C}(\beta), C_{N_C}(\beta) - The\ coefficient\ associated\ with\ the\ drift\ Angle \end{aligned} \quad (25)$$

2.3.3 THE WAVES OF THE SEA

Wave is usually a general term for wind, wave and surge. Generally speaking, waves refer to wind and waves, these are the most widely distributed on the sea surface and are the most important factor for ships to generate rocking motion at sea

1 WAVE ENERGY SPECTRUM OF WAVES

Wave is a random phenomenon in nature with the following properties：

①Fully developed wave is a random process in which all states experience a steady state

② Wave height is normally distributed, while wave amplitude is Rayleigh distributed

③Waves can be described by superposition of enough independent and random initial phase unit-regular waves, that is, wave height and wave surface Angle can be expressed respectively：

$$\xi(x,t)=\sum_{i=1}^{N}\xi_{ai}\cos(k_{wai}+w_i t+\varepsilon_i) \tag{26}$$

$$\alpha(x,t)=-\sum_{i=1}^{N}\xi_{ai}\sin(k_{wai}+w_i t+\varepsilon_i) \tag{27}$$

$N-$ *Large enough positive integer*

$\xi_{ai}, k_{wai}, w_i -$ *The corresponding parameters of the I unit regular wave*

$\varepsilon_i -$ *Random variables uniformly distributed on* $[0,2\pi]$ (*representing the initial phase*)

According to the theory of fluid dynamics, the energy of regular waves in each unit area is

$$E_i=\frac{1}{2}\rho g\xi_{ai}^2 \tag{28}$$

Because irregular waves are composed of an infinite number of regular waves, the energy of waves in the frequency band ($w, w+\triangle w$) should be:

$$E_{\triangle w}=\frac{1}{2}\rho g\sum_{w}^{w+\triangle w}\xi_{ai}^2 \tag{29}$$

The density function of wave energy spectrum is defined as

$$S_{\xi}(w)=\frac{E_{\triangle w}}{\rho g\triangle w}=\frac{1}{2}*\frac{1}{\triangle w}\sum_{w}^{w+\triangle w}\xi_{ai}^2 \tag{30}$$

If the unit wave is infinite, and ($w, w+\triangle w$) becomes [0,∞], obviously there is

$$\int_0^\infty S_\xi(w)dw = \sum_{i=1}^\infty \frac{1}{2}\xi_{ai}^2 = \sigma^2 \quad (31)$$

On type show that the wave height, wave height variance σ^2 represents the waves of the total energy per unit area, the wave energy spectrum density function is proportional to the wave of energy, it is a function of the unit wave frequency and characterization of the relative wave frequency of the wave energy distribution.

The wave energy spectrum of China's coastal areas proposed by China's Marine department is:

$$S_\xi(w) = \frac{0.74}{w^5}\exp\left\{-\frac{g^2}{V_T^2 w^2}\right\} \quad (32)$$

$$V_T - wind\ speed$$

2 SEA SCALE

Sea condition level is a quantitative description of the degree of sea surface unevenness. At present, China uses wave level to determine it. According to the height of the large wave, the significant wave height is defined as one third in the continuous time, for every 100 random waves in terms of its high transient wave from comparing the calculated before a third part of the average of the maximum transient wave height, it is known as the significant wave height h1/3. According to the position of 1/3 effective wave height in the wave scale table 1, the corresponding wave level, namely sea condition level, can be obtained.

Table 2.1 Sea level corresponds to significant wave height

Class of sea state	1/3 significant wave height H1/3 (m)
0	0.00
1	0.00-0.19
2	0.19-0.57
3	0.57-0.95
4	0.95-1.52
5	1.52-2.65
6	2.65-4.55
7	4.55-6.44
8	6.44-8.33
9	8.33-more

3 INTERFERENCE OF WAVES

Under the action of waves, the ship's course motion and roll motion will be subjected to additional disturbing moments. In the actual design simulation, the number of regular waves N and amplitude ξ_{ai} of the selected unit need to be appropriately selected.

Let the wave energy spectrum be divided into N segments, and the energy in each segment is

$$S_{\xi}(w_i)\triangle w_i = \frac{\sigma^2}{N} = constant \tag{33}$$

According to the trapezoid approximation, the wave energy spectrum curve can be divided into N segments, each segment interval is $\triangle w_i (i = 2,3,...,N)$, and the corresponding height is $S_{\xi}(w_i)$, and then we have:

$$\xi(x,t) = \sum_{i=1}^{N} \sqrt{2S_{\xi}(w_i)\triangle w_i} \cos(k_{wai} + w_i t + \varepsilon_i) \tag{34}$$

In the simulation study of automatic rudder system, the interference torque is:

$$\begin{aligned}
&N_a = ak_a \left[B^2 \sin b \frac{c\cos c - \sin c}{c^2} - c^2 \frac{b\sin b - \sin b}{b^2} \right] * \xi(t) \\
&a = \rho g (1 - e^{-k_{wa}T_w}) / k_{wa}^2 \\
&b = -(k_{wa} L / 2)\cos\gamma \\
&c = (\cos B / 2)\sin\gamma \\
&T_W - The\ cycle\ of\ the\ wave \\
&\gamma - The\ relative\ wave\ direction \\
&L - The\ length\ of\ the\ ship \\
&B - The\ width\ of\ the\ ship
\end{aligned} \tag{35}$$

The relationship between rotary moment and rudder Angle is:

$$N_r = 2k * A_r * V^2 * \delta \tag{36}$$

Where, Nr is the rudder Angle moment of the ship, Ar is the area of rudder, V is ship speed, δ is rudder Angle, and k is constant. The equivalent rudder effect of the disturbing moment can be calculated.

4 THE SIMULATION RESULTS

Below ITTC single-parameter of wave spectrum, for example, using the above method to simulate the waves, the simulation results as shown in figure 3, figure 4, figure 5 and figure 6, which significant wave height respectively is 1 m, 3 m, 5 m and 7 m, simulation step length are 0.5 S. Above is the long peak wave simulation curve and below is the ITTC single-parameter dispersion spectrum simulation curve for each.

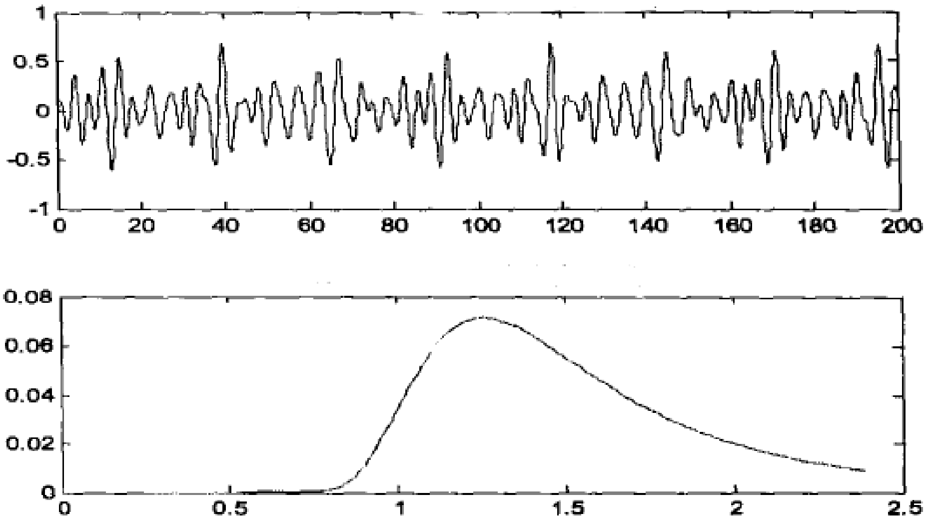


Fig. 2.2 Wave simulation at significant wave height h1/3=1m
Data from: Sun Shuai. (2016). Design of Fuzzy Controlled Fin Stabilizer Based on RBF Neural Network. *Dalian maritime university*. P.8-11

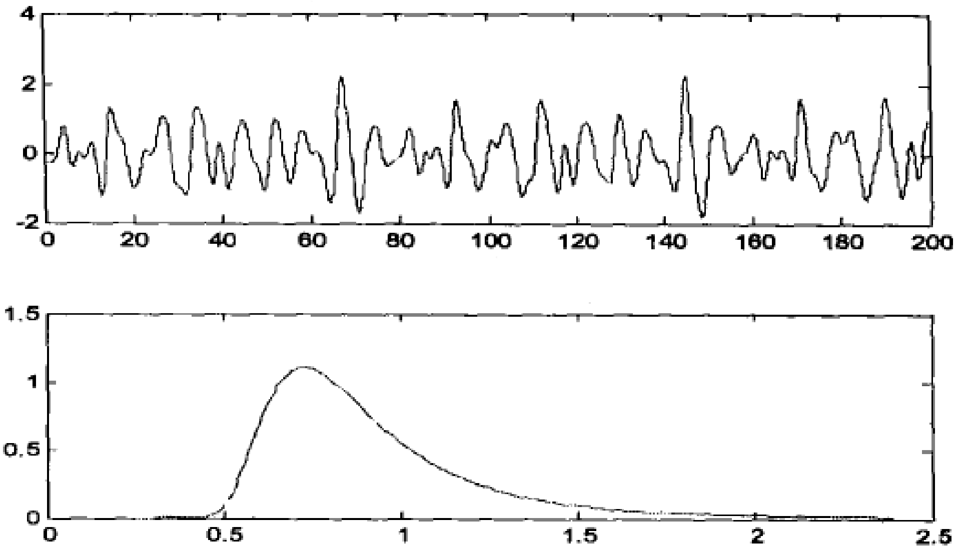


Fig. 2.3 Wave simulation at significant wave height h1/3=3m
Data from: Sun Shuai. (2016). Design of Fuzzy Controlled Fin Stabilizer Based on RBF Neural Network. *Dalian maritime university*. P.8-11

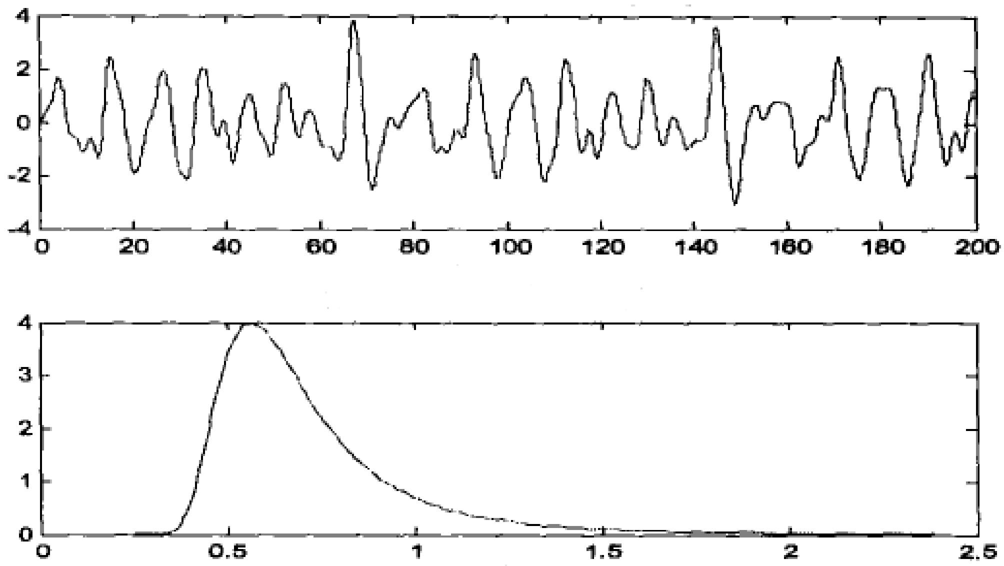


Fig. 2.4 Wave simulation at significant wave height h1/3=5m
Data from: Sun Shuai. (2016). Design of Fuzzy Controlled Fin Stabilizer Based on RBF Neural Network. *Dalian maritime university*. P.8-11

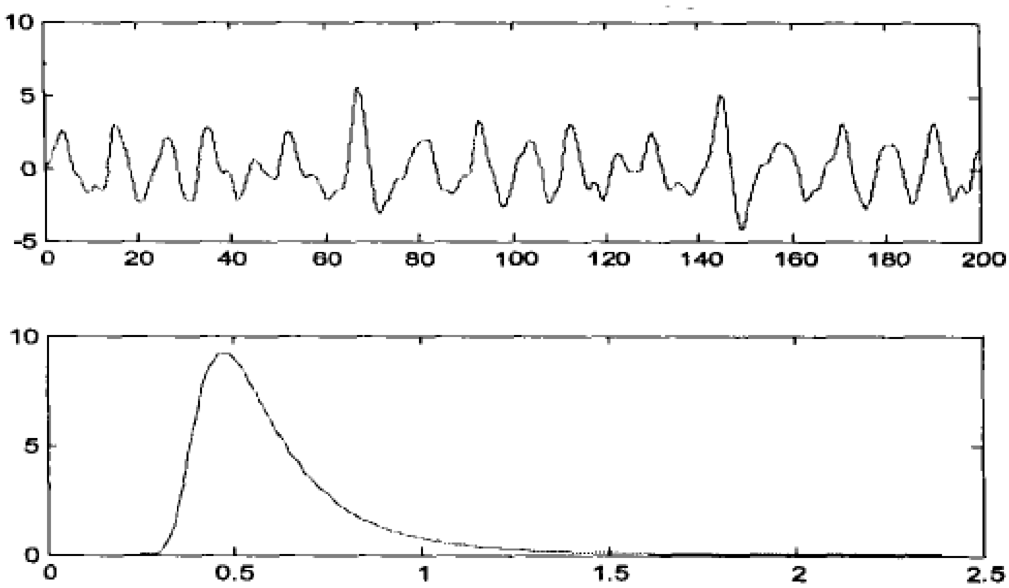


Fig. 2.5 Wave simulation at significant wave height h1/3=7m
Data from: Sun Shuai. (2016). Design of Fuzzy Controlled Fin Stabilizer Based on RBF Neural Network. *Dalian maritime university*. P.8-11

It can be seen from the above simulation results:

（1） If significant wave height is large, the wave height of the corresponding wave frequency spectrum is relatively large, and vice versa.

（2） The wave energy of significant wave height is large, and the area around the wave energy spectrum density function and coordinate axis is also large.

（3）The range of wave frequencies included in the wave frequency spectrum is actually only concentrated in a narrow frequency band, which belongs to the narrow band spectrum.

（4）With the increase of wave height, the significant part of the corresponding spectral density function or the peak point of spectral density curve moves to the low frequency.

It can be seen that the wave simulation method adopted in this section can accurately reflect the characteristics of the wave spectral density function as well as simulate a reasonable wave height.

CHAPTER 3

NONLINEAR SHIP MODEL

3.1 A RESPONSE MODEL FOR NONLINEAR SHIP MOTION

Ship motion can be described by state space model or input-output model. The former description can deal with the multi-variable movement of ships under control, and the introduction of wind, wave and flow interference is more direct and accurate, but the calculation is quite complicated. A description is also known as response model method, after it seizing the ship movement after omitting drifting velocity from δ→$\dot{\psi}$ →ψ as the main vein, obtaining the differential equation of still preserves the nonlinear influence factors, even the wind and waves interfere or become a kind of interference rudder Angle which constitute an input signal and the actual rudder angle δ into the ship model, as shown in figure 7. This model is actually a generalization of the linear Nomoto model.

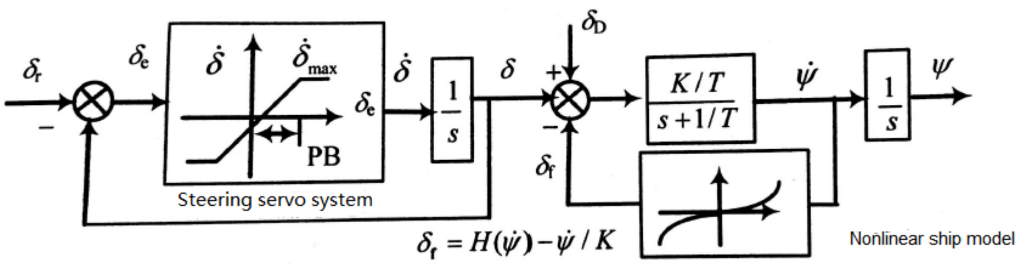


Fig. 3.1 *Yu Peng* vessel nonlinear ship mathematical model
Data from: *Ship modeling and control,* Zhang Xianku

Second-order Nomoto model is known as follows:

$$\ddot{\psi} + \frac{1}{T}\dot{\psi} = \frac{K}{T}\delta \tag{37}$$

For some ships without directional stability, the second term at the left end of equation (37) must be replaced by a non-linear term, and

$$H(\dot{\psi}) = \alpha\dot{\psi} + \beta\dot{\psi}^3 \tag{38}$$

Therefore, the nonlinear second-order ship motion response model becomes:

$$\ddot{\psi}+\frac{K}{T}H(\dot{\psi})=\frac{K}{T}\delta \tag{39}$$

Obviously, in the linear case, for equation (37) to be consistent with equation (39), there must be $\alpha=1/K, \beta=0$. In figure 7, δ_f is:

$$\dot{\psi}\rightarrow\delta_f:\delta_f=H(\dot{\psi})-\frac{1}{K}\dot{\psi}=(\alpha-\frac{1}{K})\dot{\psi}+\beta\dot{\psi}^3 \tag{40}$$

The parameters α、β、K and T are related to the speed.

