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Fuzzy-PID controlled lift feedback fin stabilizer

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Abstract: Conventional PID controllers are widely used in fin stabilizer control systems, but they have time-variations, nonlinearity, and uncertainty influencing their control effects. A lift feedback fuzzy-PID control method was developed to better deal with these problems, and this lift feedback fin stabilizer system was simulated under different sea condition. Test results showed the system has better anti-rolling performance than traditional fin-angle PID control systems.
Keywords: lift fin stabilizer; lift force feedback control; fuzzy control; PID; self-adjusting
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1 Introduction

Fin stabilizers is one of the most effective ship roll reducing equipments, which has been used for more than seventy years. Its principle is: when the fin has velocity and deflective angle, it will produce lift that comes into being torque to counteract the wave's interfering torque[1]. But there are many uncertain factors in the conventional formula to calculate the lift. Because the relationship between the lift on the fin and the fin angle is gotten by the static hydrodynamic experiment, which has great error, especially compared with the dynamic hydrodynamic experiment, the control torque gotten by the experiment can not counteract the wave torque well and the anti-rolling result is not perfect. And nearly all fin stabilizers we use now are angle-feedback systems, whose control torque is gotten by the conventional formula. People then designed a new kind of fin stabilizers with lift feedback control in which the lift of the fin is gotten not by calculated but measured directly. So the lift can be obtained more accurately and the fin stabilizer can work more efficiently.

In general fin stabilizers control system, the conventional PID control can not get good performance, for time-variation, nonlinearity and uncertainty existed in the object. Combining the tradition PID with the advanced control tactics is available for solving the above-mentioned problem[2]. Some new control arithmetic as fuzzy control, NN control and self-adaptive control have appeared in recent years. Especial the fuzzy controller is not request ascertain the accurate mathematic model, but organize the decision-making table according to the control rules, which can decide the control quantity. Aiming to lift fin stabilizers control system, fuzzy-PID control tactic is adopted in this paper, the system is not only provided with the flexibility and adaptability merit of fuzzy control, but also with the high accuracy of PID control. We emulated the control process of the lift fin stabilizer system, it has better anti-rolling performance than the traditional fin-angle control system.

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2 Lift force feedback fin stabilizers

2.1 The linear roll model of ship

There are so many uncertain factors when a ship navigates on the sea, so the roll model of ship is nonlinear. But we can analyze the movement of roll using a linear model when the angle of roll is small. As the Conolly theory the linear roll model of ship is shown:

$$(I_x + DI_x)\ddot{f} + 2N_u\dot{f} + Dhf = -(DI_x\ddot{a}_2 + 2N_u\dot{a}_2 + Dha_1), \tag{1}$$

where

I_x is inertia moment of roll, kg·m²/s;

ΔI_x is added inertia moment, kg·m²/s;

$2N_u$ is damping coefficient of roll;

D is displacement of ship, kg;

h is metacentric height of ship, m;

f is angle of roll, rad.

$$a_1 = a_{01}\sin w_e t, \tag{2}$$

$$a_2 = a_{02}\sin w_e t, \tag{3}$$

where a_{01} is the largest significant angle of wave slope corresponding to angle of wave slope, a_{02} is the largest significant angle of wave slope corresponding to velocity and acceleration of wave slope, and ω_e is the encounter frequency of ship.

