Ship Steering System Based on Fuzzy Control Using Real-Time Tuning Algorithm

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***Abstract:*-This paper studies the more efficient and easier design of the fuzzy logic controller (FLC) for course-changing and course-keeping. In this paper, we present the new method to tune the rule base in fuzzy control system. According to the change status of system error, the real-time tuning algorithm is proposed to tune the consequent part fuzzy values, hence the rule base is regulated. This paper also compares the superior performance of FLC at various operating conditions with conventional PID controller. Simulation results are given to demonstrate the method is valuable and easy to implement.**

Ⅰ.INTRODUCTION

Automatic steering control is an integral part of intelligent vehicle control system. It includes course keeping and changing. its main purpose is to ensure that ships sail in the given direction automatically in spite of changes in sea conditions, wind and other disturbances.

PID controllers have been widely used in the control of ship steering. The main problem in using these systems is that conventional PID autopilot couldn't obtain and maintain optimum control because of lacking the capacity to dynamic character or was hard to tune the controlling parameters. establish accurate mathematics model according to the different dynamic model of every ship and dynamic disturbance. So, it is extremely difficult to tune the PID controller so as to procure a good behaviour in all situations. In this paper, we design a fuzzy expert system that includes a knowledge base to store facts and rules, an inference engine to simulate experts' decision and a fuzzy interface device. To perform the ship task of steering a ship effectively, a robust autopilot system that is based on FLC methodology is designed for various outer surroundings at sea in performing course-keeping, course-changing more robustly.

Ⅱ.FUZZY CONTROLLER DESIGN FOR SHIP COUSE-CHANGING/KEEPING

In this design, the course-keeping/changing control system used in the autopilot design covered by this paper is shown in Figure 1. The autopilot design is based on fuzzy inference mechanism. The structure of fuzzy control system is shown in Fig.2. The various steps involved in the design of fuzzy controllers for ship steering system are stated below.

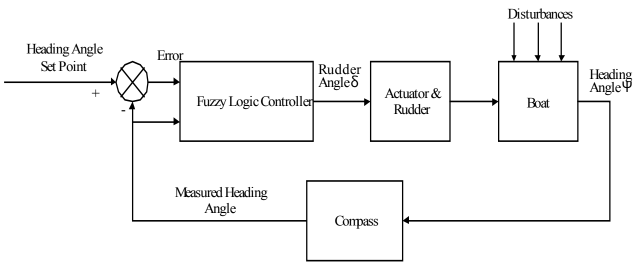

Fig 1. The ship manipulating system

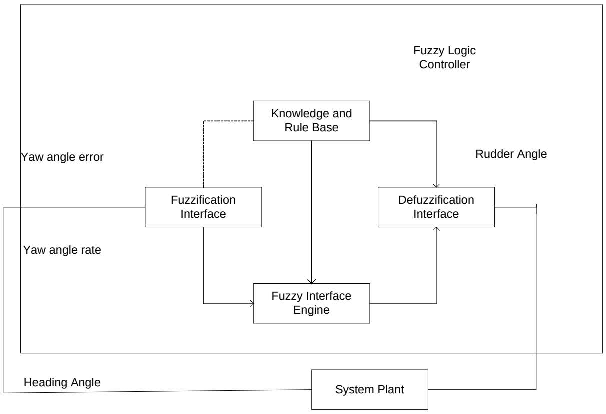

Fig 2. The structure of fuzzy control system

Step1. Identification of inputs and outputs

This step in the design identifies the key inputs that affect the system performance. The goal of the designer is to ensure that the output matches the reference. The memberships have been defined in the two inputs and one output fuzzy system. The inputs and outputs to the fuzzy controller are ① The yaw a error(ε) (reference ship course subtracted from actual course.) ② The yaw rate (ω) (previous error subtracted from current error) over one sample period. ③ The output of the controller is the rudder angle (δ_C)

Step 2. Fuzzifying the inputs and outputs

In practical applications, the control goals and system constraints are all of fuzzy characters, in order to unify them, fuzzy membership function is used to express their characters. These operators can be used to translate a linguistic description of control goals into a decision function. In this way, various forms of aggregation can be chosen giving greater flexibility for expressing the control goals. The universe of discourse (range) of the inputs and outputs are mapped into several fuzzy sets of desired shapes. The membership functions for the inputs are shown in Fig 3,4 and outputs are shown in Fig 5.

