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Heading control method of unmanned sailing boats based on fuzzy PID

Zhang Xuefei[1], *Yuan Peng*[*1,2], *Tan Junzhe*[1,2], *Wang Shujie*[1,2], *Xu Hongshen*[1], *Sun Ye*[1]

1 College of Engineering, Ocean University of China, Qingdao 266100, China

2 Ocean Engineering Key Lab of Qingdao, Qingdao 266100, China

Abstract: [**Objectives**] In order to improve the anti-jamming ability and navigation stability of the unmanned sailing boats in the changeable and unknown environment and to realize accurate control of the heading of sailing boats, a fuzzy adaptive control method combined with the traditional PID technology is proposed. [**Methods**] The Nomoto motion mathematical model with three degrees of freedom was established, and the fuzzy rules and simulation controller were built with the Simulink modeling tool of Matlab, which could optimize and adjust the PID control parameters in real time and online. In the case of different speeds and random perturbations, a comparison with the traditional PID control was made to analyze the influence of different control methods on the heading and validate it by experiments. [**Results**] The results show that the fuzzy PID method has good adaptive ability and robustness to control the heading of small unmanned sailing boats. [**Conclusions**] The study of this paper can provides references for heading control of unmanned sailing boats.

Key words: unmanned sailing boat; fuzzy PID; Nomoto model; heading control

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0 Introduction

When an unmanned sailing boat is autonomously sailing at sea, it will be affected by the marine environment, and some states deviating from the predetermined trajectory will occur. Therefore, a heading controller with strong anti-jamming ability is of great significance for the track keeping and tracking navigation of the sailing boats.

At present, the algorithms for heading control mainly include classical PID, Backstepping, Lyapunov, sliding mode control, neural network control, fuzzy control and some other combined intelligent control methods [1-2]. Many scholars have done a lot of research on the heading control of unmanned sailing boats. Among them, Deng et al. [3] and Ahmed et al. [4] controlled the course through fuzzy control and PD controller and applied them to the actual navigation path planning. Emami et al. [5] have realized the course keeping control of a small unmanned sailing boat by establishing the mathematical model of Fossen's four-degrees-of-freedom ship by using PID algorithm. According to the expert experience of steering, Wang et al. [6] summed up and formulated 245 fuzzy control rules and directly used the rudder angle as the output to realize the tracking navigation control for a 1.5 m sailing boat. Shen et al. [7] proposed an adaptive dynamic-surface heading control method based on RBF neural network for the situation that the model of an unmanned sailing boat is uncertain and the control direction and external environment disturbance are unknown. The above research uses different control methods to realize the heading control of the sailing boats. In this paper, the stability control of sailing boat heading is studied under different speeds and unknown random interfer-

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Authors: Zhang Xuefei, male, born in 1993, master. Research interest: marine-energy electromechanical equipment and instruments. E-mail: 634934319@qq.com

Yuan Peng, male, born in 1975, Ph.D., associate professor. Research interest: marine renewable energy. E-mail: yuanpeng50@hotmail.com

***Corresponding author:** Yuan Peng

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ence.

Due to its simple structure and clear physical meaning, PID controller has good control characteristics for specific scenes and precise mathematical models and is still widely used in practical projects. However, the effect of traditional PID control largely depends on the values of its control parameters K_p, K_i and K_d. It is difficult to adjust the PID control parameters online and in real time in the complex and changeable situation. Therefore, in the control process, it often shows great fluctuation and high-frequency steering, and even uncontrollable state may appear [8]. In the course of sailing, unmanned sailing boats will face the interference of wind, wave, current, and other factors. It is difficult to meet the control requirements of accurate heading only by the adjustment of traditional PID. However, fuzzy control can make corresponding control rules according to the expert experience of actual operation without the need to determine the mathematical model, so as to achieve the ideal control effect [9]. Therefore, this paper will design a kind of fuzzy adaptive controller combined with classical PID technology. According to the practical experience of adjusting PID control parameters, the corresponding fuzzy control rules are formulated to realize the dynamic adjustment of PID control parameters, so as to achieve the purpose of stable control of the sailing boats.