3.2 MODEL VALIDATION

3.2.1 BASIC SHIP PARAMETERS

The ship motion model established in this paper is based on the real ship data verification of the training ship Yu Peng vessel of Dalian maritime university. Since Yu Peng vessel was put into use in 2016, after more than two years of testing, the data has been relatively matured and completed, which makes it easier to verify the coincidence between the ship model and the actual ship.

Table 2 gives the parameters of ship in ballast and full load condition, Table 3 gives the environment and some other important parameters of the ship in the turning circle test. The ship model adopts the first order Nomoto model and has nonlinear feedback compensation term.

In order to simulate the ship more truly, the rudder characteristics are considered in the simulation, servo system is composed of a comparator, a power amplifier, a variable pump, a hydraulic steering gear and a steering gear feedback device, the range of rudder angle *δ* is [-35°,35°],The rudder speed is 5°/s. A model of wind interference is described above. The system structure of the nonlinear ship model is shown in Fig.8, the first order Nomoto model from rudder angle *δ* to roll speed *r* is shown in equation (41):

$$G_{r\delta}(s)=\frac{K}{Ts+1} \tag{41}$$

The nonlinear feedback compensation term is:

$$f(u)=(\alpha-1/K)\dot{\psi}+\beta\dot{\psi}^3 \tag{42}$$

The parameters, K=0.08, T=39.09, α=0.98, β=4.1 which formula (41) and (42) required can be calculated according to the data given in Table 2.

Table 3.1: Parameters of *Yu Peng* vessel in full load and ballast condition

Date from: *Modeling and digital simulation for control systems,* Zhang Xianku

	L/m	*B*/m	*d*/m	x_c/m	C_b	∇ / t	v / kn	A_δ/m^2
Full load	189.0	27.8	11.0	-1.8	0.72	30000	17.5	38
Ballast	189.0	27.8	6.32	-4.043	0.661	22587.6	17.26	31.67

Table 3.2: Data of turning circle test

Date from: *Modeling and digital simulation for control systems,* Zhang Xianku

Wind Scale(kn)	35	Turning Circle Diameter	633.36
Depth of Water(m)	47	Turning Circle Speed (kn)	10.2
Wind Direction(°)	P175	Turning Circle W-Speed	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 (°)	1	Time at Angle 360 (s)	472
Start Heading (°)	0.24	Time at Angle 540 (s)	697
End Heading (°)	168.96	Speed at Angle 90 (kn)	11.42
End Speed (knot)	7.75	Speed at Angle 180 (kn)	9.59
Turning Circle	697	Speed at Angle 270 (kn)	8.29
Transfer (m)	398.36	Speed at Angle 360 (kn)	7.71
Advance (m)	686.48	Speed at Angle 540 (kn)	7.75

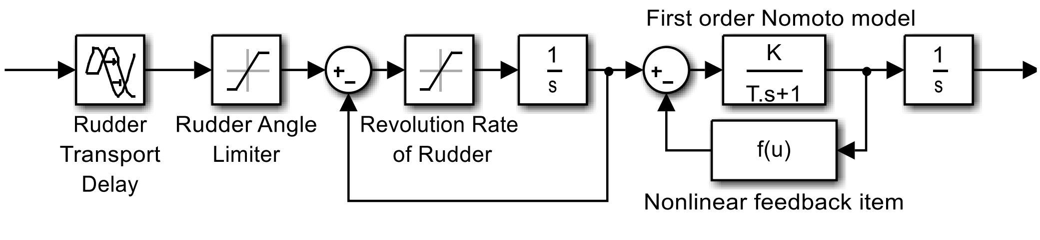


Fig. 3.2: System structure of nonlinear ship model

The *Yu Peng* vessel ship data in table 2 were used to calculate K, T index and parameters of ships based on the VC platform, so as to obtain the data of Yu Peng vessel ship. The specific VC code is shown in the appendix.

3.2.2 MODEL VALIDATION

According to simulation calculation method of *yukun* ship in the article *Linear reduction of backstepping algorithm based on nonlinear decoration* writing by Professor Zhang Xianku for ship course-keeping control system similar calculation treatment for *yupeng* ship. (Zhang Xianku, 2018, p.1-8)

The nonlinear response Nomoto model was simulated by using Matlab's Simulink toolbox and compared with the real ship ballast cycle test to test the validity of the model. Yu Peng vessel comprehensive performance test in ship ballast right back was conducted under the condition of moderate breeze, was conducted in 4 wind sea condition, joined the 4th level wind in the simulation of interference and set the wind speed of 35 kn. A model of wind interference is described above.

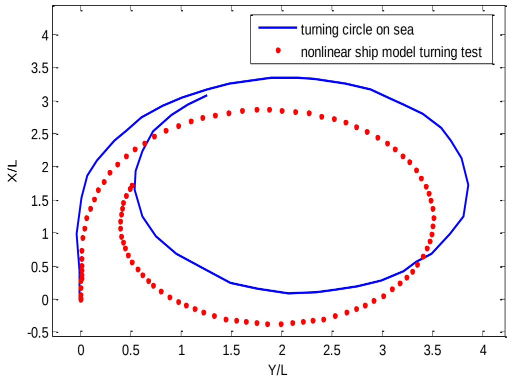


Fig. 3.3: Comparison of turning circle in hard starboard

In order to verify the conformity between the established nonlinear ship model and real ship, the simulation test of turning circle is carried in hard starboard, the simulation curve is compared with the real ship test curve, and the result is shown in Fig. 9. In the figure, the horizontal coordinate Y represents the horizontal moving distance of the ship's rotation, while the vertical coordinate X represents the longitudinal moving distance of the ship's rotation. The simulated horizontal tactical diameter is 3.10l, and the actual ship test is 3.35l. The longitudinal tactical diameter of the simulation is 3.14l, and the real ship test is 3.63l. By contrast, the result of the simulation is 86.54%, and the horizontal is 92.5% and the overall fitness is 89.52%.

The left-turn of the ballast of Yu Peng vessel ship's comprehensive performance test was carried out under the sea condition of class 7 wind, so the interference of class 7 wind was added in the simulation. The comparison between the simulation results and the actual ship test is shown in figure 10. The simulated horizontal tactical diameter is 3.15l and vertical tactical diameter is 3.30l. The actual ship test horizontal tactical diameter is 2.90L, and the test vertical tactical diameter is 2.90L. It can be seen from the comparison results that the horizontal compliance degree of simulation results is

92.0%, the longitudinal compliance degree is 87.9%, and the overall compliance degree is 90.0%. The overall coincidence degree of left-right cycle simulation results is 89.76%. It indicates that the established nonlinear Nomoto model has high precision and can be used to study the motion of *Yu Peng* vessel.

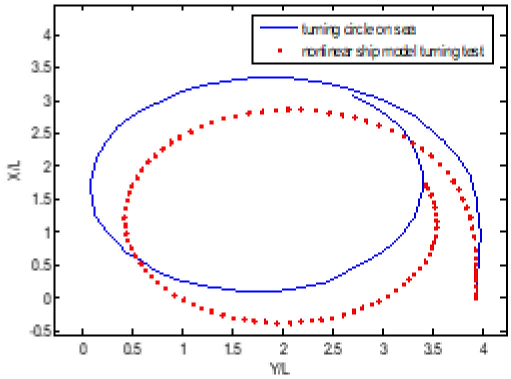


Fig. 3.4: Comparison of turning circle in hard portside

CHAPTER 4

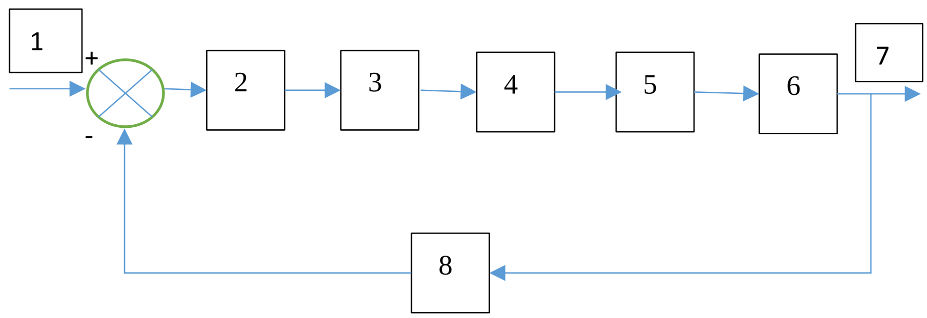
IMPROVED CONTROLLER BASED ON NFAD TECHNIQUE

4.1 FUZZY CONTROL SYSTEM

Fuzzy control belongs to computer intelligent control, and its related theoretical researches include fuzzy mathematics, fuzzy language variables and fuzzy logic reasoning. Compared with the general control system, the main difference is that the fuzzy concept is added to the system controller. Fuzzy control system consists of the following parts:

(1) Fuzzy controller.
(2) I/O interface device.
(3) The accused and the executing agency.
(4) Sensor.

A sensor is a detection device that converts the control amount of the controlled object into an electrical signal. When we select the sensor, the one with good stability and high precision should be chosen, because the quality of the sensor determines the control effect of the control system. Figure 11 below is the block diagram of the fuzzy control system. It consists mainly of the four parts described above.



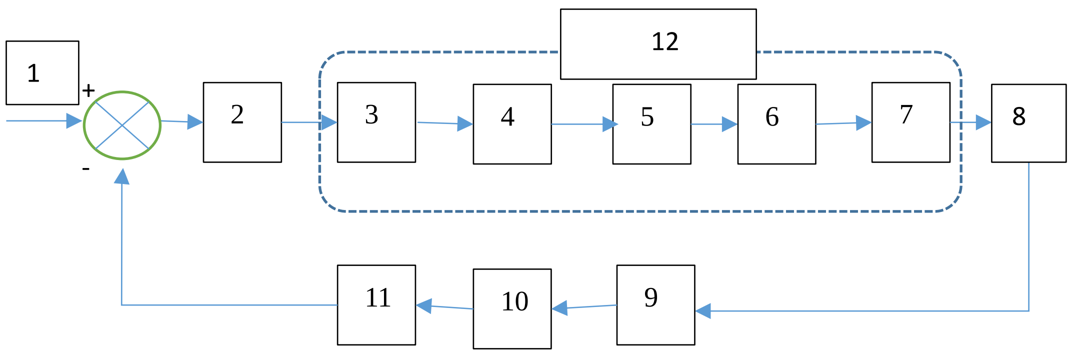
1 - A given value; 2 - A/D; 3 - Fuzzy controller; 4 - D/A;
5 - Actuator; 6 - Controlled object; 7 - Controlled quantity; 8 - The sensor.

Fig.4.1 System diagram of fuzzy control

4.1.1 FUZZY CONTROL PRINCIPLE

As can be seen from figure 11, the fuzzy controller plays an important role in the control system. It mainly realizes the following functions: in the fuzzy process of control variables, establish appropriate control rules according to operator experience, the process of fuzzy reasoning and defuzzifying the fuzzy subset after reasoning according to rules

Fuzzy control algorithm for the implementation of the process: first of all, it needs to get the current value of the controlled by sensors, and then get controlled the amount of sample points target, after comparing the two to get the error, error value input to the designed fuzzy controller, and then need to be fuzzy, after system according to the input and the inference rules set in advance, according to the synthetic subset output fuzzy control rules, finally to defuzzifying get accurate quantity on the controlled system.



1 - A given value; 2 - A/D; 3 - Computational control variable; 4 - Fuzzy quantization; 5 - Fuzzy control rule; 6 - Fuzzy inference decision; 7 – Defuzzification; 8 - D/A; 9 – Actuator; 10 - Controlled object; 11 - The sensor; 12 - Fuzzy controller.

Fig.4.2 Principle diagram of fuzzy control

4.1.2 FUZZY CONTROLLER DESIGN

The key point of designing a good fuzzy control system is to design the fuzzy controller which needs to be used in the control system. The main process is shown in figure 13 below, with the following 5 items:

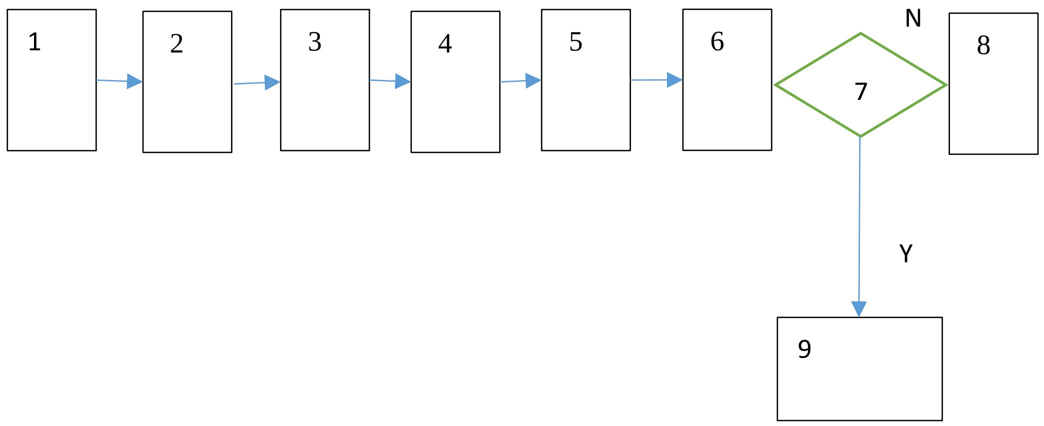
(1) First select the appropriate physical quantities of input and output according to the system requirements.

(2) Determine the appropriate theoretical domain of the input (output) variable, and select the corresponding membership function.

(3) According to the experience of the operator or the statistical data of the experiment, the control rules are constructed.

(4) Determine the method of defuzzifying and clarifying.

(5) After the above steps are completed, the control algorithm can be written for simulation or simulation analysis.



1 - System analysis; 2 - Determine the input and output physical quantities; 3 - Determine the fuzzy controller structure; 4 - Determine the fuzzy subset membership function; 5 - Establish fuzzy control rules;6 - Perform simulations or simulations; 7 - Make sure those goals are met; 8 - Adjust the parameters;9 - End of the design.

Fig.4.3 Design flow diagram of fuzzy controller

The main steps of fuzzy controller design include variable fuzzification, knowledge base building, appropriate fuzzy reasoning algorithm and defuzzification process

① Fuzzification

The process of fuzzifying a variable is to convert a certain value into a fuzzy value. In the process of fuzzification, the input error is first converted to the value within the theoretical domain, and then the fuzzy language value of the variable is determined, usually 3, 5 or 7. Obviously, the more fuzzy language values are obtained, the better control the system will be. Finally, select the appropriate membership function. Subjective selection of membership function is usually determined by statistical methods or summarize experience, the selection of membership function will affect the control effect of fuzzy controller, which usually have a trapezoid, H type Angle or Gaussian distribution.

② Knowledge base

The knowledge base includes two parts: the database where fuzzy data is stored (input variable, output variable, membership degree) and the rule library where control rules are stored. The establishment of the knowledge base is actually refers to the establishment of the fuzzy controller control rules, the establishment of the rule is based on the operator's long-term practical experience, a series of empirical knowledge is summarized as fuzzy condition control statements. The essence of fuzzy control is to transform the manual control of expert operator into the numerical operation which can be controlled by computer.