$\Delta I_x \ddot{a}_2$ and $2N_u \dot{\alpha}_2$ are much smaller than $Dh\alpha_1$ in Eq.(1), because of which we can only consider the effect of $Dh\alpha_1$. Then Eq. (1) becomes:

$$(I_x + \Delta I_x)\ddot{\phi} + 2N_u\dot{\phi} + Dh\phi = -Dh\alpha_1, \tag{4}$$

Assuming the initial condition is

$$\phi(0) = \dot{\phi}(0) = \ddot{\phi}(0) = 0,$$

the Laplace transform of Eq.(1) is written as:

$$W_c(s) = \frac{\phi(s)}{\alpha_1(s)} = \frac{1}{T_c^2 s^2 + 2T_c\zeta_c s + 1}, \tag{5}$$

where

$$T_c = \sqrt{\frac{I_x + \Delta I_x}{Dh}}, \tag{6}$$

$$\zeta_c = \frac{N_u}{Dh(I_x + \Delta I_x)}. \tag{7}$$

The natural roll period of ship is:

$$T_0 = 2\pi\sqrt{\frac{I_x + \Delta I_x}{Dh}}. \tag{8}$$

2.2 The anti-roll principle of lift force feedback fin stabilizer

The anti-rolling principle of lift feedback fin stabilizer is similar to that of the classical angle feedback fin stabilizer[3,4]. But the lift on the fin is measured by lift sensors in the lift feedback fin stabilizer system. The ship will roll because of a disturbing moment when the wave acts on it. Then the two fins will be driven to contrary angles so that they can produce a hydrodynamic righting moment, which is produced by the lift L to reduce the ship roll. It is shown in Fig.1.

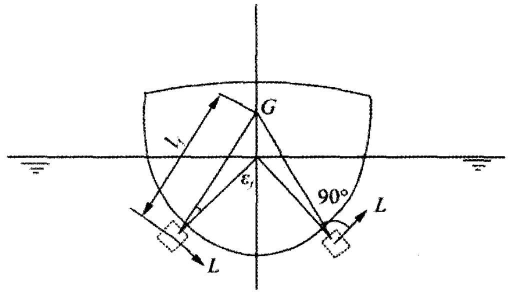

Fig.1 Lift and righting moment

The linear roll model of ship is expressed by Eq.(1), in which the right of it is the wave disturbing moment. If there exits a control moment K_c produced by the fin stabilizer, then, the Eq.1 becomes Eq.(9):

$$(I_x + \Delta I_x)\ddot{\phi} + 2N_u\dot{\phi} + Dh\phi = -Dh\alpha_1 - K_c. \tag{9}$$

If $K_c = -Dh\alpha_1$, the right of Eq.(9) becomes zero and the ship will stop rolling. There exit three moments, which are the inertia moment $(I_x + \Delta I_x)\ddot{\phi}$, the damping moment $2N_u\dot{\phi}$ and the restoring moment $Dh\phi$. They balance with the disturbing moment $Dh\alpha_1$ and the control moment K_c. If the control moment counteracts the disturbing moment, K_c should include three moment components of $A\phi$, $B\dot{\phi}$ and $C\ddot{\phi}$ where A, B and C are proportionality coefficients. Thus the control moment K_c produced by the lift fin stabilizer should be:

$$K_c = A\phi + B\dot{\phi} + C\ddot{\phi}. \tag{10}$$

Substitute Eq.(10)into Eq.(9), then it becomes:

$$(I_x + \Delta I_x + C)\ddot{\phi} + (2N_u + B)\dot{\phi} + (Dh + A)\phi = -Dh\alpha_1. \tag{11}$$

If A, B and C satisfy Eq.(12)

$$\frac{A}{Dh} = \frac{B}{2N_u} = \frac{C}{I_x + \Delta I_x} = F, \tag{12}$$

where F is a constant, Eq.(11) becomes:

$$(I_x + \Delta I_x)(1+F)\ddot{\phi} + 2N_u(1+F)\dot{\phi} + Dh(1+F)\phi = -Dh\alpha_1. \tag{13}$$

And Eq.(13) can be rewritten as follows:

$$(I_x + \Delta I_x)\ddot{\phi} + 2N_u\dot{\phi} + Dh\phi = -Dh\alpha_1(1+F)^{-1}. \tag{14}$$

Eq.(14) shows that the disturbing moment Dha_1 is reduced $(1+F)$ times. The ship roll will be compensated completely if we choose the proportionality coefficients correctly.