1 Mathematical model of unmanned sailing boats

1.1 Parameters of sailing boat model

In this paper, the self-designed unmanned sailing boat model is used as the simulation research object. The main dimensions of the hull (appendage) and sail are shown in Table 1. NACA 0018 airfoil is selected as the rudder section.

Table 1 The main dimensions of small autonomous sailboat model

Parameter	Value
Length of the saling boat L/m	2.19
Width of the sailing boat B/m	0.80
Draft T/m	0.08
Block coefficient C_b	0.89
Distance of center of gravity X_c / m	0.085
Sail area S_s/ m^2	3.25
Length of the mast l /m	1.5
Rudder speed n /(Deg·s^{-1})	10.2
Effective rudder area S_r/ m^2	0.085

1.2 Coordinate system of sailing boat motion

In the actual sea surface motion, a sailing boat can generally be approximated as a rigid body with six degrees of freedom. In order to better describe the sailing movement, two right-handed coordinate systems as shown in Fig. 1 are established. In the figure, $o_0-x_0y_0z_0$ is the inertial coordinate system centered on the ship's center of gravity at t=0, the o_0-x_0 axis is the north direction of the still water surface, the o_0-y_0 axis is the east direction of the still water surface, the o_0-z_0 axis is downwards vertical to the water surface. $o-xyz$ is the appendage coordinate system with the center of gravity of the ship as the center, the $o-x$ axis is the axis of the ship and the direction is from the stern to the bow, the $o-y$ axis is to the starboard side, and the $o-z$ axis is to the water surface. In order to facilitate the analysis of the relationship between heading angle ψ and rudder angle δ, on the premise of meeting the research requirements, the rolling, pitching, and heaving motions can be ignored, and only the swaying, forwarding, and yawing motions are considered. The sailing motion can be simplified into a mathematical model of three degrees of freedom[10-11].

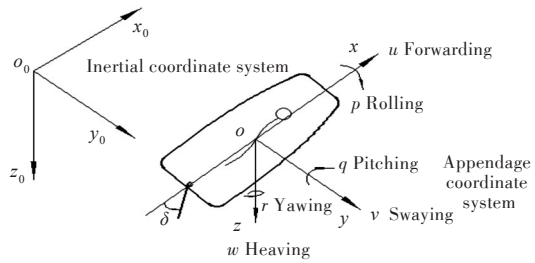

Fig.1 The coordinate system of hull

1.3 Nomoto motion mathematical model

According to Newton's theorem of momentum and moment of momentum about the motion of the center of mass, combined with the conversion relationship between a coordinate system and speed, a three-degree-of-freedom mathematical model of the unmanned sailing boat in still water is established [12-13]:

$$\begin{cases} m(\dot{u}_G - v_G r) = F_x \\ m(\dot{v}_G + u_G r) = F_y \\ I_{zG}\dot{r} = M_z \end{cases} \tag{1}$$

where m is the total mass of the boat; u_G, v_G, $\dot{u}_G$, $\dot{v}_G$ are the forward and lateral velocities at the center of gravity and their derivatives to time; r and $\dot{r}$ are the yawing angular rate and its derivative to time;

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F_x, F_y, M_z are the external forces and moments acting at the center of gravity of axes x, y, z respectively. I_{zG} is the moment of inertia of the boat around the axis z_0.

Then, from the perspective of control engineering, the relationship between the change of ship yawing angle and the motion of rudder angle is considered. According to the hydrodynamic model and the output equation of the sailing boat, the three-degree-of-freedom state-space equation in Eq. (1) is transformed into the transfer function expression, and the famous Nomoto mathematical model is simplified:

$$\frac{\psi(s)}{\delta(s)} = \frac{K}{s(Ts+1)} \tag{2}$$

where the rotational parameter K and the stability parameter T are the angular velocity after steering and the time required to reach the maximum turning angular velocity respectively; s is the Laplace transform factor.