As shown in figure 14, let the language variables be A, B, C and D. Where, A, B and C are input and D are output. The diagram (a), (b) and (C) in the fuzzy control rules can be respectively described as:

If A then D

If A and B then D

If A and B and C then D

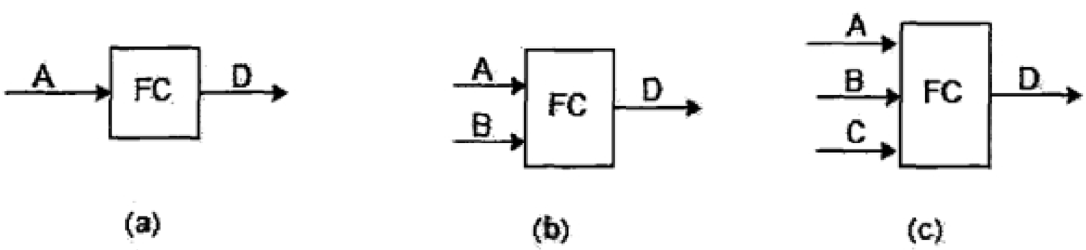


Fig.4.4 Single output fuzzy controller

In figure 14, (a), (b) and (c) are respectively one dimensional, two dimensional and three dimensional fuzzy controllers. Generally speaking, compared with (a) and (b), the performance of controller system (c) is better, but the corresponding calculation amount is also larger. (b) type fuzzy controller is usually used in real systems.

(a), (b) and (c) in Fig. 14 above are fuzzy controllers with only one output. Similarly, a fuzzy controller with multiple inputs and outputs is described by the following conditional statement:

If A1 and A2 …… and Am then U1

If A1 and A2 …… and Am then U2

……

If A1 and A2 …… and Am then Um

In practice, it is more intuitive to use the state table to describe its control rule set.

③ Fuzzy reasoning

The realization of fuzzy reasoning is to combine the input quantity of the system with the established rules, and finally deduce a fuzzy set of output control quantity. Next, a two-dimensional controller is used to explain the process of fuzzy reasoning.

Precondition:

If A=A1 and B=B1 then C=C1

Conditions:

If A=A2 and B=B2

Conclusion:

Then C= ?

The input variables were set as m=m0 and n=n0, and the membership of the output control was obtained by the common Mamdani inference algorithm as follows (43):

$$u_c(C)=\left[u_{A_1}(m_0)\wedge u_{B_1}(n_0)\wedge u_{C_1}(C)\right]\vee\left[u_{A_2}(m_0)\wedge u_{B_2}(n_0)\wedge u_{C_2}(C)\right] \tag{43}$$

Where, above equation (43) the symbol "∧" represents the minimizing operation, and the symbol "∨" represents the maximum operation.

④ Defuzzification

Defuzzification is the process of clarifying (non-fuzzifying) the fuzzy subset obtained by inference. The de-fuzzification algorithm commonly used in practice includes the method of weighted average of variables, the method of maximum membership degree and the method of median number of variables.

The result of weighted average method is:

$$X=\frac{\sum_{i=1}^{n}X_i\times u(X_i)}{\sum_{i=1}^{n}u(X_i)} \tag{44}$$

In equation (44), Xi is the element on the domain X, and u (Xi) is the membership of the corresponding element.

The realization of maximum membership degree method is the output of fuzzy subset theory to maximize the membership degree value domain, when meets the condition of more than one element, we can take the satisfier's average conditional elements or elements after taking the absolute value of maximum (small), then using the median method of defuzzification. We need to select a domain element and divide the resulting membership function curve of the output set into half the area of the X-axis

4.2 DESIGN OF FUZZY PID CONTROLLER

4.2.1 THE PRINCIPLE OF FUZZY PID CONTROLLER

In the actual engineering application, the parameters of traditional PID controller cannot be adjusted in real time, as long as the parameter is determined, it cannot be modified during the control process, this kind of method of PID parameter optimal control is difficult to realize all the working fields of the control object, especially not suitable for ship operation control in the changeable environment, therefore, the classical PID control in the course control system cannot achieve good operation results. The fuzzy PID control introduces the fuzzy idea into the traditional PID control, and three parameters can be adjusted in real time by using the fuzzy thinking.

The deviation and its rate of change are dynamic changes under different sailing conditions, and the real-time modification of PID parameters can adapt the change of their values. As shown in figure 15 block diagram of the overall system, fuzzy PID controller is given by the graph and fuzzy PID controller based on the classical PID control, fuzzy control thinking, joined the R as the expected value, y is the actual output value of the controlled object, the difference and its change rate as input of the fuzzy controller, three PID parameters Kp, Ki, and Kd as output variables, the fuzzy inference is to realize the real-time optimization of the three parameters, finally through the PID output a quantity to control the controlled object

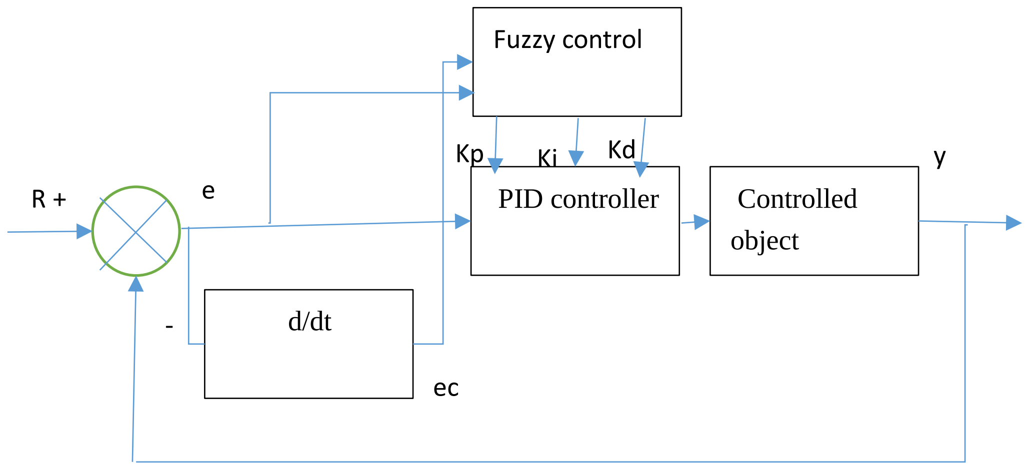


Fig.4.5 System diagram of fuzzy PID controller

4.2.2 DESIGN OF FUZZY PID CONTROLLER

The closed-loop gain shaping algorithm is used to design the controller, and the linear PID controller, as shown in equation (45), can be obtained.

$$K(s)=\frac{1}{3K}+\frac{\varepsilon}{3K}.\frac{1}{s}+\frac{T}{3K}s \tag{45}$$

However, in practical application, it is found that the controller has too long adjustment time for ships with large time constant, such as oil tankers. It shows that the effect of ship course keeping control is significantly improved by adding a positive normal number ρ in the proportion of the control rate. Finally, the actual controller is shown in formula (46), thus the initial value of the PID can be determined.

$$K(s)=\frac{1}{3K}+\rho+\frac{\varepsilon}{3K}.\frac{1}{s}+\frac{T}{3K}s \tag{46}$$

The fuzzy PID adopted in this paper is based on the different values of the input to adjust the parameters of the PID online and real time, so as to achieve better control effect. (Zhang, 2016, p192-198)

1) The determination of fuzzy subsets

The fuzzy part of the fuzzy PID controller takes the course error (*e*) and the rate of course error (*ec*), which has been processed by nonlinear function, as inputs, the adjustment value of PID parameters, ΔK_p , ΔK_i , ΔK_d , as its outputs. The input variable and output variable fuzzy were divided into seven fuzzy subset {big negative (NB), middle negative (NM), small negative (NS), zero (ZE), small positive (PS), middle positive (PM), big positive (PB)}.

2) The determination of fuzzy subset domain and membership function

Fuzzy range of course deviation (*e*) [-30, 30]; Single position: degree.

In order to facilitate analysis, the theoretical domain of deviation e was set as [-6, 6], so the quantization factor was Ke=6/30 = 0.2. The theoretical domain of course deviation rate (*ec*) is [-1, 1]. Unit: degree/second. The theoretical domain of parameter Kp is set as [-30, 30], the theoretical domain of parameter Ki is set as [-0.9, 0.9], and the theoretical domain of parameter Kd is set as [-30, 30].

The function of a variable is to use a normal triangle function.

Open the Fuzzy logic toolbox in Matlab Simulink environment under the Membership function of the editor (the Membership function editor) interface, you can set a variable of subordinate function (the Membership function), and then use Matlab intuitive picture set Membership function curve. The membership function curves of the variables selected in this paper are shown in figure 16 as follows:

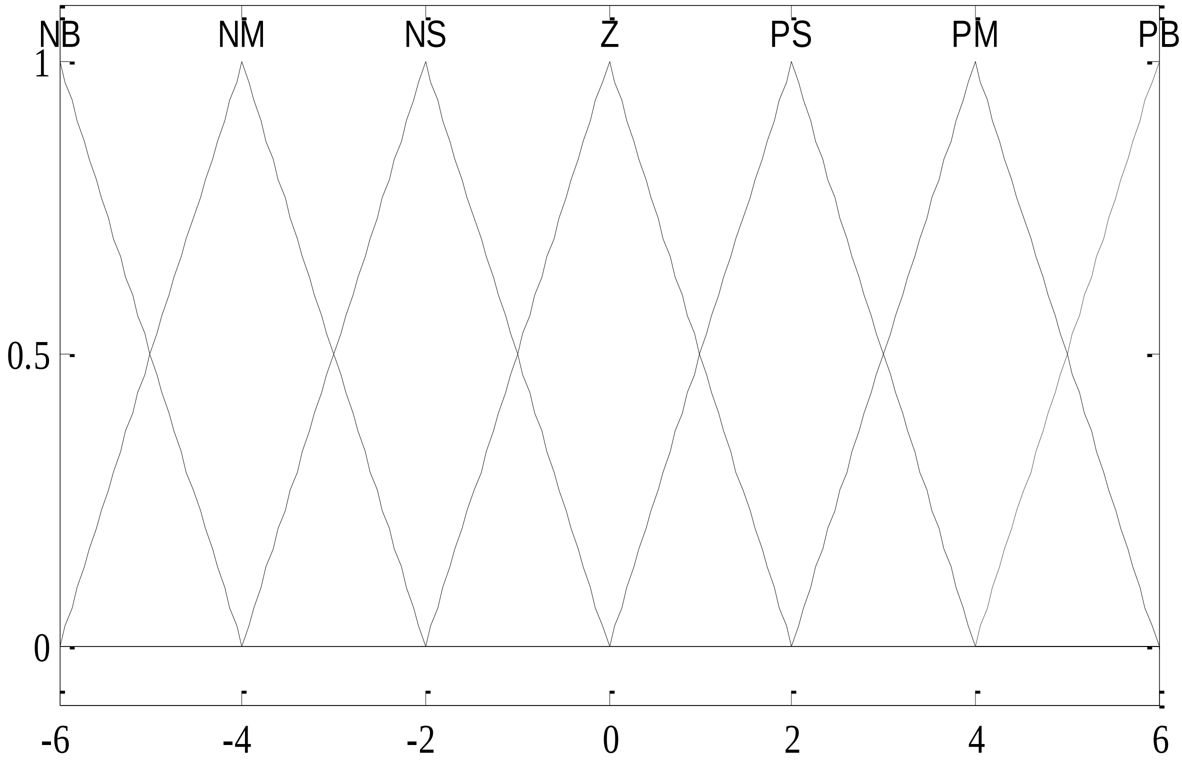


Fig.4.6 Fuzzy membership function

3) Establish control rules of fuzzy controller

According to the experience of the operator, the parameters Kp, Ki and Kd should meet the following principles respectively in the case of different course deviation e and deviation change rate ec:

a) a) Parameter Kp setting principle:
When the actual value is very different from the target value, we can increase the value of Kp, so that the system can adjust to the expected value more quickly. When the actual value is not far from the target value, the value of Kp should be reduced to reduce the overshoot of the system in order to prevent the system from being too shaken.

b) Parameter Ki setting principle:
When the actual value is very different from the target value, integration should not be added in general, and Ki value should be set as zero to avoid the system overshoot caused by the accumulation of errors. When the actual value is close to the target value, the integral action can be added appropriately, and the Ki value increases.

c) Parameter Kd setting principle:
When the difference between the actual value and the expected value is large, the value of Kd should be reduced to avoid differential oversaturation. When the difference between the actual value and the target value is small, the system can obtain good

stability by adding proper differential action, and the value of Kd should be increased. On the basis of expert experience, according to the above setting principle, the table of fuzzy rules needed in the process of fuzzy reasoning can be respectively established as shown in table 4, table 5 and table 6:

Table 4.1: Fuzzy control rules of ΔK_p

e	ec						
	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PM	PM	PB	PB	PB	PM
NM	PB	PM	PM	PB	PM	PS	ZE
NS	PM	PS	ZE	PS	ZE	NS	NM
ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE
PS	NM	NS	ZE	PS	ZE	PS	PM
PM	ZE	PS	PM	PB	PM	PM	PB
PB	PM	PB	PB	PB	PM	PM	PB

Table 4.2: Fuzzy control rules of ΔK_i

e	ec						
	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	ZE	ZE	ZE	ZE	ZE	ZE
NM	ZE	ZE	ZE	ZE	ZE	ZE	ZE
NS	ZE	ZE	PS	PM	PS	ZE	ZE
ZE	ZE	PS	PM	PB	PM	PS	ZE
PS	ZE	ZE	PD	PM	PS	ZE	ZE
PM	ZE	ZE	ZE	ZE	ZE	ZE	ZE
PB	ZE	ZE	ZE	ZE	ZE	ZE	ZE

Table 4.3: Fuzzy control rules of ΔK_d

e	ec						
	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PM	PS	NB	NM	NS	ZE
NM	PB	PM	PS	NM	NS	ZE	ZE
NS	PB	PM	PS	ZE	PS	PM	PB
ZE	PM	PS	ZE	ZE	ZE	PS	PM
PS	PB	PM	PS	ZE	PS	PM	PB
PM	ZE	ZE	NS	NM	PS	PM	PB
PB	ZE	NS	NM	NB	PS	PM	PB

4) Fuzzy reasoning

Fuzzy reasoning uses the common Mamdani reasoning algorithm. Each rule in the table can be expressed as a fuzzy relation Ri (i = 1,2...,49). For example, the formula of R1 in the parameter Kp is as follows (47):

$$R_1 = \left[(NB)_e \times (NB)_{ec}\right]^T \times (PB)_{K_P} \quad (47)$$

According to the above type we can also get other 48 Ri calculation formula, it is concluded that the 49 Ri "and" operation constitutes the general fuzzy relations, as shown in figure 17, the specific formula is as follows:

$$R = R_1 \cup R_2 \cup ... R_{49} = \bigcup_{i=1}^{49} R_i \quad (48)$$

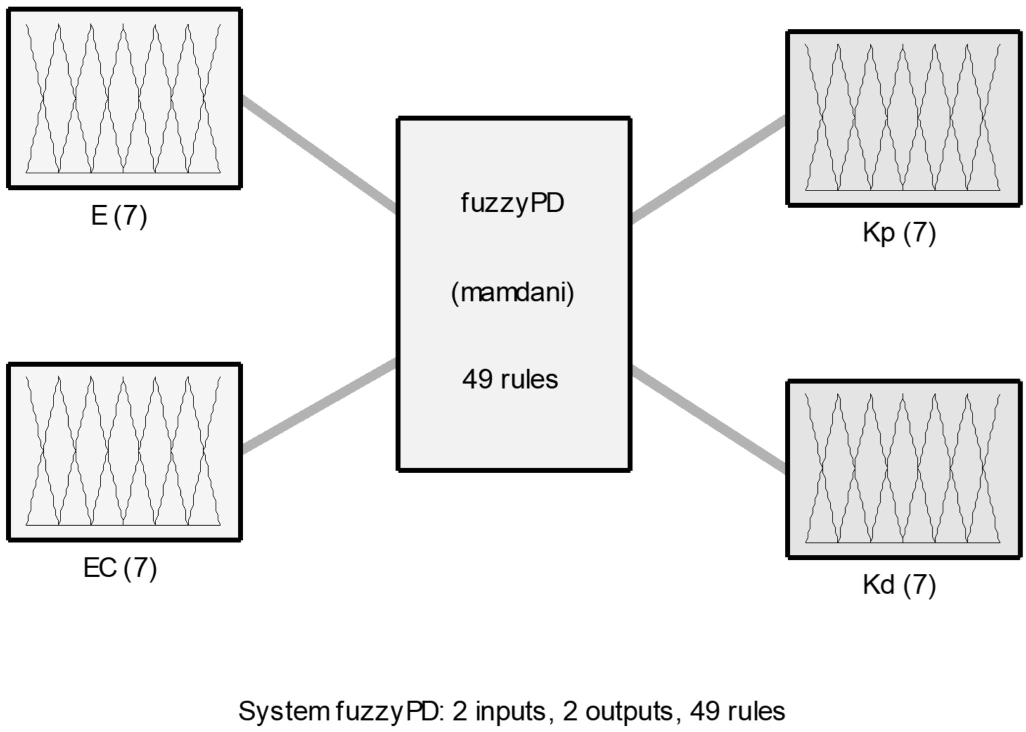


Fig.4.7: Structure of fuzzy system

If the input quantity of the controller is set as e and ec respectively, the control quantity of the parameter Kp is obtained through reasoning as follows:

$$\begin{aligned} k_p &= (e \times e_c) \circ R \\ e \times e_c &= e^T \circ e_c \end{aligned} \quad (49)$$

The operator "∘" refers to the composition of two fuzzy matrices. Fuzzy matrix multiplication and common matrix multiplication calculation method of similar, we only need to put the common matrix multiplication between the elements in the "∧" instead of with A small operation, and then take A big operation "∨" instead of adding operation.