2.3 Control structure of lift fin stabilizers

Lift Control stabilization system is made possible by mounting transducers within the fin shaft. The transducers produce an electrical signal proportional to the lift force generated by the angle of attack of the fin to local water stream direction. This lift signal is compared with the instantaneous value of lift required for ship roll stabilization. The difference is used to drive each fin until it achieves the desired lift, thereby automatically compensating for variations on the local water stream direction. The angle of the fin will change as needed until the desired lift is being achieved even though the local water stream direction is continuously changing.

"Lift Control" prevents the fin from being driven at times into the Cavitation Zone and at other times from producing a shortfall in lift. The lift forces required for stabilization are more faithfully produced, giving an improved ship roll stabilization efficiency. We can see the lift fin stabilizer control system in Fig.2.

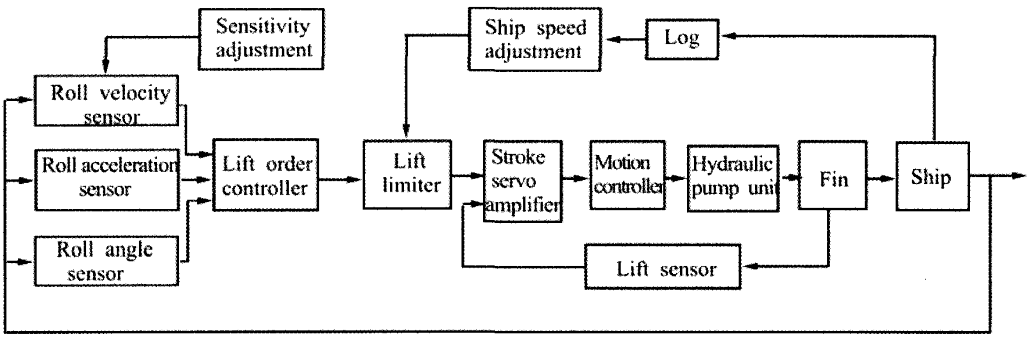

Fig.2 The lift fin stabilizer control system

Control of fin movement is automatic and is usually derived from gyroscopic sensing gear which, is based on one small, electrically driven gyroscope mounted horizontally with its axis athwart-ships. Ship's speed control is included as part of the system. The principal change in the system is the analogue computer techniques. The vertical gyro has been dispensed with, roll and roll acceleration being produced by electronically integrating and differentiating the roll velocity signal. The output from the unit is a carrier signal suitable for driving a hydraulic relay unit, or fin control unit for operating an electro-hydraulic servo-valve. So, the three signals, roll acceleration, roll velocity and roll angle, provide all the information about the ship's rolling motion necessary to obtain optimum roll reduction. Torque to counter roll is generated by the combination of the ship's roll information. The angle of tilt of the fins relative to their direction of motion through the water is determined by the control system which produces appropriate control signals.

Though the lift feedback control method can avoid the uncertainties and nonlinearities between lift and fin angle, Conolly's model we dispensed cannot well describe the ship's rolling due to the influence of many nonlinear factors, time-variation, nonlinearity and uncertainty all still existed in the object[5]. In the past, we often adopted the tradition PID control method, which cannot get good performance for many nonlinear factors above-mentioned.

Fuzzy control is an expert control system. It can make use of the existing knowledge and experience of expert and does not need to establish the strict math model of controlled object[6]. It can actualize nonlinear control when the system is nonlinear. PID-controller with fuzzy self-adjusting parameter is an intelligent controller based on the fuzzy controller adding some detecting model to amend the fuzzy controller according to the measured value online. Most of researchers don't use fuzzy theory to control the whole process, because there is steady state error existed in the fuzzy control to affect the control result.

However, the traditional PID control has the better steady state quality. Therefore, this paper combines PID control model with fuzzy self-adjusting parameter model to let them exert advantages respectively and gain an ideal control performance.