1.4 Mathematical model of steering gear

The steering gear has a certain delay effect in the actual control process, which will affect the accuracy of heading control to some extent. Generally, the steering gear can be regarded as a first-order inertial link [14]:

$$\frac{\delta}{\delta_c} = \frac{1}{T_0 s+1} \tag{3}$$

where δ_c is the target rudder angle; T_0 is the time constant of the steering gear, generally taken as 1-3 s, and $T_0 = 1$ is taken in the simulation of this paper.

2 Method of heading control for unmanned sailing boats

There are different forbidden areas for sailing boats with different characteristics when sailing on the sea. It is generally considered that the areas are between 30° and 45° against the wind. At this time, Z-type tacking is needed. In addition, sailing boats can sail in any direction [15]. But in the specific direct navigation section, the heading control methods of unmanned sailing boats will be different and the control effect will have obvious differences. In order to achieve fast response and high stability of the heading control, this paper uses the fuzzy PID control method.

2.1 Design of fuzzy PID controller

When the traditional PID algorithm controls the heading, the deviation e between the given target heading angle ψ_c and the current actual heading angle ψ is taken as the input of the controller, and the rudder angle value δ is taken as the output. For a given heading angle, the fuzzy controller will continuously output the values of K_p, K_i, K_d according to the deviation e and deviation rate e_c through the fuzzy rules. Then it will perform parallel control with the original PID value to output the target rudder angle δ_c and input the determined rudder angle value to the controlled object through the rudder system. In this way, the sailing heading is constantly adjusted until the actual heading angle and the target heading are within the expected error range and reach a stable dynamic control state. The overall control flow of the controller is shown in Fig. 2.

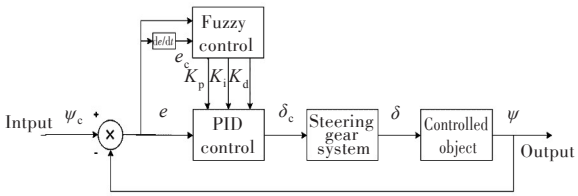

Fig.2 Fuzzy PID control system

At present, the combination of fuzzy control and PID control mainly includes mutual switching control, parallel hybrid control, and parameter tuning control. Generally, the mutual switching control method selects the fuzzy control in the larger error range and transforms it into PID control in the smaller error range. The parallel hybrid control method is based on PID tuned parameters plus fuzzy control parameters. According to fuzzy rules, the parameter tuning control method uses a fuzzy controller to control through the online tuning of PID parameters. This paper adopts the parallel hybrid control method because it is flexible.

2.2 Design of fuzzy control rules

The fuzzy control rules adopted in this paper are mainly based on the expert experience of PID turning: When the deviation e is large, in order to make the system have better tracking response performance and avoid large overshoot, the larger K_p value and the smaller K_d, K_i values should be taken. When the deviation e is medium, the smaller K_p value and the moderate K_d, K_i values should be taken for the smaller overshoot and the moderate system response. When the deviation e is small, in order to make the system have better stability perfor-

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mance and prevent the system from fluctuating near the set value, the larger K_p, K_i values should be taken. When the deviation rate e_c is large, the smaller K_d value should be taken, and in general, K_d is a moderate value. Through the actual adjustment process, 49 rules are formulated as shown in Table 2. Among them, the input e, e_c, and output K_p, K_i, K_d of the fuzzy control are all in the domain range of (−1, 1), and the fuzzy subsets are NB, NM, NS, ZE, PS, PM and PB, which respectively represent negative big, negative medium, negative small, zero, positive small, positive medium and positive big.