Similarly, the fuzzy control subset of Ki and Kd can be obtained according to the reasoning steps described above.

5) Defuzzification

Through the above reasoning process, a fuzzy subset is obtained. The fuzzy quantity must be processed in order to operate on the control object. In this paper, debarycenter method is used for defuzzification.

4.3 IMPROVED FUZZY PID CONTROLLER BASED ON NFAD TECHNIQUE

In ship motion control, it is generally required to keep the ship's course with small rudder amplitude and slow steering frequency, so as to save energy and reduce the wear of steering gear. Especially under the bad sea condition, the large rudder Angle will cause the ship's roll to increase, and bring the ship running safety hidden danger. Therefore, when designing an automatic rudder control algorithm for ships, the initial rudder Angle and frequency of rudder control should be minimized.

The control applied by conventional closed-loop control is designed according to the difference between the set value and the output of the controlled object. If the error is large, larger control is applied to reduce the output error; if the error is small, smaller control is applied. The output of the controlled object relative to the set value is a kind of feedback, the feedback is linear, the process of doing this research, the authors can consider to use nonlinear feedback, such as the square of error feedback to the controller, the benefits of adoption of error square is: when the error is small, such as when its value is less than 1 square smaller; When the error is large, the square is larger, and the control law may be designed to have better control effect. However, the effect is not ideal when the real ship is used for simulation control. When the original controller is driven by the sine function of error, it is found that although the control effect is not improved, the control energy used is greatly reduced, which is in line with the purpose of this paper. In the course of research, this paper makes a preliminary theoretical discussion and carries out a simulation analysis on the ship's course maintenance.

The nonlinear feedback technique, which is verified by simulation, is processing input of controller with a nonlinear function, as shown in Fig. 18, while the nonlinear decoration technique is from another point of view, which processing the output of the controller with a nonlinear function, as shown in Fig. 19. In this paper, we explore the technique by combining the two methods, and naturally think of the NFAD system structure, as shown in Fig. 20. In this paper, we choose the arctangent function as the nonlinear function after comparison of several simulation experiments, $g(e) = \tanh(\omega_1 e)$, $h(u) = \tanh(\omega_2 u)$, and when ω_1 =0.9, ω_2 =0.8 the comprehensive control effect is the best.

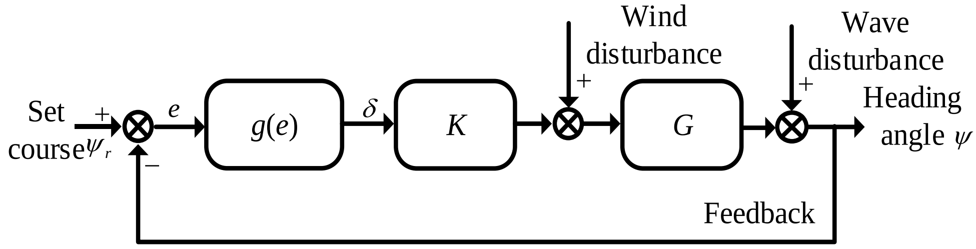


Fig. 4.8: Block diagram of nonlinear feedback system

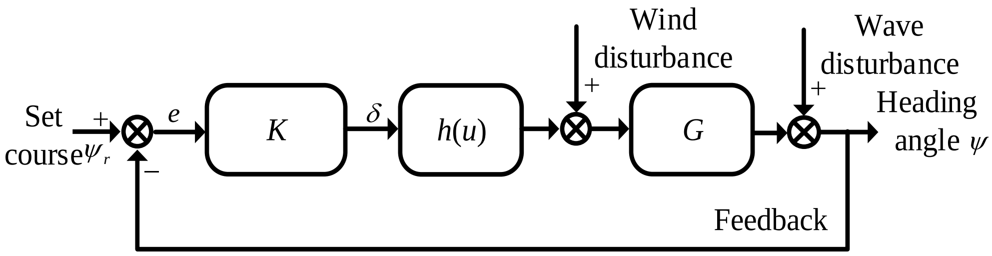


Fig.4.9: Block diagram of nonlinear decoration system

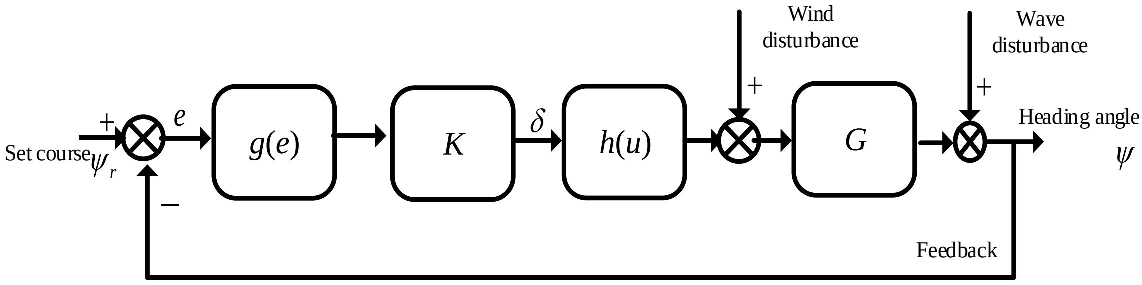


Fig. 4.10: Block diagram of NFAD system

The following is to prove the influence of NFAD technique on closed-loop system.

(1) The influence on the system steady state: If the reference input is a step signal, its amplitude is 50, according to the Taylor series expansion, the formula (50) can be obtained:

$$\tanh \omega_1 e \approx \omega_1 e, \tanh \omega_2 u \approx \omega_2 u \tag{50}$$

According to the final value theorem, the steady state output of the Fig. 7 system is:

$$\begin{aligned}
\psi(\infty) &= \lim_{s\to 0} s \frac{GK\omega_1\omega_2}{1+GK\omega_1\omega_2}\frac{\psi_r}{s} \\
&= \lim_{s\to 0} \frac{\frac{K}{s(Ts+1)}(\frac{1}{3K}+\rho+\frac{\varepsilon}{3T}.\frac{1}{s}+\frac{T}{3K}s)\omega_1\omega_2}{1+\frac{K}{s(Ts+1)}(\frac{1}{3K}+\rho+\frac{\varepsilon}{3T}.\frac{1}{s}+\frac{T}{3K}s)\omega_1\omega_2}\psi_r \\
&= \lim_{s\to 0} \frac{K(T^2s^2+Ks+3KT\rho s+K\varepsilon)\omega_1\omega_2}{3KTs^2(Ts+1)+K(T^2s^2+Ks+3KT\rho s+K\varepsilon)\omega_1\omega_2}\psi_r \\
&= \psi_r
\end{aligned} \tag{51}$$

So the output steady state error of the system is 0, that is, the NFAD technique has no additional influence on the steady state of the system.

(2) The influence on the dynamic performance of the system: the transfer function from the input (ψ_r) to the output (ψ) of the system is:

$$\frac{\psi}{\psi_r} = \frac{GK\omega_1\omega_2}{1+GK\omega_1\omega_2} \tag{52}$$

Known, ω_1<1, ω_2<1, and so $\omega_1\omega_2$<1, according to closed-loop gain shaping theory, the open loop frequency characteristic of the system meets the requirements of low frequency high gain and high frequency low gain, therefore, in the low frequency range, compared with the closed loop transfer function $GK/(1+GK)$, the formula (53) has little influence on the dynamic performance of the system, the addition of $\omega_1\omega_2$ to the system has little effect on the dynamic performance of the system.

(3) The influence on the output of the system: the output transfer function from the input (ψ_r) to the rudder angle (δ) of the controller is:

$$\frac{\delta}{\psi_r} = \frac{K\omega_1\omega_2}{1+GK\omega_1\omega_2} \tag{53}$$

Same as the analysis of formula (52), the magnitude of numerator reduction is larger than that of denominator in formula (53), so the addition of $\omega_1\omega_2$ will reduce the control output.

(4) When *e* and *u* are larger, $\tanh\omega_1 e \approx \omega_1 e$, $\tanh\omega_2 u \approx \omega_2 u$ will no longer be established, it is difficult to prove the influence of NFAD technique in the system, this paper will not discuss it at present.

CHAPTER 5

SIMULATION VERIFICATION AND RESULT ANALYSIS

In the controller, ρ is equal to 2 when simulation happens, the wind and wave disturbance in simulation are also need to be considered. The actual wind can be divided into mean wind and impulse wind. The influence of mean wind can be represented by equivalent rudder angle in simulation, while the impulse wind is replaced by white noise. Assuming that the Beaufort wind scale is 6, wind direction is 100°， ship course is 50° and the equivalent rudder angle is 0.95°, the wave disturbance is simulated by formula (54):

$$y(s) = h(s)w(s) \tag{54}$$

Among them, $w(s)$ is the zero mean Gauss white noise, $h(s)$ is a two order wave transfer function, the $h(s)$ used in this paper is:

$$h(s)=\frac{0.4198s}{s^2+0.3638s+0.3675} \tag{55}$$

The system simulation block diagram is shown in Fig. 21.

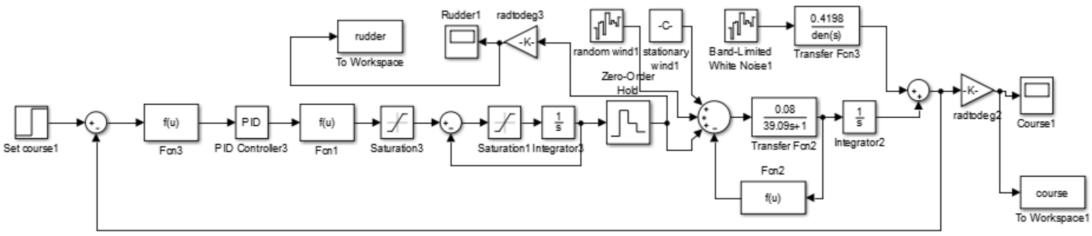


Fig. 5.1: System simulation block diagram

Figure 21 shows the operating mechanism of NFAD. In past experiments, the time interval of each steering is usually set as 6s, that is, 6s controls the rudder once. However, according to the feedback of the actual situation, the 6s steering often causes wear and tear on the equipment and is not conducive to energy saving. So this paper discusses the feasibility of 8s one - time steering.

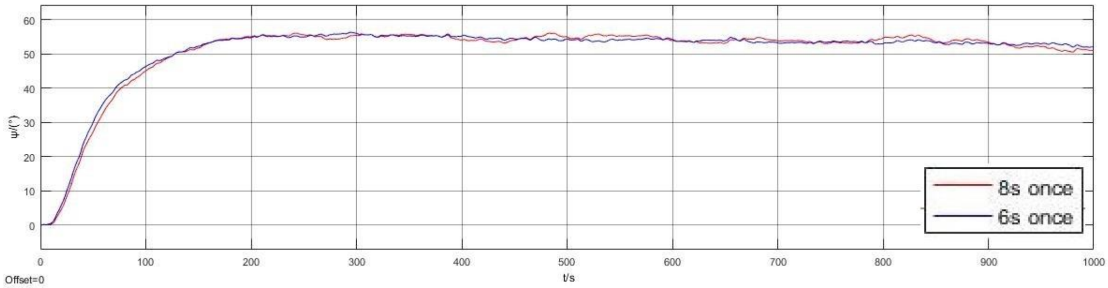


Fig. 5.2: Comparison of course between 8s once and 6s once

Can be found from the figure 22, although at the beginning of the 6 s operating a course to rise faster than 8 s operation, but both eventually reach stable time needed for the course of the basic same, and are relatively fast, about 200 s.

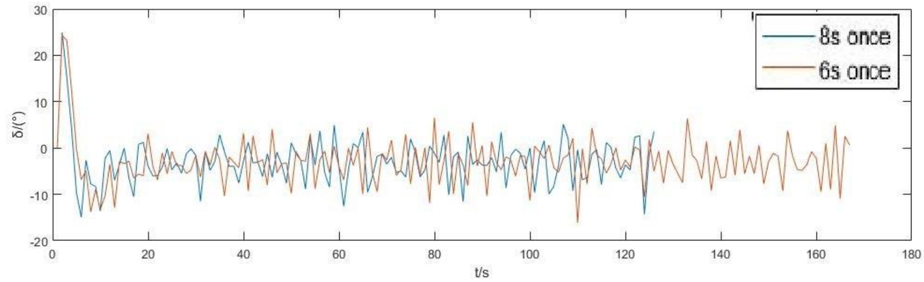


Fig. 5.3: Comparison of rudder angle between 8s once and 6s once

Fig. 23 shows the change of rudder Angle under two steering modes. First of all, it can be seen that the change range of rudder Angle is basically the same under the two kinds of steering modes. At the beginning, both of them operate in a large direction and then adjust in the opposite direction. It can be seen that the length of time interval has little effect on rudder Angle amplitude. It can be found that 8s has performed about 125 operations in one operation, but 6s has performed about 167 operations in one operation, obviously 8s has reduced the number of operations by about 25%.

It can be seen from the results that the increase of time interval has little effect on the operation effect, but the number of steering decreases. It can reduce the wear of steering gear system and the thrust loss when steering. Measured from the representative energy performance indicator function $J = \int \delta^2 dt$ commonly used in the control field, it is $J = \sum_k \delta^2(k)$ after discretization, J of 6s one operation is 6127.88, J of 8s one operation is 4430.05, reduced by 28%

CHAPTER 6

CONCLUSIONS

In this paper, using nonlinear feedback and decoration acts the role of technology to the input and output of fuzzy PID controller for nonlinear process, designing a new ship course-keeping controller, and nurtures the yupeng round simulation experiment was carried out to validate the effectiveness of the new controller, at the same time the original changed from 6 s a steering to 8 s, on the premise of guarantee good course-keeping characteristic, achieved the goal that reduce equipment loss and energy saving, this suggests that the nonlinear feedback acts the role of technology design of ship course-keeping controller has the characteristics of energy saving and strong robustness.

References

Ansari, N., & Hou, E. (1997). Computational Intelligence for Optimization. *Springer US*.

Baker, J. E. (1985). Adaptive Selection Methods for Genetic Algorithms. *Proc. First International Conference on Genetic Algorithms and Their Applications (Vol.263, pp.867-872).*

Clarke, D. P., Gedling, P., & Hine, G. (1983). The application of manoeuvring criteria in hull design using linear theory. *Naval Architect, 125*, 45-68.

Dovgobrod, G. M. (2012). Development of an adaptive algorithm for ship motion control on a nonlinear path. *Gyroscopy & Navigation, 3(1),* 41-46.

Du, J., Abraham, A., Yu, S., & Zhao, J. (2014). Adaptive dynamic surface control with nussbaum gain for course-keeping of ships. *Engineering Applications of Artificial Intelligence, 27(1)*, 236-240.

Feng Tiecheng. (1980). Ship sway and control. *National defense industry press*.

Fan Yunsheng, Mu Dongdong, Zhang Xianku, Wang Guofeng & Guo Chen. (2018). Course keeping control based on integrated nonlinear feedback for a USV with POD-like propulsion. *Journal of Navigation*, 1-21.

Fan Sheming, Zhu Weimin & Li Zhichun. (1999). Prediction method for ship maneuverability based on artificial neural networks. *Shipbuilding of China*.

Harl, N., & Balakrishnan, S. N. (2012). Impact time and angle guidance with sliding mode control. *IEEE Transactions on Control Systems Technology, 20(6)*, 1436-1449.