3 Design of double model controller for lift fin stabilizer system

3.1 Realization of fuzzy-PID controller

The basic structure block diagram of the lift fin stabilizer system based on PID control with fuzzy self-adjusting parameter is shown as Fig.3.

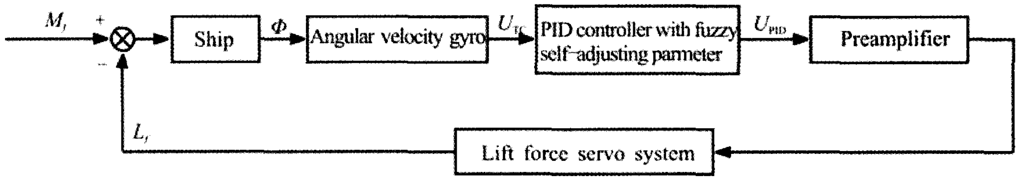

Fig.3 The lift fin stabilizers control system with Fuzzy-PID controller

The design framework of PID-controller with fuzzy self-adjusting parameter is as Fig.4.

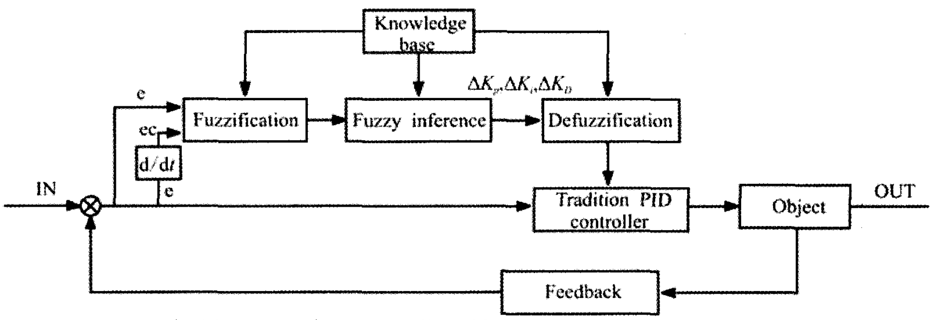

Fig.4 Structure of PID controller with fuzzy self-adjusting parameter

Fuzzy controller is the core of the fuzzy control system, and which is the maximal difference link compared with other systems. The basic structure of the fuzzy control system is given in Fig.3, including the fuzzification, fuzzy inference, defuzzification and quantization of the input data and output data etc. The fuzzification link just change the accurate input variable into fuzzy variable, namely, the input signal is mapped into one point in a comparable universe of discourse, then it is translated into one fuzzy subset. The knowledge database includes the knowledge of the concrete application field and the request we need. It is composed of database and rule base generally. And the database mainly includes membership functions of all sorts of variables, scale transform factor and grades of fuzzy space. Rule base includes a group of control rules expressed by the familiar human symbolic language, which derived from people's knowledge and experiment. Fuzzy inference is the core of fuzzy controller, which has the ability simulated human that based on the fuzzy conception. The processing of defuzzification is to change the control variable produced by fuzzy inference into the accurate variable that can be applied in actual. It includes two processes: transform the fuzzy variable into the accurate variable in the universe of discourse by difuzzification, then, change the accurate variable into the actual control variable according to range switching.

PID-controller with fuzzy self-adjusting parameter combines fuzzy controller with tradition PID controller[7,8]. The error e between the expectation and the actual value and the error interconversion rate ec are both defined as the input variables. Let ΔK_p, ΔK_i, and ΔK_d be the output variables, which are the PID parameters' correction.

The design procedure of this controller is introduced as follows:

1) Define the input and output variables, viz. the fuzzy controller's dimension. Where the error e and error rate ec are defined as input, and PID parameters K_p, K_i, K_d or PID parameters increments $\Delta K_p, \Delta K_i, \Delta K_d$ are defined as output.