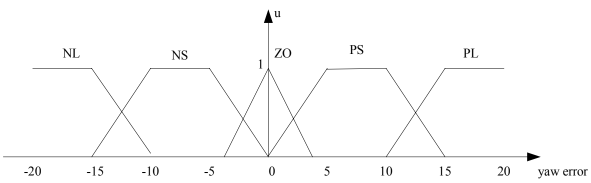

Fig 3. Membership functions for yaw error (ε)

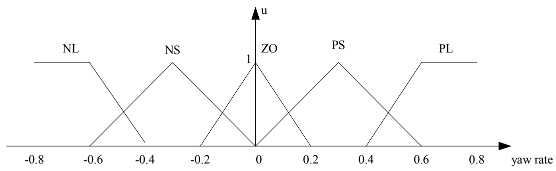

Fig 4. Membership functions for yaw rate (ω)

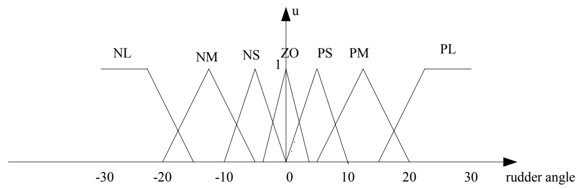

Fig 5. Membership functions for rudder angle (δ_c)

Step 3. Development of rule base

A fuzzy system is characterized by a set of linguistic statements based on expert knowledge. The expert knowledge is usually as "if-then" rules, which are easily implemented by fuzzy conditional statements in fuzzy logic. Fuzzy control rules have the form of fuzzy conditional statements that relate the state variables in the antecedent and process control variables in the consequence. The general form of the fuzzy control rules in the case of two-input single-output systems is:

IF x is A_1 and y is B_1 THEN z is C_1

IF x is A_2 and y is B_2 THEN z is C_2

……….

IF x is A_n and y is B_n THEN z is C_n

where x, y, and z are linguistic variables representing the process state variable and control variable, respectively. A_n, B_n and C_n are the linguistic values of the linguistic variables x, y and z in the universe of discourse U, V, and W, respectively[1][2].

The initial rule base is given by the experience of expert. It captures much of the behaviour of a skilled pilot or a helmsman. The fuzzy control rules for the ship manipulating system is :

If ε is NL and ω is PL then δ is PL

If ε is NL and ω is PS then δ is PL

……..

If ε is PS and ω is PL then δ is NL

Rules that were developed in the work are given in

Table1.

Table1

The rules table

<table>
<tr><td colspan="2" rowspan="2">δ_c</td><td colspan="5">ε</td></tr>
<tr><td>NL</td><td>NS</td><td>ZO</td><td>PS</td><td>PL</td></tr>
<tr><td rowspan="5">ϖ</td><td>PL</td><td rowspan="5">PL</td><td>NS</td><td colspan="2">NL</td><td rowspan="5">NL</td></tr>
<tr><td>PS</td><td>ZO</td><td colspan="2">NS</td></tr>
<tr><td>ZO</td><td>PS</td><td>ZO</td><td>NS</td></tr>
<tr><td>NS</td><td colspan="2">PS</td><td>ZO</td></tr>
<tr><td>NL</td><td colspan="2">PL</td><td>PS</td></tr>
</table>

Step 4. Defuzzification

The output is defuzzified to get a final value of the control. The widely used the center of area method strategy generates the center of gravity of the possibility distribution of a control action. The center of area method [3]is used in this application to give the defuzzifed rudder value as

$$Z^* = \frac{\sum_{i=1}^{n} C(u_i) \times u_i}{\sum_{i=1}^{n} C(u_i)}$$

where , u_i is the membership value of the output set i , $C(u_i)$ is the corresponding value. It is obvious that the output Z^* is mainly depended on consequent $C(u_i)$. So, It is simple to tune the consequent fuzzy value $C(u_i)$ of rule for rule justification. Finally, the control surface is shown in Fig 6.