Hu Yaohua, & Jia xinle. (1998). Generalized predictive control applied to ship course and track maintenance. *China shipbuilding (1)*, 36-41.

He Yubin, Xu Liqin, Yan Guirong, & Xu Jianxue. (1998). Neural network self-learning PSD control of electro-hydraulic servo coordinated loading system. *Machine tool and hydraulic (3)*, 3-4.

He Yubin, & li Xinzhong. (2000). Neural network control technology and its application. *Science press.*

Holzhü, & Ter, T. (1997). LQG approach for the high-precision track control of ships. , 144(2), 121-127.

Jin Hongzhang. (1987). Real-time simulation and spectrum analysis of long peak wave random waves. *Marine engineering (1)*, 24-30.

Jia Xinle & Zhang Xianku. (2015). Wind equivalent rudder Angle and its application. *China shipbuilding (3)*, 116-123.

Jia Xinle & Zhang Xianku. (2002). Intelligent control of ship motion and H∞ infinity robust control. *Dalian maritime university press*.

J. Van Amerongen. (1982). Adaptive steering of ships: a model-reference approach to improved manoeuvring and economical course keeping. *Electrical Engineering Mathematics & Computer Science.*

J. Van Amerongen & Van Lemke, H. R. (1980). Criteria for optimum steering of ships.

Li Bing, Fang Min & Wang Hongbo. (2006). Design and implementation of fuzzy PID level control system. *Journal of Hefei university of technology (natural science edition)*, 29(11), 1370-1374.

Li Guoyong & Xie Keming. (2005). Digital simulation and CAD of control system. *Electronic industry press*.

Li Yanxiong, Zhang Xue, Li Xianku, Zhang Yuhan, Yang Jichen & He Qianhua. (2018). Mobile phone clustering from speech recordings using deep representation and spectral clustering. *IEEE Transactions on Information Forensics & Security*, 13(4), 965-977.

Liu Cheng, Zou Zaojian, & Li Tieshan. (2013). Ship autopilot control based on combined backstepping and sliding-mode technique. *Icic Express Letters Part B Applications An International Journal of Research & Surveys, 4*, 225-230.

Liu Xiuwen, Yin Yong, Jin Yicheng & Zhang Xinyu. (2010). Design radar signal interface for navigation Radar/ARPA simulator using radar display. *Circuits, communications and System (Vol.1, pp.442-445)*. IEEE.

Nguyen, D. H., & Widrow, B. (2002). Neural networks for self-learning control systems. *International Journal of Control*, 10(3), 18-23.

Nomoto, K., Taguchi, K., Honda, K., & Hirano, S. (1957). On the steering qualities of ships. *International Shipbuilding Progress*, 4(35), 354-370.

Nicolau, V. (2007). Neuro-Fuzzy System for Intelligent Course Control of Underactuated Conventional Ships. *International Workshop on Soft Computing Applications* (pp.95-101). IEEE.

Park, J. Y., & Kim, N. (2014). Design of an adaptive backstepping controller for auto-berthing a cruise ship under wind loads. *International Journal of Naval Architecture & Ocean Engineering*, 6(2), 347-360.

Ren, J., & Liu, L. (2013). Adaptive neural network control for ship steering system using filtered backstepping design. *Journal of Applied Sciences*, 13(10), 1691-1697.

Sun Shuai. (2016). Design of Fuzzy Controlled Fin Stabilizer Based on RBF Neural Network. *Dalian maritime university*. P.8-11: Unpublished doctoral dissertation

Witkowska, A., Tomera, M., & Mierzchalski, R. (2007). A backstepping approach to ship course control. *International Journal of Applied Mathematics & Computer Science*, 17(1), 73-85.

Wang Ning. (1992). Intelligent control of adaptive neural networks. *Information and control*, 21(4), 235-239.

Wang Shunhuang, & Shudi Qian. (2005). Intelligent control system and its application, (second edition). *Machinery industry press.*

Xiao Fangbing, Jin Yicheng, Yin Yong & Li Yongjin. (2010). *Design and Research of Marine Search and Rescue Simulation System*. IEEE Computer Society.

Yang Yansheng, Yu Xiaoli, & Jia Xinle. (1999). Design of robust PID automatic rudder of ship course. *Journal of Dalian maritime university*, 25(4), 11-15.

Yao Zhang, Hearn, G. E., & Sen, P. (1996). A neural network approach to ship track-keeping control. Oceanic Engineering IEEE Journal of, 21(4), 513-527.

Zhang Guoqing & Zhang XianKu. (2014). Concise robust adaptive path-following control of under actuated ships using DSC and MLP. *IEEE Journal of Oceanic Engineering*, 39(4), 685-694.

Zhang Guoqing, Zhang XianKu & Wei Guan. (2014). Concise robust adaptive path-following control for under actuated ships. *Journal of Harbin Engineering University*, 35(9), 1053-1059.

Zheng Mukun, li Lina, & Chen guoquan. (2017). Performance test and optimization of fuzzy self-tuning PID course control algorithm. *Journal of Jimei University (natural science edition)*, 22(2), 25-30.

Zhang Qiang, Zhang XianKu & Nam-kyun Im. (2017). Ship nonlinear-feedback course keeping algorithm based on MMG model driven by bipolar sigmoid function for berthing.

International Journal of Naval Architecture & Ocean Engineering, 9(5).

Zhang Qiang, Zhang XianKu, University, D. M. & University, S. J. (2016). A ship maneuvering model and application in harbor considering reversing characteristics of propeller. *Shipbuilding of China*.

Zhang Weihua, & Zhao Mingjun. (2005). Effects of dimensionless method on reliability of comprehensive evaluation results and its empirical analysis. *Statistics and information BBS*, 20(3), 33-36.

Zhang Xianku. (2010) Nonlinear control for ship course-keeping based on Lyapunov stability [J]. *Journal of Southwest Jiaotong University*, 2010, 45(1): 140-143.

Zhang Xianku. Modeling and digital simulation for control systems[M]. *Dalian Maritime University Press*, 2013.

Zhang Xianku, & Jia Xinle. (2006). Ship motion control. *National defense industry press.*

Zhang Xianku. (2010). Ship control system. *Dalian maritime university.*

Zhang Xianku, Ren Junsheng & Zhang Xiufeng. (2014). Ship modeling and control. *Dalian maritime university press*.

Zhang Xianku, Zhang Guoqing. (2016). Design of ship course-keeping autopilot using a sine function-based nonlinear feedback technique [J]. *The Journal of Navigation*, 2016, 69, 246-256.

Zhang Xianku, Zhang Guoqing, Zhang Shuhui. (2013). Researches on the Williamson turn for very large carriers. *Naval Engineers Journal*, 125(4).

Zhang Xianku, Feng Yongxiao. (2017). Control algorithm of YUPENG ship autopilot based on tangent function nonlinear feedback[J].*Journal of Measurement Science and Instrumentation*.2017,8(1): 73-78.

Zhang Xianku, Yang Guangping, Zhang Qiang & University, D. M. (2016). A kind of bipolar sigmoid function decorated nonlinear ship course keeping algorithm. *Journal of Dalian Maritime University*.

Zhang XianKu, Zhang Qiang, Ren Hongxiang,Yang Guangping (2018). Linear reduction of backstepping algorithm based on nonlinear decoration for ship course-keeping control system. *Ocean Engineering* 147, 2018,1-8

Zhang XianKu & Zhang Guoqing. (2013). Stabilization of pure unstable delay systems by the mirror mapping technique. *Journal of Process Control*, 23(10), 1465-1470.

Zhang XianKu & Jin Yicheng. (2007). Mathematical model of nonlinear responding ship motion for car carrier. *Journal of Harbin Engineering University*.

Zhang XianKu, Hong Biguang, Jin Yicheng & Yin Yong. (2006). Simulating test of ship navigation safety evaluation using ship handling simulator. *Oceans* (pp.1902-1905 Vol. 2). IEEE.

Zhang XianKu, Jin Yicheng, Yin Yong & Ren Hongxiang. (2012). Ship motion modeling and simulation in Ship Handling Simulator. *International Conference on Audio, Language and Image Processing* (Vol.12, pp.1051-1056). IEEE.

Zhang Zhiheng, Zhang XianKu & Zhang Guoqing. (2017). Nonlinear Response Mathematical Model of YUPENG Ship. *Chinese Control Conference (international)* (pp.4688-4691).

APPENDIX

1 VC CODE TO CALCULATE K, T INDEX, AND PARAMETERS OF SHIPS

```
Double m_dLpp;
Double m_dBreadth;
Double m_dDraft;
Double m_dCb;
Double m_dDisplacement;
Double m_dSpeed;
Double m_dXc;
Double m_dRudderArea;

OnShipData()
{
   CShipData dlg;
   dlg.m_dBreadth            =ShipBreath;
   dlg.m_dCb                 =ShipCb;
   dlg.m_dDisplacement       =displacement;
   dlg.m_dDraft              =ShipDraft;
   dlg.m_dLpp                =ShipLength;
   dlg.m_dRudderArea         =RudderArea;
   dlg.m_dSpeed              =DesignSpeed;
   dlg.m_dXc                 =ShipXc;
   if(dlg.DoModal()==IDOK)
   {
   ShipBreath                =dlg.m_dBreadth;
   ShipCb                    =dlg.m_dCb;
   displacement              = dlg.m_dDisplacement;
   ShipDraft                 =dlg.m_dDraft;
   ShipLength                =dlg.m_dLpp;
   RudderArea                =dlg.m_dRudderArea;
   DesignSpeed               =dlg.m_dSpeed;
   ShipXc                    =dlg.m_dXc;
   }
}

OnShipKT()
{
   double   a11,a12,a21,a22;
   double   b11,b21;
   double   L,B,dm,Cb,Xc,m,Ar;
   double   V,S;
   double   Yv l _ l,Yr l _ l,Nv l _ l,Nr l _ l,Yv_ l,Yr_ l Nv_ l, Yrudder_ l, Nrudder_l;
   double   dYv_l, dYr_l, dNv_l, dNr_l;
   double   WaterDensity = 1.025;
   double   m_l, Xc_l;
   L=ShipLength;
   B=ShipBreadth;
   dm=ShipDraft;
   Cb=ShipCb;
   Ar=RudderArea;
   Xc=ShipXc;
   m=displacement*WaterDensity;   // m^3
   V=DesignSpeed;
   m_l     = m/(05*WaterDensity*L*L*L);
   Xc_l    = Xc/L;
   Yvl_l = -(1+016*Cb*B/dm-51*(B/L)*(B/L))*pi*(dm/L)*(dm/L);
   Yrl_l = -(067*B/L-00033*((B/dm)^2))*pi*((dm/L)^2);
   Nvl_l = -(11*B/L-0041*B/dm)*pi*((dm/L)^2);
   Nrl_l = -(1/12+0017*Cb*B/dm-033*B/L)*pi*((dm/L)^2);
   Yv_l    = -(1+04*Cb*B/dm)*pi*((dm/L)^2);
   Yr_l    = -(-05+22*B/L-0080*B/dm)*pi*((dm/L)^2);
   Nv_l    = -(05+24*dm/L)*pi*((dm/L)^2);
   Nr_l    = -(025+0039*B/dm-056*B/L)*pi*((dm/L)^2);
   Yrudder_l = 3*Ar/L/L;
   Nrudder_l = -(05)*Yrudder_l;
   lzz = m*L*L/16.0;
   lzz_l = lzz/(05*WaterDensity*(L^5));
   dYv_l = -03*Yrudder_l;
   dYr_l = -05*dYv_l;
   dNv_l = -05*dYv_l;
   dNr_l = 025*dYv_l;
   Yv_l    = Yv_l+dYv_l;
   Yr_l    = Yr_l+dYr_l;
   Nv_l    = Nv_l+dNv_l;
   Nr_l    = Nr_l+dNr_l;
```

```
    S = ((Izz_l-Nrl_l)*(m_l-Yvl_l)-(m_l*Xc_l-Nvl_l)*(m_l*Xc_l-Yrl_l))*L;
    a11 = ((Izz_l-Nrl_l)*Yv_l-(m_l*Xc_l-Yrl_l)*Nv_l)*V/S;
    a12 = ((Izz_l-Nrl_l)*(Yr_l-m_l)-(m_l*Xc_l-Yrl_l)*(Nr_l-m_l*Xc_l))*L*V/S;
    a21 = (-(m_l*Xc_l-Nvl_l)*Yv_l+(m_l-Yvl_l)*Nv_l)*V/L/S;
    a22 = (-(m_l*Xc_l-Nvl_l)*(Yr_l-m_l)+(m_l-Yvl_l)*(Nr_l-m_l*Xc_l))*V/S;
    b11 = ((Izz_l-Nrl_l)*Yrudder_l+(m_l*Xc_l-Yrl_l)*Nrudder_l)*V*V/S;
    b21 = (-(m_l*Xc_l-Nvl_l)*Yrudder_l+(m_l-Yrl_l)*Nrudder_l)*V*V/L/S;
    dK    = (b11*a21-b21*a11)/(a11*a22-a12*a21);
    dT    = -(a11+a22)/(a11*a22-a12*a21)-b21/(b11*a21-b21*a11);
    CShipKT ktdlg;
    Ktdlg.m_dShipK=dK;
    Ktdlg.m_dShipT=dT;
    Ktdlg.m_dShipKK=dK/(V/L);
    Ktdlg.m_dShipTT=dT(L/V);
    Ktdlg.DoModal();
}
```