Table 2 Fuzzy control rules for K_p, K_i and K_d

e	e_c						
	NB	NM	NS	ZE	PS	PM	PB
NB	PB,NB,PS	PB,NM,NB	PM,NM,NB	PM,NM,NB	PS,NS,NB	PS,ZE,NM	ZE,ZE,ZE
NM	PB,NB,PS	PM,NM,NB	PM,NM,NB	PS,NS,NM	PS,NS,NM	ZE,ZE,NS	NS,ZE,ZE
NS	PM,NB,ZE	PM,NB,NM	PS,NS,NM	PS,NS,NM	ZE,ZE,NS	NS,PS,NS	NS,PS,PS
ZE	PM,NM.ZE	PS,NB,NM	PS,NS,NS	ZE,ZE,ZE	NS,PS,NS	NS,PM,NS	NM,PM,PM
PS	PS,NM,ZE	PS,NS,NS	ZE,ZE,ZE	NS,PS,ZE	NS,PS,ZE	NM,PM,ZE	NM,PB,PB
PM	PS,ZE,PB	ZE,ZE,ZE	NS,PS,PS	NS,PS,PS	NM,PM,PS	NM,PB,PS	NB,PB,PB
PB	ZE,ZE,PB	NS,ZE,ZE	NS,PS,PM	NM,PM,PM	NM,PM,PS	NB,PB,PS	NB,PB,PB

Note: The three values in columns 2 to 8 in the table are K_p, K_i and K_d values respectively.

In the simulation process, the inputs e and e_c are normalized, and then the appropriate gain is added to the outputs K_p, K_i, and K_d according to the PID control range. The variable subset interval of e and e_c is shown in Fig. 3 (a), and the membership functions are smf, zmf, and trimf. The variable subset interval of K_p, K_i and K_d is shown in Fig. 3 (b), and the membership function is trimf. At the same time, the fuzzy control method of Mamdani is adopted, and the fuzzy intersection, or, reasoning, clustering output and defuzzification methods of the variable subset are "min", "max", "min", "max" and "centroid" respectively.

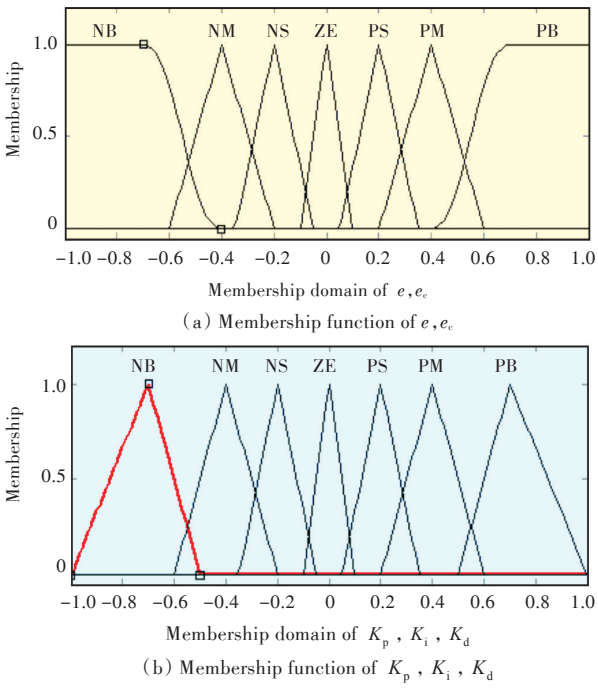

Fig.3 Fuzzy variable subset

2.3 Construction of controller simulation model

With the help of Simulink simulation tool of Matlab, according to the control principle of PID and the fuzzy PID controller designed in Fig. 2, the traditional PID control simulation model as shown in Fig. 4 (a) and the fuzzy PID control simulation model as shown in Fig. 4 (b) are built. The control process is shown in Fig. 5. Firstly, the deviation and deviation rate are calculated according to the comparison between the set target heading angle and the current actual heading angle to judge whether the sailing boat is in the target heading. If there is a yaw, the controller will adjust the rudder to control the heading and finally achieve the target heading. The parallel hybrid controller in fuzzy PID will continuously detect e and e_c during operation. Based on the fuzzy rules and the method of fuzzy reasoning, three control parameters of the controller are generated online and in real time, and then the rudder angle is controlled by superposition of the set fixed PID parameters, so as to realize the heading control.