2) Define the span of both input and output variables, then ascertain quantification grade, quantification

factor and factor of proportionality of every variable.

3) Define the fuzzy subset in the quantized universe of discourse of each variable. We should ascertain the amount of fuzzy subset firstly, then the language variables of each subset and membership functions of all language variables.

4) Define fuzzy control rule. In fact, the process is summarized the aggregate of some fuzzy condition sentences, which are according to people's experience. Then, the principle in the process of defining the rules is to make the dynamic and static state performance of the system optimum.

5) Draw up the fuzzy control table. On the basis of the control rules, assured input and output variables, the output of fuzzy controller are determined. The output are the setting of PID parameters, list their relationship with the input, then, a control table is formed. In general, three parameters of PID controller are adjusted respectively, so we can set up three fuzzy control tables.

3.2 Fuzzy adjustment rule of PID parameters

The error and error rate are substituted into the fuzzy control table, we can get the new PID parameters, then, the last output can be figured out according to the PID algorithmic, viz. the control variable of the system.

In lift fin stabilizers control system, the formula of PID controller is usually shown as follows:

$$L_{\mathrm{PID}}(s) = (k_{IL}\frac{1}{T_I s+1} + k_{DL}\frac{T_{D1}s}{(T_{D1}s+1)(T_{D2}s+1)} + k_{pL})\phi(s). \tag{15}$$

We present a set of adjusting principle aiming to each of e and ec, taking the self-adjustment process of K_p as a expatiated object:

1) When $|e|$ is more big, K_p should be choose bigger value to quicken the response speed of system, at the same time, K_d should be lesser. For avoiding differential coefficient oversaturation, error $|e|$ is maybe largen instantaneously at the beginning that may be exceed permissive range of the control process. Meanwhile, integral process must be restrict to avoid system response produce biggish overshoot, even to cause integral saturation. K_i is usual chosen zero, for cancelling integral process.

2) When both $|e|$ and $|ec|$ are median size, K_p should be lessening and K_i be adequate value, which avoid the overshoot of system response. K_d is need to be adequate on this condition to ensure the response speed of system.

3) If $|e|$ is lesser to the set value, increase K_p and K_i for favourable steady state performance of control system. K_d value is also important both for avoiding oscillating near to the set value and anti-jamming performance of the system. In generally, if $|ec|$ is lesser, K_d can be bigger, while K_d should be smaller if $|ec|$ is bigger. $|ec|$ expresses the change rate of error here, if $|ec|$ is bigger, then, K_p should be lesser and $K_i\sqrt{b^2-4ac}$ can be bigger, too.

Fuzzy control rules of parameters $\Delta K_p, \Delta K_i, \Delta K_d$ can be acquired, according to the PID parameters effect and the request of the different error and error rate. For clarifying the grade of e, ec and K_p, K_i, K_d, we define seven fuzzy subsets in each universe of discourse, with corresponding linguistic variables of E or EC $\{\mathrm{NB, NM, NS, ZO, PS, PM, PB}\}$. Initial fuzzy control rules table of K_p with self-adjusting is shown in Table 1 (K_p, K_d in a similar way):

Table 1 Fuzzy Control Rules of ΔK_p

ΔK_p	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z0	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

We can see from the Table, the first fuzzy control rule of if $\mathrm{E} = \mathrm{NB}$ and $\mathrm{EC} = \mathrm{NB}$, then $\Delta K_p = \mathrm{PB}$ ΔK_p is expressed as follows:

3.3 Fuzzy inference and defuzzification

Realization of fuzzification need to create the relationship between the discrete exact value and the fuzzy variable denoted by fuzzy language, namely ascertain each element's membership function corresponding to fuzzy language variable in universe of discourse. Triangle and Gauss functions are common membership function we used. The system is adopted the triangle function with some characteristics as symmetry, uniform distribution and intersectant of each, which also has H-resolution and high sensitivity.