2 IMPROVED FUZZY PID CONTROLLER BASED ON NFAD TECHNIQUE BASED ON MATLAB

```
Model {
    Name                    "backstep56"
    Version             8.7
    MdlSubVersion           1
    SavedCharacterEncoding    "GBK"
    GraphicalInterface {
        NumRootInports          0
        NumRootOutports         0
        ParameterArgumentNames    ""
        ComputedModelVersion       "1.407"
        NumModelReferences          0
        NumTestPointedSignals     0
        NumProvidedFunctions       0
        NumRequiredFunctions       0
    }
    ScopeRefreshTime       0.035000
    OverrideScopeRefreshTime on
    DisableAllScopes       on
    DataTypeOverride       "UseLocalSettings"
    DataTypeOverrideAppliesTo "AllNumericTypes"
    MinMaxOverflowLogging     "UseLocalSettings"
    MinMaxOverflowArchiveMode "Overwrite"
    FPTRunName                  "Run 1"
    MaxMDLFileLineLength       120
    LastSavedArchitecture      "win64"
    Object {
        $PropName                   "BdWindowsInfo"
        $ObjectID                 1
        $ClassName                  "Simulink.BDWindowsInfo"
        Object {
            $PropName                   "WindowsInfo"
            $ObjectID                 2
            $ClassName                  "Simulink.WindowInfo"
            IsActive                  [1]
            Location                    [309.0, 274.0, 1208.0, 525.0]
            Object {
        $PropName           "ModelBrowserInfo"
        $ObjectID           3
        $ClassName          "Simulink.ModelBrowserInfo"
        Visible             [0]
        DockPosition             "Left"
        Width                 [50]
        Height                [50]
        Filter              [9]
            }
            Object {
        $PropName           "ExplorerBarInfo"
        $ObjectID           4
        $ClassName          "Simulink.ExplorerBarInfo"
        Visible             [1]
            }
            Object {
        $PropName           "EditorsInfo"
        $ObjectID           5
        $ClassName          "Simulink.EditorInfo"
        IsActive            [1]
        ViewObjType         "SimulinkTopLevel"
```

```
    LoadSaveID          "0"
    Extents             [1158.0, 347.0]
    ZoomFactor          [0.91115498519249738]
    Offset              [-102.74011375947998, -30.253656554712904]
      }
    }
}
Created              "Sat Sep 28 10:27:15 2002"
Creator              "lenovo"
UpdateHistory           "UpdateHistoryNever"
ModifiedByFormat        "%<Auto>"
LastModifiedBy          "66666"
ModifiedDateFormat         "%<Auto>"
LastModifiedDate       "Sat Jun 16 14:18:04 2018"
RTWModifiedTimeStamp       451059315
ModelVersionFormat          "1.%<AutoIncrement:407>"
ConfigurationManager       "none"
SampleTimeColors      off
SampleTimeAnnotations     off
LibraryLinkDisplay         "none"
WideLines          off
ShowLineDimensions         off
ShowPortDataTypes     off
ShowEditTimeErrors         on
ShowEditTimeWarnings      off
ShowEditTimeAdvisorChecks off
ShowPortUnits          off
ShowDesignRanges       off
ShowLoopsOnError       on
IgnoreBidirectionalLines off
ShowStorageClass       off
ShowTestPointIcons         on
ShowSignalResolutionIcons on
ShowViewerIcons        on
SortedOrder            off
VariantCondition      off
ExecutionContextIcon       off
ShowLinearizationAnnotations on
ShowVisualizeInsertedRTB on
ShowMarkup             on
BlockNameDataTip       off
BlockParametersDataTip    off
BlockDescriptionStringDataTip off
ToolBar             on
StatusBar           on
BrowserShowLibraryLinks off
FunctionConnectors         off
BrowserLookUnderMasks     off
SimulationMode          "normal"
PauseTimes              "5"
NumberOfSteps           1
SnapshotBufferSize         10
SnapshotInterval       10
NumberOfLastSnapshots     0
LinearizationMsg       "none"
Profile             off
ParamWorkspaceSource       "MATLABWorkspace"
AccelSystemTargetFile     "accel.tlc"
AccelTemplateMakefile     "accel_default_tmf"
AccelMakeCommand       "make_rtw"
TryForcingSFcnDF       off
Object {
    $PropName              "DataLoggingOverride"
    $ObjectID              6
    $ClassName             "Simulink.SimulationData.ModelLoggingInfo"
    model_              "backstep56"
    Array {
      Type               "Cell"
      Dimension              1
      Cell               "backstep56"
      PropName               "logAsSpecifiedByModels_"
    }
    Array {
      Type               "Cell"
      Dimension              1
      Cell               ""
      PropName               "logAsSpecifiedByModelsSSIDs_"
    }
}
ExtModeBatchMode       off
ExtModeEnableFloating     on
ExtModeTrigType        "manual"
ExtModeTrigMode        "normal"
ExtModeTrigPort        "1"
ExtModeTrigElement         "any"
ExtModeTrigDuration       1000
ExtModeTrigDurationFloating "auto"
```

```
ExtModeTrigHoldOff          0
ExtModeTrigDelay       0
ExtModeTrigDirection       "rising"
ExtModeTrigLevel       0
ExtModeArchiveMode          "off"
ExtModeAutoIncOneShot     off
ExtModeIncDirWhenArm       off
ExtModeAddSuffixToVar     off
ExtModeWriteAllDataToWs off
ExtModeArmWhenConnect     on
ExtModeSkipDownloadWhenConnect off
ExtModeLogAll            on
ExtModeAutoUpdateStatusClock on
ShowModelReferenceBlockVersion off
ShowModelReferenceBlockIO off
Array {
   Type                    "Handle"
   Dimension                  1
   Simulink.ConfigSet {
      $ObjectID                  7
      Version                     "1.16.2"
      Array {
   Type                    "Handle"
   Dimension           9
   Simulink.SolverCC {
      $ObjectID            8
      Version               "1.16.2"
      StartTime            "0.0"
      StopTime              "3000.0"
      AbsTol                "auto"
      FixedStep            "0.1"
      InitialStep              "auto"
      MaxNumMinSteps          "-1"
      MaxOrder             5
      ZcThreshold                "auto"
      ConsecutiveZCsStepRelTol "10*128*eps"
      MaxConsecutiveZCs     "1000"
      ExtrapolationOrder          4
      NumberNewtonIterations    1
      MaxStep                "auto"
      MinStep               "auto"
      MaxConsecutiveMinStep     "1"
      RelTol                "1e-3"
      SolverMode                "Auto"
      EnableConcurrentExecution off
      ConcurrentTasks        off
      Solver                "ode45"
      SolverName                 "ode45"
      SolverJacobianMethodControl "auto"
      ShapePreserveControl       "DisableAll"
      ZeroCrossControl       "UseLocalSettings"
      ZeroCrossAlgorithm          "Nonadaptive"
      AlgebraicLoopSolver        "TrustRegion"
      SolverInfoToggleStatus    off
      IsAutoAppliedInSIP          off
      SolverResetMethod     "Fast"
      PositivePriorityOrder     off
      AutoInsertRateTranBlk     off
      SampleTimeConstraint       "Unconstrained"
      InsertRTBMode            "Whenever possible"
   }
   Simulink.DataIOCC {
      $ObjectID            9
      Version               "1.16.2"
      Decimation                 "1"
      ExternalInput           "[t, u]"
      FinalStateName          "xFinal"
      InitialState             "xInitial"
      LimitDataPoints         on
      MaxDataPoints            "1000"
      LoadExternalInput     off
      LoadInitialState       off
      SaveFinalState          off
      SaveCompleteFinalSimState off
      SaveFormat                 "Array"
      SignalLoggingSaveFormat "ModelDataLogs"
      SaveOutput                 on
      SaveState           off
      SignalLogging           on
      DSMLogging                 on
      InspectSignalLogs     off
      VisualizeSimOutput          on
      StreamToWorkspace     off
      StreamVariableName          "streamout"
      SaveTime              on
      ReturnWorkspaceOutputs    off
      StateSaveName            "xout"
```

```
    TimeSaveName             "tout"
    OutputSaveName           "yout"
    SignalLoggingName      "sigsOut"
    DSMLoggingName           "dsmout"
    OutputOption             "RefineOutputTimes"
    OutputTimes              "[]"
    ReturnWorkspaceOutputsName "out"
    Refine                 "1"
    LoggingToFile          off
    LoggingFileName        "out.mat"
    LoggingIntervals       "[-inf, inf]"
  }
  Simulink.OptimizationCC {
    $ObjectID          10
    Version            "1.16.2"
    Array {
      Type                "Cell"
      Dimension              8
      Cell                "BooleansAsBitfields"
      Cell                "PassReuseOutputArgsAs"
      Cell                "PassReuseOutputArgsThreshold"
      Cell                "ZeroExternalMemoryAtStartup"
      Cell                "ZeroInternalMemoryAtStartup"
      Cell                "OptimizeModelRefInitCode"
      Cell                "NoFixptDivByZeroProtection"
      Cell                "UseSpecifiedMinMax"
      PropName                "DisabledProps"
    }
    BlockReduction         off
    BooleanDataType        off
    ConditionallyExecuteInputs on
    DefaultParameterBehavior "Tunable"
    UseDivisionForNetSlopeComputation "off"
    UseFloatMulNetSlope        off
    DefaultUnderspecifiedDataType "double"
    UseSpecifiedMinMax          off
    InlineInvariantSignals   off
    OptimizeBlockIOStorage   on
    BufferReuse              on
    EnhancedBackFolding        off
    CachingGlobalReferences off
    GlobalBufferReuse     on
    StrengthReduction     off
    ExpressionFolding     on
    BooleansAsBitfields        off
    BitfieldContainerType     "uint_T"
    EnableMemcpy              on
    MemcpyThreshold        64
    PassReuseOutputArgsAs     "Structure reference"
    PassReuseOutputArgsThreshold 12
    ExpressionDepthLimit      128
    LocalBlockOutputs     on
    RollThreshold           5
    StateBitsets            off
    DataBitsets             off
    ActiveStateOutputEnumStorageType "Native Integer"
    ZeroExternalMemoryAtStartup on
    ZeroInternalMemoryAtStartup on
    InitFltsAndDblsToZero     off
    NoFixptDivByZeroProtection off
    EfficientFloat2IntCast   off
    EfficientMapNaN2IntZero on
    OptimizeModelRefInitCode off
    LifeSpan             "inf"
    MaxStackSize             "Inherit from target"
    BufferReusableBoundary   on
    SimCompilerOptimization "off"
    AccelVerboseBuild     off
  }
  Simulink.DebuggingCC {
    $ObjectID          11
    Version            "1.16.2"
    RTPrefix           "error"
    ConsistencyChecking        "none"
    ArrayBoundsChecking        "none"
    SignalInfNanChecking      "none"
    SignalRangeChecking        "none"
    ReadBeforeWriteMsg          "UseLocalSettings"
    WriteAfterWriteMsg          "UseLocalSettings"
    WriteAfterReadMsg     "UseLocalSettings"
    AlgebraicLoopMsg      "warning"
    ArtificialAlgebraicLoopMsg "warning"
    SaveWithDisabledLinksMsg "warning"
    SaveWithParameterizedLinksMsg "none"
    CheckSSInitialOutputMsg on
    UnderspecifiedInitializationDetection "Classic"
    MergeDetectMultiDrivingBlocksExec "none"
```

```
    CheckExecutionContextPreStartOutputMsg off
    CheckExecutionContextRuntimeOutputMsg off
    SignalResolutionControl "TryResolveAllWithWarning"
    BlockPriorityViolationMsg "warning"
    MinStepSizeMsg          "warning"
    TimeAdjustmentMsg       "none"
    MaxConsecutiveZCsMsg    "error"
    MaskedZcDiagnostic      "warning"
    IgnoredZcDiagnostic     "warning"
    SolverPrmCheckMsg       "none"
    InheritedTsInSrcMsg     "warning"
    MultiTaskDSMMsg         "warning"
    MultiTaskCondExecSysMsg "none"
    MultiTaskRateTransMsg   "error"
    SingleTaskRateTransMsg  "none"
    TasksWithSamePriorityMsg "warning"
    SigSpecEnsureSampleTimeMsg "warning"
    CheckMatrixSingularityMsg "none"
    IntegerOverflowMsg      "warning"
    Int32ToFloatConvMsg     "warning"
    ParameterDowncastMsg    "error"
    ParameterOverflowMsg    "error"
    ParameterUnderflowMsg   "none"
    ParameterPrecisionLossMsg "warning"
    ParameterTunabilityLossMsg "warning"
    FixptConstUnderflowMsg  "none"
    FixptConstOverflowMsg   "none"
    FixptConstPrecisionLossMsg "none"
    UnderSpecifiedDataTypeMsg "none"
    UnnecessaryDatatypeConvMsg "none"
    VectorMatrixConversionMsg "none"
    InvalidFcnCallConnMsg   "error"
    FcnCallInpInsideContextMsg "EnableAllAsError"
    SignalLabelMismatchMsg  "none"
    UnconnectedInputMsg     "warning"
    UnconnectedOutputMsg    "warning"
    UnconnectedLineMsg      "warning"
    SFcnCompatibilityMsg    "none"
    FrameProcessingCompatibilityMsg "error"
    UniqueDataStoreMsg      "none"
    BusObjectLabelMismatch  "warning"
    RootOutportRequireBusObject "warning"
    AssertControl           "UseLocalSettings"
    AllowSymbolicDim        on
    ModelReferenceIOMsg     "none"
    ModelReferenceMultiInstanceNormalModeStructChecksumCheck "error"
    ModelReferenceVersionMismatchMessage "none"
    ModelReferenceIOMismatchMessage "none"
    UnknownTsInhSupMsg      "warning"
    ModelReferenceDataLoggingMessage "warning"
    ModelReferenceSymbolNameMessage "warning"
    ModelReferenceExtraNoncontSigs "error"
    StateNameClashWarn      "none"
    SimStateInterfaceChecksumMismatchMsg "warning"
    SimStateOlderReleaseMsg "error"
    InitInArrayFormatMsg    "warning"
    StrictBusMsg            "ErrorLevel1"
    BusNameAdapt            "WarnAndRepair"
    NonBusSignalsTreatedAsBus "none"
    SymbolicDimMinMaxWarning "warning"
    LossOfSymbolicDimsSimulationWarning "warning"
    LossOfSymbolicDimsCodeGenerationWarning "error"
    BlockIODiagnostic       "none"
    SFUnusedDataAndEventsDiag "warning"
    SFUnexpectedBacktrackingDiag "warning"
    SFInvalidInputDataAccessInChartInitDiag "warning"
    SFNoUnconditionalDefaultTransitionDiag "warning"
    SFTransitionOutsideNaturalParentDiag "warning"
    SFUnconditionalTransitionShadowingDiag "warning"
    SFUndirectedBroadcastEventsDiag "warning"
    SFTransitionActionBeforeConditionDiag "warning"
    SFOutputUsedAsStateInMooreChartDiag "error"
    IntegerSaturationMsg    "warning"
    AllowedUnitSystems      "all"
    UnitsInconsistencyMsg   "warning"
    AllowAutomaticUnitConversions on
  }
  Simulink.HardwareCC {
    $ObjectID               12
    Version                 "1.16.2"
    ProdBitPerChar          8
    ProdBitPerShort         16
    ProdBitPerInt           32
    ProdBitPerLong          32
    ProdBitPerLongLong      64
    ProdBitPerFloat         32
    ProdBitPerDouble        64
```

```
    ProdBitPerPointer      32
    ProdLargestAtomicInteger "Char"
    ProdLargestAtomicFloat    "None"
    ProdIntDivRoundTo      "Undefined"
    ProdEndianess             "Unspecified"
    ProdWordSize              32
    ProdShiftRightIntArith    on
    ProdLongLongMode       off
    ProdHWDeviceType       "32-bit Generic"
    TargetBitPerChar       8
    TargetBitPerShort      16
    TargetBitPerInt        32
    TargetBitPerLong       32
    TargetBitPerLongLong       64
    TargetBitPerFloat      32
    TargetBitPerDouble         64
    TargetBitPerPointer        32
    TargetLargestAtomicInteger "Char"
    TargetLargestAtomicFloat "None"
    TargetShiftRightIntArith on
    TargetLongLongMode          off
    TargetIntDivRoundTo         "Undefined"
    TargetEndianess         "Unspecified"
    TargetWordSize          32
    TargetPreprocMaxBitsSint 32
    TargetPreprocMaxBitsUint 32
    TargetHWDeviceType          "Specified"
    TargetUnknown            on
    ProdEqTarget             on
    UseEmbeddedCoderFeatures on
    UseSimulinkCoderFeatures on
  }
  Simulink.ModelReferenceCC {
    $ObjectID            13
    Version              "1.16.2"
    UpdateModelReferenceTargets "IfOutOfDateOrStructuralChange"
    EnableRefExpFcnMdlSchedulingChecks on
    CheckModelReferenceTargetMessage "error"
    EnableParallelModelReferenceBuilds off
    ParallelModelReferenceErrorOnInvalidPool on
    ParallelModelReferenceMATLABWorkerInit "None"
    ModelReferenceNumInstancesAllowed "Multi"
    PropagateVarSize       "Infer from blocks in model"
    ModelReferencePassRootInputsByReference on
    ModelReferenceMinAlgLoopOccurrences off
    PropagateSignalLabelsOutOfModel off
    SupportModelReferenceSimTargetCustomCode off
  }
  Simulink.SFSimCC {
    $ObjectID            14
    Version              "1.16.2"
    SFSimEcho            on
    SimCtrlC             on
    SimIntegrity             on
    SimUseLocalCustomCode     off
    SimParseCustomCode          on
    SimBuildMode              "sf_incremental_build"
    SimGenImportedTypeDefs    off
  }
  Simulink.RTWCC {
    $BackupClass              "Simulink.RTWCC"
    $ObjectID            15
    Version              "1.16.2"
    Array {
      Type                  "Cell"
      Dimension                 16
      Cell                  "IncludeHyperlinkInReport"
      Cell                  "GenerateTraceInfo"
      Cell                  "GenerateTraceReport"
      Cell                  "GenerateTraceReportSl"
      Cell                  "GenerateTraceReportSf"