The actual heading of a sailing boat is not only controlled by the rudder but also influenced by factors such as wind, sail, wave, and current. These factors often show strong nonlinearity and time-varying nature, so it is difficult to predict and establish accurate mathematical model in advance. These unknown factors will eventually affect the heading of the sailing boat and cause certain yaw phenomenon. In the simulation model, with the random interference module in a specific range, the random number be-

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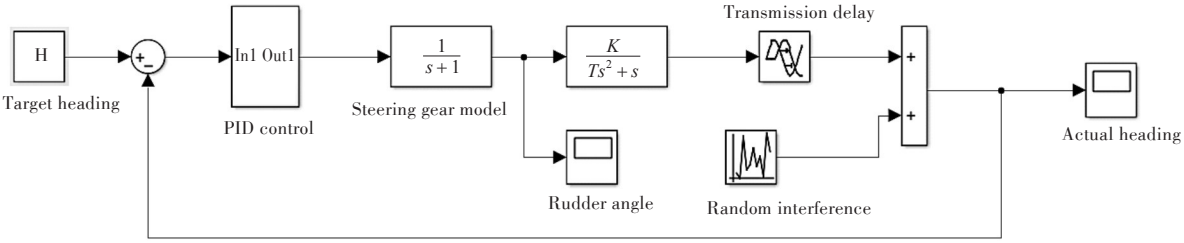
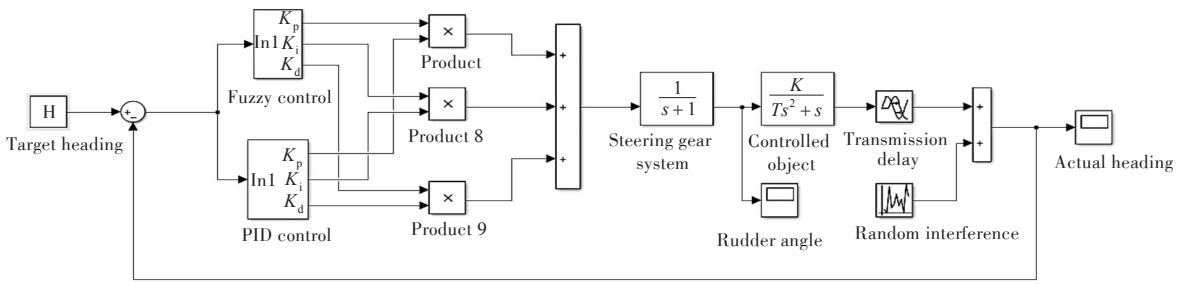


(a) PID control model



(b) Fuzzy PID control model

Fig.4 Controller simulation model

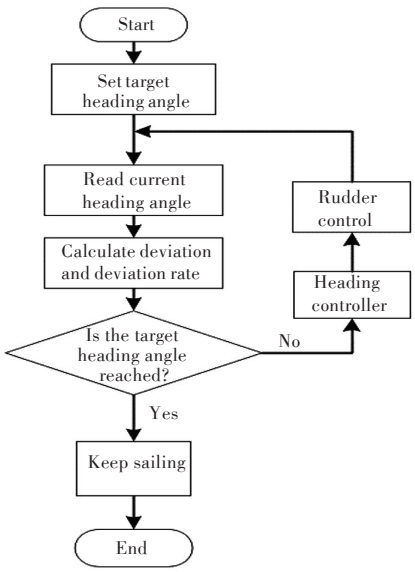


Fig.5 Control flow chart

tween −4 and 4 is generated every 0.5 s. At the same time, the rudder angle monitoring module is also added, which can test whether the control method of the controller has good dynamic control performance.

3 Simulation analysis and test comparison

3.1 Simulation analysis

In this paper, a real-scale sailing boat model is used for simulation research. It is assumed that the initial heading angle and rudder angle of the ship are both 0, the target heading angle is set as $\psi_c = 120°$, and the ship is in the non-upwind navigation area. According to the theoretical calculation formula, there are $K_p = T \cdot W_n^2/K$, $K_i = T \cdot W_n^3/K$ and $K_d = (2T \cdot \varepsilon \cdot W_n^2 - 1)/K$, where W_n and ε are the natural frequency and relative attenuation coefficient of the system. The PID control parameters K_p = 0.42, K_i =0.001, and K_d =1.12 are obtained by appropriate modification. Because of the different navigation speeds, the turning parameter K and stability parameter T are different. When the navigation speeds V are 2.0, 2.5, 3.0 m/s respectively, the turning parameters are −21.99, −27.49, −32.98 respectively, and the stability parameters are −22.96, −18.36, −15.30 respectively.