On the basis of the above-mentioned fuzzy rules, the corresponding output can be educed by error e and error rate ec reasoning. First of all, the membership grade of each output variable need to be calculated, for example, the membership grade of the first fuzzy rule of ΔK_p is calculated by Eq.(16):

$$\mu_{\Delta K_p} = \min\left\{\mu_{\Delta K_p}(\mathrm{E}), \mu_{\Delta K_p}(\mathrm{EC})\right\}, \quad (16)$$

where min expresses calculated minimum, and μ denotes the membership function. By the same steps, all membership grades adjusted by the fuzzy rules of output can be produced according to the error and error rate. And ΔK_p can be calculated accordingly to Eq.(17) by virtue of the measured values of error and error rate in one sampling time.

$$\Delta K_p = \frac{\sum_{j=1}^{J} \mu_j(\Delta K_p)}{\sum_{j=1}^{J} \mu_j(\Delta K_p)} \Delta K_{pj}, \quad (17)$$

where $\mu_j(\Delta K_p)(j = 1,2,\cdots J)$ is the jth membership grade of ΔK_p derived from all kinds of combined relationship between e and ec correspond to Table 1, J is the number of the fuzzy rules and ΔK_{pj} is the value of the jth fuzzy rule. In a similar way, the process of fuzzy inference and defuzzification of ΔK_i and ΔK_d is the same to ΔK_p by similar equation. In generally, defuzzification is adopted the method of weighted mean, the adjustments of PID parameters can be calculated under the condition of different error and error rate. But all these values are not by way of corrected parameters, they are now still fuzzy quantities, so, the corresponding $\Delta K_p, \Delta K_i$, and ΔK_d are needed to transform into the exact values.

The adjusting equation of PID parameters is expressed in Eq.(18):

$$\begin{Bmatrix} K_p = K_{p0} + \Delta K_p \\ K_i = K_{i0} + \Delta K_i \\ K_d = K_{d0} + \Delta K_d \end{Bmatrix}, \quad (18)$$

where K_{p0}, K_{i0}, and K_{d0} are the initial value of K_p, K_i, and K_d, which are found by routine way, $\Delta K_p, \Delta K_i$, and ΔK_d are the output of fuzzy controller, viz. the calibrating data of PID parameters.

4 Simulation results

We give the simulation of stabilized ship applying PID controller with fuzzy self-adjusting parameters. The parameters in emulator we used are shown as follows.

Tonnage $D = 1457.26\,\mathrm{t}$, shiplength $L = 98\,\mathrm{m}$, waterline breadth $B = 10.2\,\mathrm{m}$, draft $T = 3.1\,\mathrm{m}$, metacentric height $h = 1.15\,\mathrm{m}$, resonance period $T_\phi = 7.8\,\mathrm{s}$, so the ship model is referred to

$$\frac{\phi(s)}{M(s)} = \frac{0.394\,8\mathrm{e}^{-7}}{s^2 + 0.281\,74s + 0.648\,36},$$

and the fin is adopted NACA0015.

In this paper, the simulation is based on the significant wave height $h_{1/3} = 3.8\,\mathrm{m}$ and speed of ship $v = 22\,\mathrm{kn}$. Figs.5~13 illustrate the behaviors of the fin stabilizer control system.