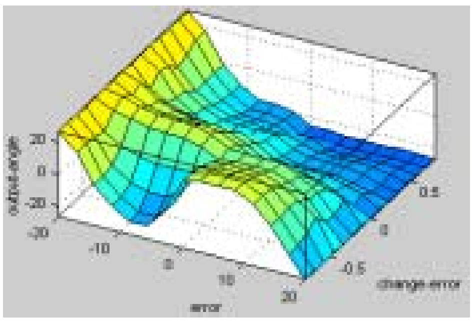

Fig 6. The control surface

Step 5. Establish fuzzy rule-based ship steering system

Although the design of a fuzzy controller does not depend on a mathematical model of the process, such a model is necessary to simulate the various motions of the ship.

Consider the following nonlinear ship's dynamics model[4][5]:

$$\left.\begin{aligned} (m+m_x)\dot{u} - (m+m_y)vr &= X_H + X_P + X_R \\ (m+m_y)\dot{v} + (m+m_x)ur &= Y_H + Y_P + Y_R \\ (I_{zz} + J_{zz})\dot{r} &= N_H + N_P + N_R \end{aligned}\right\} \quad (1)$$

The relation of the rudder angle signal δ and the ship's course ψ can be represented by the differential equation:

$$T_1T_2\dddot{\varphi} + (T_1+T_2)\ddot{\varphi} + \dot{\varphi} = K(1+T_3)\delta \quad (2)$$

where *K, T1, T2* and *T3* are the parameters which represent the ship's dynamics. These parameters are basically determined by the dimensions and forms of the vessel and also depend on operating conditions such as ship speed, load or ballast situation, draft, trim and water depth.

$$T_1T_2 = \frac{(m+m_y)(I_{zz}+J_{zz})}{C}; \quad T_1+T_2 = \frac{-(m+m_y)N_r - (I_{zz}+J_{zz})Y_v}{C}$$

$$K = \frac{N_vY_\delta - N_\delta Y_v}{C}; \quad T_3 = \frac{(m+m_y)N_\delta}{N_vY_\delta - N_\delta Y_v};$$

$$C = Y_nN_r - N_v\{Y_r - (m+m_x)u_0\}$$

Expressed as a differential equation:

$$T\ddot{\varphi} + \dot{\varphi} = K\delta \quad (3)$$

This attractively simple model provides a reasonably accurate representation of the performance of vessels when they keep a straight course or one with only slight changes. However, if the characteristics of the vessel's rotation are to be studied, a non-linear term [6]can be added to the linear model:

$$T_1T_2\dddot{\varphi} + (T_1+T_2)\ddot{\varphi} + kH_B\dot{\varphi} = K(1+T_3)\delta \quad (4)$$

where $H_B(\psi)$ is a non-linear function of ψ which is obtained from the relation between $\dot{\psi}$ and δ in the steady state by means of the spiral test. This can be approximated by:

$$H_B(\psi) = b_3\dot{\psi} + b_1\dot{\psi} \quad (5)$$

If equation (3)is used, we get $T\ddot{\varphi} + H_N\dot{\varphi} = K\delta$ (6)

With $H_N(\psi) = n_3 \psi^3 + n_1 \psi$. (7)

This paper uses the non-linear model given by equation (6) for the design of the controller and for performing the simulations.

In this paper we consider wave disturbances during course keeping. We shall deal with 2nd-order wave transfer function approximation. This model is written as:

$$h(s) = \frac{K_\omega s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \quad (8)$$

A linear state-space model can be obtained by transforming this expression to the time-domain by:

$$\frac{d^2 y}{dt^2} + 2\zeta\omega_0 \frac{dy}{dt} + \omega_0^2 y = K_\omega \frac{d\omega}{dt} \quad (9)$$

Defining $\frac{dx_{h1}}{dt} = x_{h2}$ and $x_{h2} = y_h$,we can write state-space model as:

$$\begin{bmatrix} \frac{dx_{h1}}{dt} \\ \frac{dx_{h2}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega_0^2 & -2\zeta\omega_0 \end{bmatrix} \begin{bmatrix} x_{h1} \\ x_{h2} \end{bmatrix} + \begin{bmatrix} 0 \\ K\omega \end{bmatrix} \omega_h \quad (10)$$

where ω_h is a zero-mean white noise process. This model is highly applicable for control systems design due to its simplicity.