The comparison results of the two control simulations at different navigation speeds are shown in Fig. 6. It can be seen from the figure that the two control methods can both achieve heading control, but the control effect is different. When the speed is V=2.0 m/s, the traditional PID control achieves the target heading angle at about 3 s, and the maximum overshoot of 20° appears, which tends to be stable in about 10 s. The adjustment time of fuzzy PID control is about 6 s without overshoot. When the speed is V = 2.5 m/s, the traditional PID stability control time is about 9 s and the maximum overshoot is 10°. The adjustment time of fuzzy PID control is about 7 s without overshoot. When the speed is V = 3.0 m/s, the regulating time of traditional PID control is about 12 s, the maximum overshoot is 5°, and there is some fluctuation. The regulating time of fuzzy PID control is about 6 s without overshoot.

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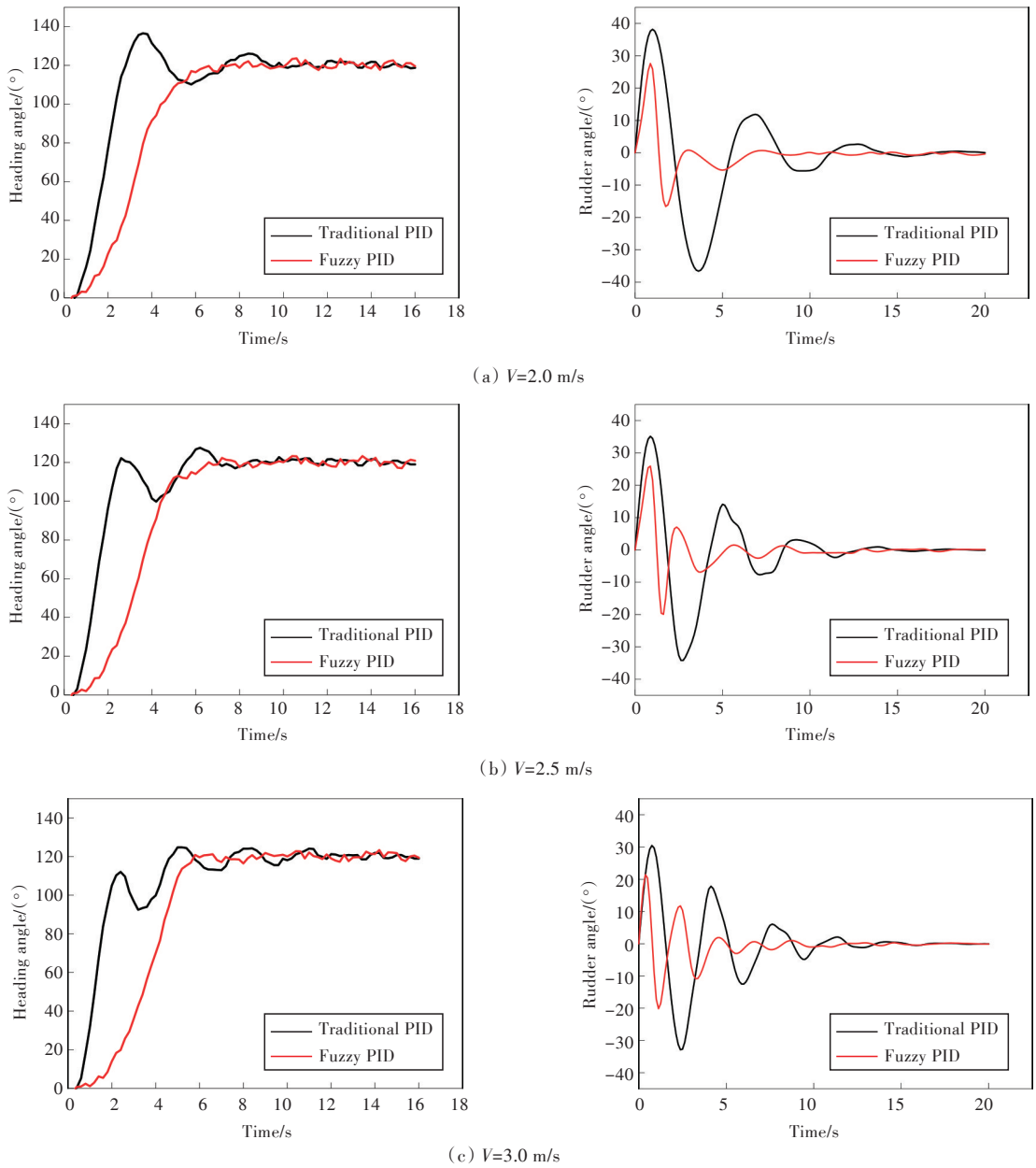