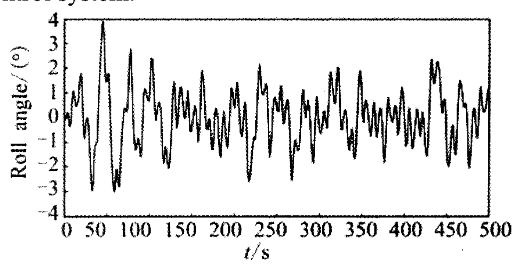

Fig.5 Roll angle of unstabilized ship at $\beta = 30^\circ$

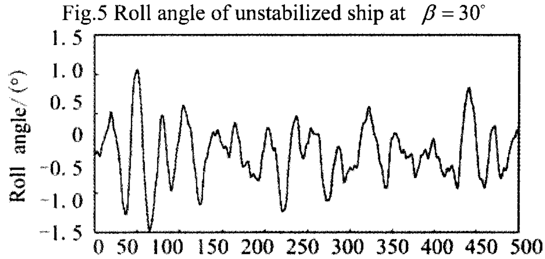

Fig.6 Roll angle of ship with fin angle fins at $\beta = 30^\circ$

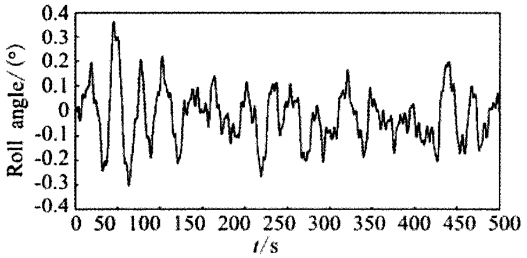

Fig.7 Roll angle of ship with lift fins at $\beta = 30^\circ$

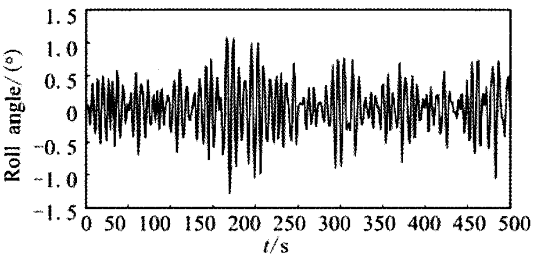

Fig.8 Roll angle of unstabilized ship at $\beta = 90^\circ$

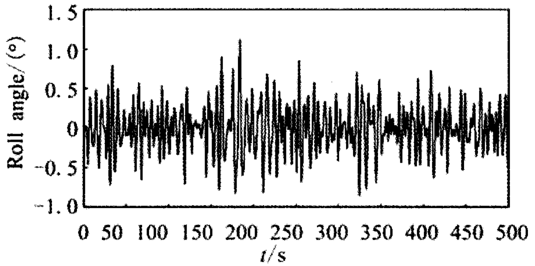

Fig.9 Roll angle of ship with fin angle fins at $\beta = 90^\circ$

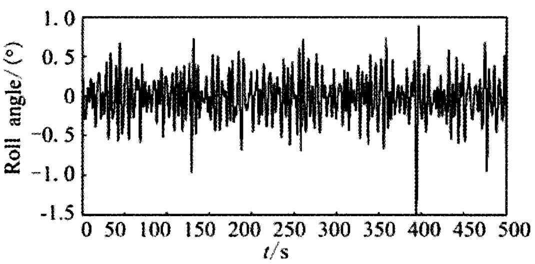

Fig.10 Roll angle of ship with lift fins at $\beta = 90^\circ$

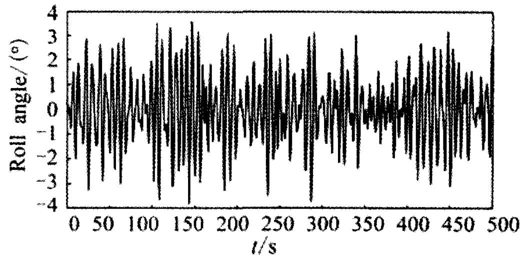

Fig.11 Roll angle of unstabilized ship at $\beta = 135^\circ$

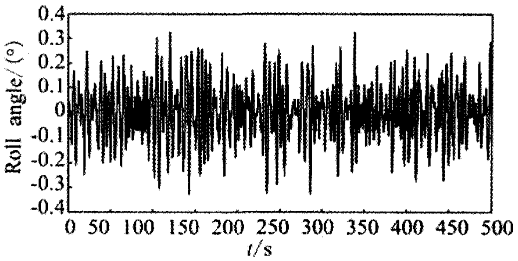

Fig.12 Roll angle of ship with fin angle fins at $\beta = 135^\circ$

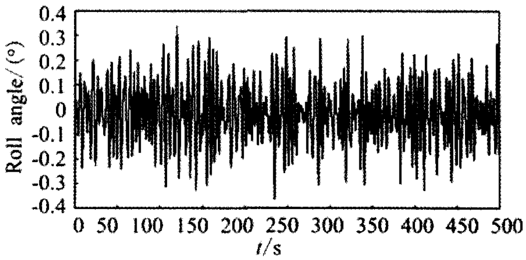

Fig.13 Roll angle of ship with lift fins at $\beta = 135^\circ$

So the roll angle of lift fin stabilizers with PID controller with fuzzy self-adjusting parameter has better anti-rolling performance than the fin angle fins with traditional PID controller.

Table 2 Statistics of roll angles with two control methods in different directions

Encounter angle /(°)	Unstabilized ship		Fin angle fin with PID controller			Lift fin with fuzzy-PID controller		
	Mean /(°)	variance	Mean /(°)	variance	Anti-roll effect /%	Mean /(°)	variance	Anti-roll effect /%
30	0.884 5	0.527 9	0.274 9	0.048 1	68.92	0.090 2	0.004 6	89.80
45	1.561 1	1.388 3	0.464 5	0.131 4	70.24	0.223 1	0.026 3	85.70
60	2.549 7	3.111 7	0.539 9	0.139 4	78.82	0.171 8	0.014 4	93.26
90	2.992 5	5.666 0	0.242 5	0.036 2	91.9	0.238 8	0.035 6	92.02
120	1.743 9	1.869 0	0.150 4	0.010 0	91.37	0.157 0	0.011 8	91.00
135	1.156 4	0.764 6	0.097 6	0.005 1	91.56	0.108 9	0.005 2	90.58
150	0.687 4	0.279 9	0.058 9	0.002 0	91.43	0.070 5	0.002 4	89.70

*The statistics are calculated by absolute value of roll angle

Study all simulation results and the analysis table of roll angle statistics, the lift fin applying PID controller with self-adjusting parameter is satisfying in all kinds of sea condition.