      Cell                  "GenerateTraceReportEml"
      Cell                  "PortableWordSizes"
      Cell                  "GenerateWebview"
      Cell                  "GenerateCodeMetricsReport"
      Cell                  "GenerateCodeReplacementReport"
      Cell                  "GenerateMissedCodeReplacementReport"
      Cell                  "GenerateErtSFunction"
      Cell                  "CreateSILPILBlock"
      Cell                  "CodeExecutionProfiling"
      Cell                  "CodeProfilingSaveOptions"
      Cell                  "CodeProfilingInstrumentation"
      PropName                    "DisabledProps"
    }
    SystemTargetFile       "grt.tlc"
    HardwareBoard            "None"
    TLCOptions               ""
```

```
GenCodeOnly               off
MakeCommand               "make_rtw"
GenerateMakefile       on
PackageGeneratedCodeAndArtifacts off
TemplateMakefile       "grt_default_tmf"
PostCodeGenCommand           ""
Description               ""
GenerateReport          off
SaveLog               off
RTWVerbose               on
RetainRTWFile            off
ProfileTLC               off
TLCDebug              off
TLCCoverage               off
TLCAssert            off
RTWUseLocalCustomCode     off
RTWUseSimCustomCode        off
Toolchain             "Automatically locate an installed toolchain"
BuildConfiguration          "Faster Builds"
IncludeHyperlinkInReport off
LaunchReport              off
PortableWordSizes     off
CreateSILPILBlock     "None"
CodeExecutionProfiling    off
CodeExecutionProfileVariable "executionProfile"
CodeProfilingSaveOptions "SummaryOnly"
CodeProfilingInstrumentation off
SILDebugging              off
TargetLang               "C"
IncludeBusHierarchyInRTWFileBlockHierarchyMap off
GenerateTraceInfo     off
GenerateTraceReport        off
GenerateTraceReportSl     off
GenerateTraceReportSf     off
GenerateTraceReportEml    off
GenerateWebview        off
GenerateCodeMetricsReport off
GenerateCodeReplacementReport off
GenerateMissedCodeReplacementReport off
RTWCompilerOptimization "off"
RTWCustomCompilerOptimizations ""
CheckMdlBeforeBuild        "Off"
SharedConstantsCachingThreshold 1024
Array {
  Type                    "Handle"
  Dimension               2
  Simulink.CodeAppCC {
    $ObjectID               16
    Version                 "1.16.2"
    Array {
  Type                    "Cell"
  Dimension            24
  Cell                   "IgnoreCustomStorageClasses"
  Cell                   "ParameterTuningSideEffectCode"
  Cell                   "IgnoreTestpoints"
  Cell                   "InsertBlockDesc"
  Cell                   "InsertPolySpaceComments"
  Cell                   "SFDataObjDesc"
  Cell                   "MATLABFcnDesc"
  Cell                   "SimulinkDataObjDesc"
  Cell                   "DefineNamingRule"
  Cell                   "SignalNamingRule"
  Cell                   "ParamNamingRule"
  Cell                   "InternalIdentifier"
  Cell                   "InlinedPrmAccess"
  Cell                   "CustomSymbolStr"
  Cell                   "CustomSymbolStrGlobalVar"
  Cell                   "CustomSymbolStrType"
  Cell                   "CustomSymbolStrField"
  Cell                   "CustomSymbolStrFcn"
  Cell                   "CustomSymbolStrFcnArg"
  Cell                   "CustomSymbolStrBlkIO"
  Cell                   "CustomSymbolStrTmpVar"
  Cell                   "CustomSymbolStrMacro"
  Cell                   "CustomSymbolStrUtil"
  Cell                   "ReqsInCode"
  PropName              "DisabledProps"
    }
    ForceParamTrailComments off
    GenerateComments             on
    CommentStyle             "Auto"
    IgnoreCustomStorageClasses on
    IgnoreTestpoints             off
    IncHierarchyInIds            off
    MaxIdLength               31
    PreserveName             off
    PreserveNameWithParent    off
```

```
    ShowEliminatedStatement off
    OperatorAnnotations         off
    IncAutoGenComments           off
    SimulinkDataObjDesc         off
    SFDataObjDesc             off
    MATLABFcnDesc             off
    IncDataTypeInIds            off
    MangleLength              1
    CustomSymbolStrGlobalVar "$R$N$M"
    CustomSymbolStrType         "$N$R$M_T"
    CustomSymbolStrField       "$N$M"
    CustomSymbolStrFcn          "$R$N$M$F"
    CustomSymbolStrFcnArg      "rt$I$N$M"
    CustomSymbolStrBlkIO       "rtb_$N$M"
    CustomSymbolStrTmpVar      "$N$M"
    CustomSymbolStrMacro       "$R$N$M"
    CustomSymbolStrUtil        "$N$C"
    DefineNamingRule            "None"
    ParamNamingRule              "None"
    SignalNamingRule            "None"
    InsertBlockDesc             off
    InsertPolySpaceComments off
    SimulinkBlockComments     on
    MATLABSourceComments       off
    EnableCustomComments       off
    InternalIdentifier          "Shortened"
    InlinedPrmAccess             "Literals"
    ReqsInCode                off
    UseSimReservedNames        off
  }
  Simulink.GRTTargetCC {
    $BackupClass              "Simulink.TargetCC"
    $ObjectID                 17
    Version                   "1.16.2"
    Array {
  Type                  "Cell"
  Dimension            13
  Cell                  "GeneratePreprocessorConditionals"
  Cell                  "IncludeMdlTerminateFcn"
  Cell                  "SupportNonInlinedSFcns"
  Cell                  "SuppressErrorStatus"
  Cell                  "ERTCustomFileBanners"
  Cell                  "GenerateSampleERTMain"
  Cell                  "GenerateTestInterfaces"
  Cell                  "ModelStepFunctionPrototypeControlCompliant"
  Cell                  "GenerateAllocFcn"
  Cell                  "PurelyIntegerCode"
  Cell                  "SupportComplex"
  Cell                  "SupportAbsoluteTime"
  Cell                  "SupportContinuousTime"
  PropName              "DisabledProps"
    }
    TargetFcnLib              "ansi_tfl_table_tmw.mat"
    TargetLibSuffix              ""
    GenFloatMathFcnCalls       "NOT IN USE"
    TargetLangStandard          "C89/C90 (ANSI)"
    CodeReplacementLibrary    "None"
    UtilityFuncGeneration     "Auto"
    ERTMultiwordTypeDef         "System defined"
    ERTMultiwordLength          256
    MultiwordLength             2048
    GenerateFullHeader          on
    InferredTypesCompatibility off
    GenerateSampleERTMain      off
    GenerateTestInterfaces    off
    ModelReferenceCompliant on
    ParMdlRefBuildCompliant on
    CompOptLevelCompliant      on
    ConcurrentExecutionCompliant on
    IncludeMdlTerminateFcn    on
    GeneratePreprocessorConditionals "Disable all"
    CombineOutputUpdateFcns off
    CombineSignalStateStructs off
    SuppressErrorStatus         off
    ERTFirstTimeCompliant      off
    IncludeFileDelimiter       "Auto"
    ERTCustomFileBanners       off
    SupportAbsoluteTime         on
    LogVarNameModifier          "rt_"
    MatFileLogging              on
    MultiInstanceERTCode       off
    CodeInterfacePackaging    "Nonreusable function"
    SupportNonFinite            on
    SupportComplex               on
    PurelyIntegerCode           off
    SupportContinuousTime      on
    SupportNonInlinedSFcns    on
```

```
          SupportVariableSizeSignals off
          ParenthesesLevel           "Nominal"
          CastingMode                "Nominal"
          MATLABClassNameForMDSCustomization "Simulink.SoftwareTarget.GRTCustomization"
          ModelStepFunctionPrototypeControlCompliant off
          CPPClassGenCompliant       on
          AutosarCompliant           off
          GRTInterface               on
          GenerateAllocFcn           off
          UseToolchainInfoCompliant on
          GenerateSharedConstants on
          UseMalloc                  off
          ExtMode                    off
          ExtModeStaticAlloc         off
          ExtModeTesting             off
          ExtModeStaticAllocSize     1000000
          ExtModeTransport           0
          ExtModeMexFile             "ext_comm"
          ExtModeIntrfLevel          "Level1"
          RTWCAPISignals             off
          RTWCAPIParams              off
          RTWCAPIStates              off
          RTWCAPIRootIO              off
          GenerateASAP2              off
          MultiInstanceErrorCode     "Error"
        }
        PropName                     "Components"
      }
    }
    SlCovCC.ConfigComp {
      $ObjectID            18
      Version              "1.16.2"
      Description          "Simulink Coverage Configuration Component"
      Name                 "Simulink Coverage"
      CovEnable            off
      CovScope             "EntireSystem"
      CovIncludeTopModel   on
      RecordCoverage       off
      CovPath              "/"
      CovSaveName          "covdata"
      CovMetricSettings    "dw"
      CovNameIncrementing  off
      CovHtmlReporting     on
      CovForceBlockReductionOff on
      CovEnableCumulative  on
      CovSaveCumulativeToWorkspaceVar on
      CovSaveSingleToWorkspaceVar on
      CovCumulativeVarName "covCumulativeData"
      CovCumulativeReport  off
      CovSaveOutputData    on
      CovOutputDir         "slcov_output/$ModelName$"
      CovDataFileName      "$ModelName$_cvdata"
      CovReportOnPause     on
      CovModelRefEnable    "Off"
      CovExternalEMLEnable off
      CovSFcnEnable        on
      CovBoundaryAbsTol    1e-05
      CovBoundaryRelTol    0.01
      CovUseTimeInterval   off
      CovStartTime         0
      CovStopTime          0
    }
    PropName             "Components"
      }
      Name                 "Configuration"
      CurrentDlgPage       "Solver"
      ConfigPrmDlgPosition [ 420, 220, 1500, 860 ]
    }
    PropName                 "ConfigurationSets"
  }
  Simulink.ConfigSet {
    $PropName                "ActiveConfigurationSet"
    $ObjectID                7
  }
  Object {
    $PropName                "DataTransfer"
    $ObjectID                19
    $ClassName               "Simulink.GlobalDataTransfer"
    DefaultTransitionBetweenSyncTasks "Ensure deterministic transfer (maximum delay)"
    DefaultTransitionBetweenAsyncTasks "Ensure data integrity only"
    DefaultTransitionBetweenContTasks "Ensure deterministic transfer (minimum delay)"
    DefaultExtrapolationMethodBetweenContTasks "None"
    AutoInsertRateTranBlk    [0]
  }
  ExplicitPartitioning     off
  BlockDefaults {
    ForegroundColor        "black"
```

```
    BackgroundColor         "white"
    DropShadow              off
    NamePlacement           "normal"
    FontName                "Helvetica"
    FontSize                10
    FontWeight              "normal"
    FontAngle               "normal"
    ShowName                on
    BlockRotation           0
    BlockMirror             off
  }
  AnnotationDefaults {
    HorizontalAlignment     "center"
    VerticalAlignment       "middle"
    ForegroundColor         "black"
    BackgroundColor         "white"
    DropShadow              off
    FontName                "Helvetica"
    FontSize                10
    FontWeight              "normal"
    FontAngle               "normal"
    UseDisplayTextAsClickCallback off
  }
  LineDefaults {
    FontName                "Helvetica"
    FontSize                9
    FontWeight              "normal"
    FontAngle               "normal"
  }
  MaskDefaults {
    SelfModifiable          "off"
    IconFrame               "on"
    IconOpaque              "opaque"
    RunInitForIconRedraw    "off"
    IconRotate              "none"
    PortRotate              "default"
    IconUnits               "autoscale"
  }
  MaskParameterDefaults {
    Evaluate                "on"
    Tunable                 "on"
    NeverSave               "off"
    Internal                "off"
    ReadOnly                "off"
    Enabled                 "on"
    Visible                 "on"
    ToolTip                 "on"
  }
  BlockParameterDefaults {
    Block {
      BlockType             Constant
      Value                 "1"
      VectorParams1D        on
      SamplingMode          "Sample based"
      OutMin                "[]"
      OutMax                "[]"
      OutDataTypeStr        "Inherit: Inherit from 'Constant value'"
      LockScale             off
      SampleTime            "inf"
      FramePeriod           "inf"
      PreserveConstantTs    off
    }
    Block {
      BlockType             Fcn
      Expr                  "sin(u[1])"
      SampleTime            "-1"
    }
    Block {
      BlockType             Gain
      Gain                  "1"
      Multiplication        "Element-wise(K.*u)"
      ParamMin              "[]"
      ParamMax              "[]"
      ParamDataTypeStr      "Inherit: Same as input"
      OutMin                "[]"
      OutMax                "[]"
      OutDataTypeStr        "Inherit: Same as input"
      LockScale             off
      RndMeth               "Floor"
      SaturateOnIntegerOverflow on
      SampleTime            "-1"
    }
    Block {
      BlockType             Integrator
      ExternalReset         "none"
      InitialConditionSource "internal"
      InitialCondition      "0"
```

```
      LimitOutput            off
      UpperSaturationLimit      "inf"
      LowerSaturationLimit      "-inf"
      WrapState              off
      WrappedStateUpperValue    "pi"
      WrappedStateLowerValue    "-pi"
      ShowSaturationPort        off
      ShowStatePort          off
      AbsoluteTolerance          "auto"
      IgnoreLimit            off
      ZeroCross              on
      ContinuousStateAttributes "''"
    }
    Block {
      BlockType              Saturate
      UpperLimitSource            "Dialog"
      UpperLimit             "0.5"
      LowerLimitSource            "Dialog"
      LowerLimit             "-0.5"
      LinearizeAsGain            on
      ZeroCross              on
      SampleTime              "-1"
      OutMin                 "[]"
      OutMax                  "[]"
      OutDataTypeStr              "Inherit: Same as input"
      LockScale              off
      RndMeth                 "Floor"
    }
    Block {
      BlockType              Scope
      DefaultConfigurationName "Simulink.scopes.TimeScopeBlockCfg"
      NumInputPorts          "1"
      Floating               off
    }
    Block {
      BlockType              Step
      Time               "1"
      Before                 "0"
      After              "1"
      SampleTime              "-1"
      VectorParams1D              on
      ZeroCross              on
    }
    Block {
      BlockType              Sum
      IconShape              "rectangular"
      Inputs                 "++"
      CollapseMode            "All dimensions"
      CollapseDim            "1"
      InputSameDT             on
      AccumDataTypeStr            "Inherit: Inherit via internal rule"
      OutMin                 "[]"
      OutMax                  "[]"
      OutDataTypeStr              "Inherit: Same as first input"
      LockScale              off
      RndMeth                 "Floor"
      SaturateOnIntegerOverflow on
      SampleTime              "-1"
    }
    Block {
      BlockType              ToWorkspace
      VariableName           "simulink_output"
      MaxDataPoints          "1000"
      Decimation             "1"
      SaveFormat              "Array"
      Save2DSignal           "Inherit from input (this choice will be removed - see release notes)"
      FixptAsFi              off
      NumInputs               "1"
      SampleTime              "0"
    }
    Block {
      BlockType              TransferFcn
      Numerator              "[1]"
      Denominator            "[1 2 1]"
      AbsoluteTolerance          "auto"
      ContinuousStateAttributes "''"
      Realization            "auto"
    }
    Block {
      BlockType              ZeroOrderHold
      SampleTime              "1"
    }
  }
  System {
    Name               "backstep56"
    Location               [309, 274, 1517, 799]
    Open               on
```

```
    ModelBrowserVisibility    off
    ModelBrowserWidth         200
    ScreenColor               "white"
    PaperOrientation          "landscape"
    PaperPositionMode         "auto"
    PaperType                 "usletter"
    PaperUnits                "inches"
    TiledPaperMargins         [0.500000, 0.500000, 0.500000, 0.500000]
    TiledPageScale            1
    ShowPageBoundaries        off
    ZoomFactor                "91"
    ReportName                "simulink-default.rpt"
    SIDHighWatermark          "27"
    Block {
      BlockType               Reference
      Name                    "Band-Limited\nWhite Noise1"
      SID                     "1"
      Ports                   [0, 1]
      Position                [585, 15, 615, 45]
      ZOrder                  -1
      LibraryVersion          "1.386"
      SourceBlock             "simulink/Sources/Band-Limited\nWhite Noise"
      SourceType              "Band-Limited White Noise."