(a) V=2.0 m/s

(b) V=2.5 m/s

(c) V=3.0 m/s

Fig.6 Simulation comparison of two control methods

The main control performance parameters of traditional PID control and fuzzy PID control are shown in Table 3. It can be seen from the table that compared with traditional PID, fuzzy PID has shorter stable regulation time and a smaller steering angle, and there is no obvious overshoot and fluctuation. Due to the fixed parameters of traditional PID, the rudder control is usually carried out when there are a certain overshoot and deviation after the ship reaches the target heading angle. However, the fuzzy PID can dynamically adjust the parameters and control the rudder in advance when it is about to reach the target heading angle so that it has a good control effect and strong adaptive ability in the face of different navigation speeds and complex marine environment interference.

Table 3 Comparison between traditional PID and fuzzy PID control

Navigation speed V /(m·s^{-1})	Control method	Stable regulation time/s	Maximum steering angle/(°)	Whether there is overshoot
2.0	Traditional PID	10	38	Yes
	Fuzzy PID	6	26	No
2.5	Traditional PID	9	34	Yes
	Fuzzy PID	7	22	No
3.0	Traditional PID	12	32	Yes
	Fuzzy PID	6	21	No

3.2 Test comparison

The hull structure of this test is shown in Fig. 7. The control board used in this test includes the master control board and the drive board. The sensors equipped mainly include the ultrasonic wind speed

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and direction indicator, the sail angle encoder, the electronic compass, GPS, and the temperature and humidity transmitter. The actuators include the brushless direct current motor for turning the sail and the electric push rod for steering. GPRS and 2.4 GHz wireless communication are used for different distances. At the ground base station, the monitoring software of unmanned sailing boat monitors the real-time returned data and control data. The monitoring software of the unmanned sailing boat is an MFC application program written by Visual Studio software, which can monitor the status of the ship, modify parameters and record data files. The execution signal is transmitted from the base station to the master control module of the boat through Modbus, and then the control signal is transmitted to the driver module through CAN bus to realize the control of the actuators.