In general the PID control method is employed in fin stabilizers, it is a difficult thing that make certain its parameters. Due to the uncertainties of natural rolling period T and non-dimensional roll damping ξ of ship, so the parameters of PID controller should be set up in sea trial period. But when T and ξ are changed with time in practical vessel, the parameters we acquired can not satisfy the expected anti-rolling effect any more, only high performance in the adjacent corresponding T and ξ based on the sea trial data. In addition, the traditional fin angle fin with PID control is not yet anti-roll well under the condition of quarter head sea. It is also observed from statistics that the PID controller employed in the fin stabilizer can get immense anti-rolling effect only near the encounter angle 135°. So the simple PID control method is lack of the flexibility and adaptability of fuzzy control, and the fuzzy-PID controller we designed has steady anti-rolling performance in all sorts of sea conditions. Otherwise, the setups of fuzzy control rules and some parameters will be more soundness, with the accumulating of our experiential knowledge and grope in depth, in the research process of the controller.

5 Conclusions

We analyze the defects of fin angle feedback stabilizer caused by the hydrodynamic coefficient and show the principle of lift feedback fin stabilizer control system. The error caused by the hydrodynamic factors in calculating the lift force can be avoided, because the lift force of lift fin stabilizers is measured directly. Applying the PID controller with fuzzy self-adjusting parameter in lift fin stabilizer can adapt the uncertainty of the ship model and is effective to stabilize the ship. The lift fin control system is not only provided with the flexibility and adaptability merit of fuzzy control, but also with the high accuracy of PID control. All the research and outcome of this paper have significant consult for practical fin stabilization in vessel.

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Fuzzy-PID controlled lift feedback fin stabilizer

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