      ContentPreviewEnabled   off
      Cov                     "[0.00001]"
      Ts                      "0.5"
      seed                    "[23341]"
      VectorParams1D          on
    }
    Block {
      BlockType               Scope
      Name                    "Course1"
      SID                     "2"
      Ports                   [1]
      Position                [860, 74, 890, 106]
      ZOrder                  -2
      ScopeSpecificationString                    "Simulink.scopes.TimeScopeBlockCfg('CurrentConfiguration',
extmgr.ConfigurationSet(extm"
      "gr.Configuration('Core','General UI',true),extmgr.Configuration('Core','Source UI',true),extmgr.Configuration('S"

"ources','WiredSimulink',true,'DataLoggingVariableName','ScopeData1','DataLoggingSaveFormat','StructureWithTime
',"

"'DataLoggingMaxPoints','15000','DataLoggingLimitDataPoints',true,'DataLoggingDecimation','1','DataLoggingDecim
at"
      "eData',true),extmgr.Configuration('Visuals','Time        Domain',true,'SerializedDisplays',{struct('MinYLimReal','-
1.00"

"000','MaxYLimReal','1.00000','YLabelReal','','MinYLimMag','0.00000','MaxYLimMag','1.00000','LegendVisibility','o"
      "ff','XGrid',true,'YGrid',true,'PlotMagPhase',false,'AxesColor',[0      0      0],'AxesTickColor',[0.686274509803922
0.6862"
      "74509803922       0.686274509803922],'ColorOrder',[1       1       0.0666666666666667;0.0745098039215686
0.623529411764706 1;1 0.4"
      "11764705882353                    0.16078431372549;0.392156862745098                    0.831372549019608
0.0745098039215686;0.717647058823529 0.27450"
      "9803921569            1;0.0588235294117647                1                1;1                0.0745098039215686
0.650980392156863],'Title','%<SignalLabel>','LineProper"

"tiesCache',{{}},'UserDefinedChannelNames',{{}},'NumLines',1,'LineNames',{{'radtodeg2'}},'ShowContent',true,'Plac"
      "ement',1)},'DisplayPropertyDefaults',struct('MinYLimReal','-
1.00000','MaxYLimReal','1.00000','YLabelReal','','Mi"

"nYLimMag','0.00000','MaxYLimMag','1.00000','LegendVisibility','off','XGrid',true,'YGrid',true,'PlotMagPhase',fal"
      "se,'AxesColor',[0              0              0],'AxesTickColor',[0.686274509803922              0.686274509803922
0.686274509803922],'ColorOrder',[1 1"
      "        0.0666666666666667;0.0745098039215686        0.623529411764706        1;1        0.411764705882353
0.16078431372549;0.39215686274509"
      "8           0.831372549019608           0.0745098039215686;0.717647058823529           0.274509803921569
1;0.0588235294117647 1 1;1 0.07450980"
      "39215686
0.650980392156863],'Title','%<SignalLabel>','LinePropertiesCache',{{}},'UserDefinedChannelNames',{{}},'"
      "NumLines',0,'LineNames',{{[]}},'ShowContent',true,'Placement',1)),extmgr.Configuration('Tools','Plot
Navigation'"

",true,'OnceAtStop',false,'PreviousZoomMode','ZoomX','PreviousAutoscale','XY'),extmgr.Configuration('Tools','Meas"
      "urements',true,'Version','2016a')),'Version','2016a','Location',[1555 461 2512 934])"
    }
    Block {
      BlockType               Fcn
      Name                    "Fcn1"
      SID                     "27"
      Position                [190, 103, 240, 137]
      ZOrder                  3
      Expr                    "tanh(0.7*u)"
    }
    Block {
      BlockType               Fcn
```

```
      Name                  "Fcn2"
      SID                   "3"
      Position              [600, 175, 660, 205]
      ZOrder                -3
      BlockMirror           on
      NamePlacement         "alternate"
      Expr                  "(00.98-1/0.08)*u+4.1*u*u*u"
    }
    Block {
      BlockType             Fcn
      Name                  "Fcn3"
      SID                   "4"
      Position              [45, 103, 95, 137]
      ZOrder                -4
      Expr                  "tanh(0.9*u)"
    }
    Block {
      BlockType             Integrator
      Name                  "Integrator2"
      SID                   "5"
      Ports                 [1, 1]
      Position              [695, 100, 725, 130]
      ZOrder                -5
    }
    Block {
      BlockType             Integrator
      Name                  "Integrator3"
      SID                   "6"
      Ports                 [1, 1]
      Position              [415, 105, 445, 135]
      ZOrder                -6
    }
    Block {
      BlockType             Reference
      Name                  "PID Controller3"
      SID                   "7"
      Ports                 [1, 1]
      Position              [130, 105, 160, 135]
      ZOrder                -7
      LibraryVersion        "1.13"
      SourceBlock           "simulink_need_slupdate/PID Controller"
      SourceType            "PID Controller"
      ContentPreviewEnabled off
      P                     "1/(0.31*3)"
      I                     "0.001/(0.31*3)"
      D                     "64.53/(0.31*3)"
    }
    Block {
      BlockType             Scope
      Name                  "Rudder1"
      SID                   "8"
      Ports                 [1]
      Position              [325, 30, 355, 60]
      ZOrder                -8
      BlockMirror           on
      NamePlacement         "alternate"
      ScopeSpecificationString "Simulink.scopes.TimeScopeBlockCfg('CurrentConfiguration',
extmgr.ConfigurationSet(extm"
      "gr.Configuration('Core','General UI',true),extmgr.Configuration('Core','Source UI',true),extmgr.Configuration('S"

"ources','WiredSimulink',true,'DataLoggingVariableName','ScopeData2','DataLoggingSaveFormat','StructureWithTime
',"

"'DataLoggingMaxPoints','11000','DataLoggingLimitDataPoints',true,'DataLoggingDecimation','1','DataLoggingDecima
t"
      "eData',true),extmgr.Configuration('Visuals','Time Domain',true,'SerializedDisplays',{struct('MinYLimReal','-25',"
      "'MaxYLimReal','40','YLabelReal','','MinYLimMag','0','MaxYLimMag','10','LegendVisibility','off','XGrid',true,'YGr"
      "id',true,'PlotMagPhase',false,'AxesColor',[0 0 0],'AxesTickColor',[0.686274509803922 0.686274509803922
0.6862745"
      "09803922],'ColorOrder',[1 1 0.0666666666666667;0.0745098039215686 0.623529411764706 1;1
0.411764705882353 0.1607"
      "8431372549;0.392156862745098 0.831372549019608 0.0745098039215686;0.717647058823529
0.274509803921569 1;0.058823"
      "5294117647 1 1;1 0.0745098039215686
0.650980392156863],'Title','%<SignalLabel>','LinePropertiesCache',{{}},'User"

"DefinedChannelNames',{{}},'NumLines',1,'LineNames',{{'radtodeg3'}},'ShowContent',true,'Placement',1)},'DisplayPr"
      "opertyDefaults',struct('MinYLimReal','-
25','MaxYLimReal','40','YLabelReal','','MinYLimMag','0','MaxYLimMag','10'"
      ",'LegendVisibility','off','XGrid',true,'YGrid',true,'PlotMagPhase',false,'AxesColor',[0 0 0],'AxesTickColor',[0."
      "686274509803922 0.686274509803922 0.686274509803922],'ColorOrder',[1 1
0.0666666666666667;0.0745098039215686 0.6"
      "23529411764706 1;1 0.411764705882353 0.16078431372549;0.392156862745098 0.831372549019608
0.0745098039215686;0.7"
      "17647058823529 0.274509803921569 1;0.0588235294117647 1 1;1 0.0745098039215686
0.650980392156863],'Title','%<Sig"
```

```
"nalLabel>','LinePropertiesCache',{{}},'UserDefinedChannelNames',{{}},'NumLines',0,'LineNames',{{[]}},'ShowConten"
	"t',true,'Placement',1)),extmgr.Configuration('Tools','Plot Navigation',true,'OnceAtStop',false),extmgr.Configura"
	"tion('Tools','Measurements',true,'Version','2016a')),'Version','2016a','Location',[485 309 929 576])"
    }
    Block {
      BlockType		      Saturate
      Name		      "Saturation1"
      SID		      "9"
      Ports		      [1, 1]
      Position		      [365, 105, 395, 135]
      ZOrder		      -9
      InputPortMap	      "u0"
      UpperLimit	      "5*3.1415926/180"
      LowerLimit	      "-5*3.1415926/180"
    }
    Block {
      BlockType		      Saturate
      Name		      "Saturation3"
      SID		      "10"
      Ports		      [1, 1]
      Position		      [265, 105, 295, 135]
      ZOrder		      -10
      InputPortMap	      "u0"
      UpperLimit	      "25*3.14159265/180.0"
      LowerLimit	      "-25*3.14159265/180.0"
    }
    Block {
      BlockType		      Step
      Name		      "Set course1"
      SID		      "11"
      Position		      [-75, 105, -45, 135]
      ZOrder		      -11
      Time		      "0"
      After		      "50*3.14/180"
      SampleTime	      "0"
    }
    Block {
      BlockType		      Sum
      Name		      "Sum5"
      SID		      "12"
      Ports		      [2, 1]
      Position		      [320, 110, 340, 130]
      ZOrder		      -12
      ShowName		      off
      IconShape		      "round"
      Inputs		      "|+-"
    }
    Block {
      BlockType		      Sum
      Name		      "Sum6"
      SID		      "13"
      Ports		      [4, 1]
      Position		      [560, 100, 590, 130]
      ZOrder		      -13
      ShowName		      off
      IconShape		      "round"
      Inputs		      "|+++-"
    }
    Block {
      BlockType		      Sum
      Name		      "Sum7"
      SID		      "14"
      Ports		      [2, 1]
      Position		      [-10, 110, 10, 130]
      ZOrder		      -14
      ShowName		      off
      IconShape		      "round"
      Inputs		      "|+-"
    }
    Block {
      BlockType		      Sum
      Name		      "Sum8"
      SID		      "15"
      Ports		      [2, 1]
      Position		      [755, 80, 775, 100]
      ZOrder		      -15
      ShowName		      off
      IconShape		      "round"
      Inputs		      "|++"
    }
    Block {
      BlockType		      ToWorkspace
      Name		      "To Workspace"
      SID		      "16"
      Ports		      [1]
      Position		      [225, 25, 285, 55]
      ZOrder		      -16
```

```
    VariableName              "rudder"
    MaxDataPoints             "inf"
    SampleTime                "-1"
  }
  Block {
    BlockType                 ToWorkspace
    Name                      "To Workspace1"
    SID                       "17"
    Ports                     [1]
    Position                  [860, 170, 920, 200]
    ZOrder                    -17
    VariableName              "course"
    MaxDataPoints             "inf"
    SampleTime                "-1"
  }
  Block {
    BlockType                 TransferFcn
    Name                      "Transfer Fcn2"
    SID                       "18"
    Position                  [610, 97, 670, 133]
    ZOrder                    -18
    Numerator                 "[0.08]"
    Denominator               "[39.09 1]"
  }
  Block {
    BlockType                 TransferFcn
    Name                      "Transfer Fcn3"
    SID                       "19"
    Position                  [650, 12, 710, 48]
    ZOrder                    -19
    Numerator                 "[0.4198]"
    Denominator               "[1 0.3638 0.3675]"
  }
  Block {
    BlockType                 ZeroOrderHold
    Name                      "Zero-Order\nHold"
    SID                       "20"
    Position                  [475, 100, 515, 140]
    ZOrder                    -20
    NamePlacement             "alternate"
    SampleTime                "8"
  }
  Block {
    BlockType                 Gain
    Name                      "radtodeg2"
    SID                       "21"
    Position                  [805, 75, 835, 105]
    ZOrder                    -21
    Gain                      "180/3.14"
  }
  Block {
    BlockType                 Gain
    Name                      "radtodeg3"
    SID                       "22"
    Position                  [380, 30, 410, 60]
    ZOrder                    -22
    BlockMirror               on
    NamePlacement             "alternate"
    Gain                      "180/3.14"
  }
  Block {
    BlockType                 Reference
    Name                      "random wind1"
    SID                       "23"
    Ports                     [0, 1]
    Position                  [460, 15, 490, 45]
    ZOrder                    -23
    LibraryVersion            "1.386"
    SourceBlock               "simulink/Sources/Band-Limited\nWhite Noise"
    SourceType                "Band-Limited White Noise."
    ContentPreviewEnabled     off
    Cov                       "[0.0001]"
    Ts                        "0.5"
    seed                      "[23341]"
    VectorParams1D            on
  }
  Block {
    BlockType                 Constant
    Name                      "stationary\nwind1"
    SID                       "24"
    Position                  [515, 15, 545, 45]
    ZOrder                    -24
    Value                     "3*3.14/180"
  }
  Line {
    ZOrder                    1
    SrcBlock                  "Set course1"
```

```
    SrcPort		    1
    DstBlock		    "Sum7"
    DstPort		    1
}
Line {
    ZOrder		    2
    SrcBlock		    "radtodeg2"
    SrcPort		    1
    Points		    [0, 0]
    Branch {
ZOrder		    3
DstBlock		    "Course1"
DstPort		    1
    }
    Branch {
ZOrder		    4
Points		    [0, 95]
DstBlock		    "To Workspace1"
DstPort		    1
    }
}
Line {
    ZOrder		    5
    SrcBlock		    "Sum5"
    SrcPort		    1
    DstBlock		    "Saturation1"
    DstPort		    1
}
Line {
    ZOrder		    6
    SrcBlock		    "Saturation1"
    SrcPort		    1
    DstBlock		    "Integrator3"
    DstPort		    1
}
Line {
    ZOrder		    7
    SrcBlock		    "Transfer Fcn2"
    SrcPort		    1
    Points		    [0, 0]
    Branch {
ZOrder		    8
DstBlock		    "Integrator2"
DstPort		    1
    }
    Branch {
ZOrder		    9
DstBlock		    "Fcn2"
DstPort		    1
    }
}
Line {
    ZOrder		    10
    SrcBlock		    "Sum6"
    SrcPort		    1
    DstBlock		    "Transfer Fcn2"
    DstPort		    1
}
Line {
    ZOrder		    11
    SrcBlock		    "Integrator2"
    SrcPort		    1
    DstBlock		    "Sum8"
    DstPort		    2
}
Line {
    ZOrder		    12
    SrcBlock		    "Sum8"
    SrcPort		    1
    Points		    [5, 0]
    Branch {
ZOrder		    13
DstBlock		    "radtodeg2"
DstPort		    1
    }
    Branch {
ZOrder		    14
Points		    [0, 130; -785, 0]
DstBlock		    "Sum7"
DstPort		    2
    }
}
Line {
    ZOrder		    15
    SrcBlock		    "Band-Limited\nWhite Noise1"
    SrcPort		    1
    DstBlock		    "Transfer Fcn3"
```

```
    DstPort                    1
}
Line {
    ZOrder                     16
    SrcBlock                   "Transfer Fcn3"
    SrcPort                    1
    Points                     [20, 0; 0, 60]
    DstBlock                   "Sum8"
    DstPort                    1
}
Line {
    ZOrder                     17
    SrcBlock                   "Fcn2"
    SrcPort                    1
    Points                     [-20, 0]
    DstBlock                   "Sum6"
    DstPort                    4
}
Line {
    ZOrder                     18
    SrcBlock                   "stationary\nwind1"
    SrcPort                    1
    Points                     [4, 0]
    DstBlock                   "Sum6"
    DstPort                    1
}
Line {
    ZOrder                     19
    SrcBlock                   "random wind1"
    SrcPort                    1
    Points                     [10, 0; 0, 60; 35, 0; 0, 25]
    DstBlock                   "Sum6"
    DstPort                    2
}
Line {
    ZOrder                     20
    SrcBlock                   "radtodeg3"
    SrcPort                    1
    Points                     [0, 0]
    Branch {
ZOrder              21
DstBlock            "Rudder1"
DstPort             1
    }
    Branch {
ZOrder              22
Points              [0, 40; -195, 0; 0, -45]
DstBlock            "To Workspace"
DstPort             1
    }
}
Line {
    ZOrder                     23
    SrcBlock                   "Saturation3"
    SrcPort                    1
    DstBlock                   "Sum5"
    DstPort                    1
}
Line {
    ZOrder                     24
    SrcBlock                   "Sum7"
    SrcPort                    1
    DstBlock                   "Fcn3"
    DstPort                    1
}
Line {
    ZOrder                     25
    SrcBlock                   "Fcn3"
    SrcPort                    1
    DstBlock                   "PID Controller3"
    DstPort                    1
}
Line {
    ZOrder                     26
    SrcBlock                   "PID Controller3"
    SrcPort                    1
    DstBlock                   "Fcn1"
    DstPort                    1
}
Line {
    ZOrder                     27
    SrcBlock                   "Integrator3"
    SrcPort                    1
    Points                     [0, 0]
    Branch {
ZOrder              28
DstBlock            "Zero-Order\nHold"
```

```
	  DstPort		  1
	}
	Branch {
	  ZOrder		  29
	  Points		  [0, 40; -120, 0]
	  DstBlock		  "Sum5"
	  DstPort		  2
	}
      }
      Line {
	ZOrder			30
	SrcBlock		"Zero-Order\nHold"
	SrcPort			1
	Points			[10, 0]
	Branch {
	  ZOrder		  31
	  Points		  [0, 25; 24, 0]
	  DstBlock		  "Sum6"
	  DstPort		  3
	}
	Branch {
	  ZOrder		  32
	  Points		  [0, -25; -90, 0; 0, -50]
	  DstBlock		  "radtodeg3"
	  DstPort		  1
	}
      }
      Line {
	ZOrder			35
	SrcBlock		"Fcn1"
	SrcPort			1
	DstBlock		"Saturation3"
	DstPort			1
      }
    }
}
```