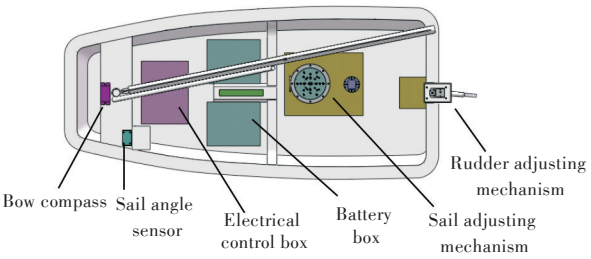


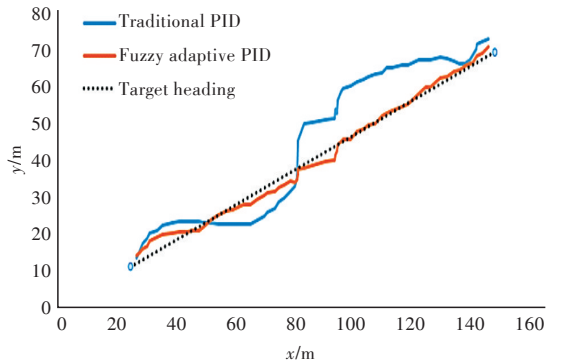
Fig.7 Ship structure

During the test, the heading angle of the sailing boat is detected in real time by electronic compass and is compared with the target heading angle. The heading deviation is obtained as the input of the controller, and the rudder angle value is output by traditional PID or fuzzy PID to control the steering angle of the actuators. During the test, the target heading angle is set as 25°, and the track and heading angle of the boat are shown in Fig. 8 (a) and Fig. 8 (b). Traditional PID and fuzzy PID are used respectively to control the given heading of the sailing boat respectively. The lake test is shown in Fig. 8 (c). Under the small wind and current disturbance, for the sailing boat sailing in the non-upwind direction, it can be seen from the comparison results of test data that both fuzzy PID and traditional PID can achieve the control of the target heading, but the track deviation and heading angle fluctuation of traditional PID are great, while fuzzy PID can reach the target heading angle faster and more stably. In general, fuzzy PID has a better heading control effect.

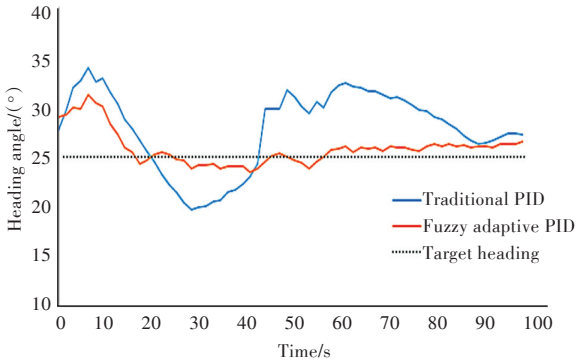
4 Conclusions

In this paper, the self-designed model of the unmanned sailing boat is taken as the research object. According to the actual characteristic parameters of a sailing boat, the mathematical model of its motion is established. The fuzzy PID method is used to design the controller to carry out simulation control of the heading of sailing boats. It is compared with the traditional PID control method and verified by experiments.

Through the simulation of heading control and the analysis of the test results, it is found that the two control methods for sailing boats are different when they reach the same heading angle at different navigation speeds. The fuzzy PID controller has the advantages of fast stability adjustment time, small overshoot and steering angle, and strong anti-interference ability, which can realize the stable control of



(a) Comparison of navigation track



(b) Target heading angle

(c) Lake test of the sailing boat

Fig.8 Experimental comparison results

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the heading of sailing boats. According to the overall comparison results, the fuzzy PID method can be applied to the heading control of small-scale unmanned sailing boats and has certain reference value for the intelligent heading control of unmanned sailing boats. In the future, this method can also be applied to further consider the linkage control of sails and rudders and to investigate its influence and control effect on the heading of sailing boats.

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基于模糊PID的无人帆船航向控制方法

张雪飞[1], 袁鹏[*1,2], 谭俊哲[1,2], 王树杰[1,2], 徐泓燊[1], 孙烨[1]

1 中国海洋大学 工程学院,山东 青岛 266100

2 青岛市海洋可再生能源重点实验室,山东 青岛 266100

摘　要:[**目的**]无人帆船在复杂海况下会出现航向状态不稳定的现象,为提高帆船在多变和未知环境下的抗干扰能力与航行的稳定性,实现对帆船航向的准确控制,提出一种结合传统PID技术的模糊自适应控制方法。[**方法**]建立响应型三自由度的Nomoto运动数学模型,借助Matlab的Simulink建模工具搭建模糊规则和仿真控制器,对PID控制参数进行实时在线优化调整。分别在不同航速和加入随机扰动下,与传统PID控制进行对比研究,分析不同的控制方法对航向的影响情况,并通过试验进行对比验证。[**结果**]结果表明,应用模糊PID方法控制小型无人帆船的航向,具有较好的自适应能力和较强的鲁棒性。[**结论**]研究成果可为无人帆船的航向控制设计提供参考。

关键词:无人帆船;模糊PID;Nomoto模型;航向控制

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