The original fuzzy controller designed in the ship steering system is tested by simulation in Matlab using Simulink with Fuzzy Logic Toolbox.

Fig 7 shows the heading response curve of fuzzy rule-based ship steering control system.

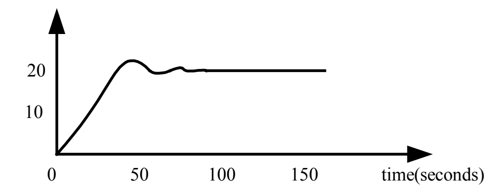

Fig 7. The heading response curve of control system

Ⅲ. TUNE THE FUZZY RULES

Some methods to adjust the initial rule base are researched.[7][8][9] The initial rule bases was established. And these parameters are generally off-line determined by the designers' experience from the process control point of view. Then, we will tune the rule bases to satisfy desired performance specifications.

In this paper, we need the simple and easy method to modify the rules. We proposed the real-time tuning algorithm to tune the consequent part fuzzy values of predictive controllers using fuzzy arithmetic operations according to the change status of system error, hence the rule base is regulated.

Let *r* be the desirable output of system, the errors *e* between desirable output and the response of system can be given as follow:

e ＝ r － yi i = 1, 2, 3

In order to tune the fuzzy control system and to get tuning rules base, here the error *e* is parted into three linguistic value as show in figure 8. The control *u* is parted into five linguistic values, shown as figure 9.

The fuzzy control system is implemented by computer, and then the response status is sampled according to the constant period. If the error *e* between the desirable output of system and the actual one in instant t had been known, so that the error *e* in instant (t+1) would decide how the control value *u* in distant t is tuned. The tuning rules given above can be expressed by the tuning rules base table shown as table 2.

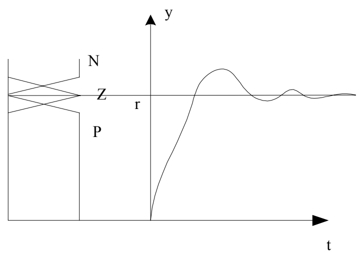

Fig 8. Membership functions for inputs

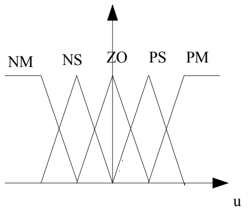

Fig 9. Membership functions for control u

TABLE 2

The tuning rules table

u(t)		e(t)		
		N	ZE	P
e(t+1)	P	NB	NM	NS
	ZE	NS	ZE	PS
	N	PS	PM	PB

The Fig 10 shows the control surface after tuning. The response curve of error after tuning is show in Fig 11. The heading curve after tuning in Fig 11 is obviously better than the curve before tuning in Fig7.

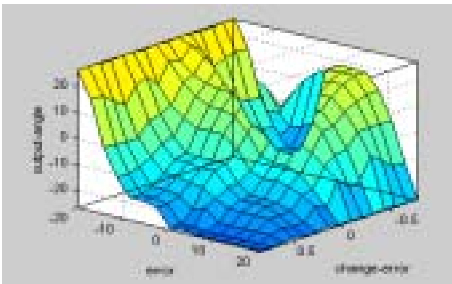

Fig 10. The control surface after tuning

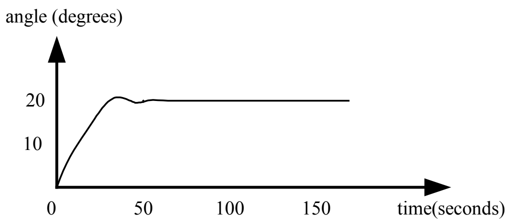

Fig 11. The heading response curve of control system after tuning

Ⅳ.FUZZY CONTROLLER VERSUS PID CONTROLLER

An autopilot must fulfil two objectives: course-keeping and course-changing. In the first case, the control objective is to maintain the ship's heading following the desired course (*y(t)* =constant). In the second case, the aim is to implement the course change without oscillations and in the shortest time possible. In both situations, the operability of the system must be independent of the disturbances produced by the wind, the waves and the currents.

As stated earlier, to compare the performance of the ship manipulating control system with the fuzzy controller designed in this paper and the conventional PID controller with the best results.

For course-changing and course-keeping of the ship manipulating system, the performance of the fuzzy controller designed and PID controller is implemented in MATLAB/Simulink environment.

For large signal transient in course-changing, the response to course-change manoeuvres of 20 degrees were obtained. The yaw response of the two kinds of controllers was shown in Fig 12. And the rudder response was show in Fig 13.

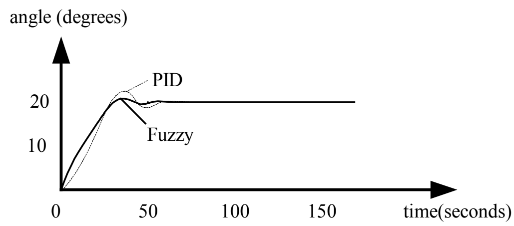

Fig12. Course-changing manoeuvres: the heading response

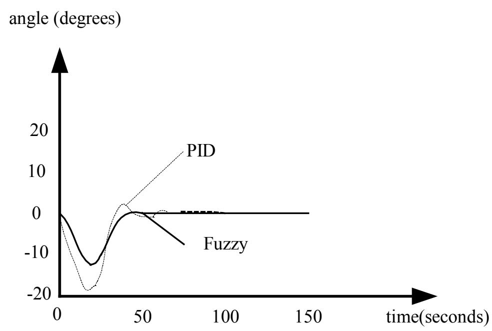

Fig 13 Couse-changing manoeuvres: the rudder response

Fig 12 shows the yaw angle errors between the desired and obtained yaw responses. It can be observed that the fuzzy controller obtains a perfect performance for the course-changing manoeuvres. The fuzzy controller produces a good behaviour with errors below 1 degree. With the PID controller, the errors are far greater. And the lower rudder response for the manoeuvre in fuzzy control system is shown in Fig 13.

For course-keeping manoeuvres in the presence of external disturbances. The yaw response of the two kinds of controllers designed under the worst case conditions of the ship system which exist random disturbance was shown in Fig 14. And the rudder response was show in Fig 15.

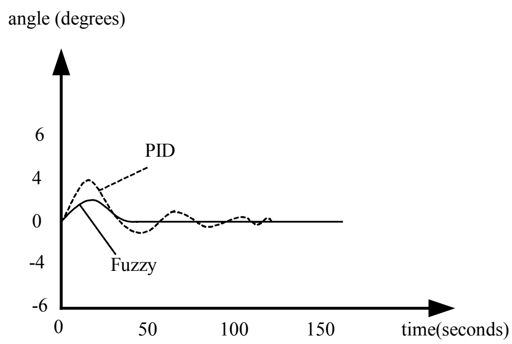

Fig.14. Course-keeping manoeuvres: the heading response with random disturbance

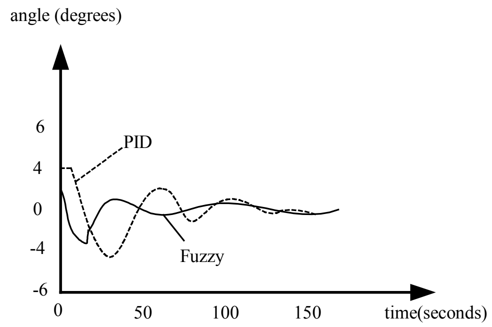

Fig.15.Couse-keeping manoeuvres: the rudder response with random disturbance

Fig 14 and Fig 15 show that a decrease in oscillations can be achieved by the fuzzy controller. Fuzzy controller avoid oscillations in the course-keeping control system which exists random disturbance. The fuzzy controller is having a better performance than PID controller.

Ⅴ.CONCLUSION

This paper describes the design of a fuzzy controller for the control of course-changing and course-keeping manoeuvres in ship manipulating system. Through the using real-time tuning algorithm via simulation-optimization for the tuning of the fuzzy controller, values were obtained which enable a satisfactory behaviour in different manoeuvring situations. The superiority of the fuzzy controller over the classical PID controller is also shown by simulation result .

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