Study on a New and Effective Fuzzy PID Ship Autopilot

Minh-Duc Le*, and Lan-Anh Nguyen**

* Vietnam Shipbuilding Industry Corporation (VINASHIN), Hanoi, Vietnam
(Tel : +84-4-7339697; E-mail: le_minh_duc@yahoo.com)
**Tula State University, Lenin pr, .92 Tula , 300600, Russia
(Tel : +81-3-000-0000; E-mail: aarai@japan.ac.jp)

Abstract: Ship Autopilots are usually designed based on the PD and PID controllers because of simplicity, reliability and easy to construct. However their performance in various environmental conditions is not as good as desired. This disadvantage can be overcome by adjusting works or constructing adaptive controllers. But those methods are complex and not easy to do.

This paper presents a new method for constructing a Ship Autopilot based on the combination of Fuzzy Logic Control (FLC) and Linear Control Theory (PID control). The new Ship Autopilot has the advantages of both the PID and FLC control methodologies: easy to construct, and optimal control laws can be established based on ship masters' knowledge. Therefore, the new ship autopilot can be well adapted with parameter variations and strong environment effects. Simulation using MATLAB software for a ship with real parameters shows high effectiveness of the Fuzzy PID autopilot in course keeping and course changing manoeuvres in comparison with the ordinary PID ship autopilots.

Keywords: PID control, Linear control, Sliding Mode Control Methodology, Fuzzy Logic Control, Ship Autopilots, Ship Steering Dynamics

1. INTRODUCTION

In the last twenty years, together with the drastic development of micro-electronics and control theory, several new and effective methods have been proposed and developed for designing Ship Autopilots [1], [2], [3], [4], [5]. Ship Autopilots designed based on the PD and PID controllers are simple, reliability and easy to construct, however their performance in various environmental conditions is not as good as desired. Therefore, Ship Autopilots with PD or PID controllers are usually required aids from operators to adjust controllers' parameters corresponding to navigating conditions. This adjusting work is called "weather adjustment" and is an undesirable work for the operators. Parameter adjustment is a difficult task and if carried out not properly it can cause damages to machines and unnecessary fuel consumptions. Another more effective method is to construct adaptive controllers based on ship models. This method can be used for various types of ship described by nonlinear mathematical models. But on the other hand, it also has several disadvantages, one of these is its completeness since the range of parameters and environmental disturbances is usually very large.

A new method for constructing Ship Autopilots based on Variable Structure Controllers (VSC) or the so called Sliding Mode Controllers (SMC) was proposed by Papoulias and Healey. Using this method one can construct high quality Ship Autopilots that is not much influenced by variations of parameters and disturbances. Although the traditional Sliding Mode Controllers have several advantages, they have also a very weak point that is the saturation in the sliding surface. Working in this state, the controllers have to operate in rather high frequency that causes wasting energy largely and reduces the quality of the controllers [6], [7], [8].

Recently, a tendency that is of much interested is to combine actively various methodologies for exploiting the advantages of each one [6], [9], [10]. One of the most effective solutions is combining Linear Control Theory and Fuzzy Logic Control (FLC). This paper presents a new method to rise the quality of the Ship Autopilots, that is the Fuzzy PID Autopilots (FPID Autopilots) based on the combination of FLC and PID Autopilot. The new Ship Autopilot has the advantages of both the FLC and PID control methodologies. For example, a system of optimal control laws can be established based on ship operator experts' knowledge, so that the designed Ship Autopilot has behaviors similar to that operated by human being. Moreover, one notable advantage of the new Ship Autopilot is that it can be adapted with complicated ship steering systems with parameter variations and strong environmental effects.

In the first part of this paper, ship hydrodynamics and mathematical models used for expressing ship motions in steering maneuvers are presented. The second part of the paper gives summary of PID Ship Autopilot, FLC and their combination to construct the FPID Ship Autopilot. The new method has been applied to construct a FPID Ship Autopilot for a ship with real parameters. To verify effectiveness of the FPID Ship Autopilot, simulation of several ship steering maneuvers has been carried out with MATLAB software. Results of this simulation are presented in comparison with the ordinary PID Ship Autopilot in the third part of this paper. And finally, some main conclusions are drawn and future research directions are given.

2. THE MATHEMATICAL MODEL EXPRESSING SHIP STEERING DYNAMICS

2.1 General structure of a ship automatic steering system

The general structure of ship automatic steering system [11] is shown in Fig. 1.

The system consists of:

- A steering equipment (steering machine): used to produce necessary forces for rotating rudder an required angle δ in an interval and keep the rudder at a fixed angle while ship is moving.
- Ship: control object.
- Gyrocompass: used to find the real ship heading angle ψ. This angle is compared with desired heading angle Ψ_d to calculate control error of heading:

$$\Delta\psi = \psi_d - \psi \qquad (1)$$

Based on this error, steering machines generates control signal to deflect rudder into a suitable angle to reduce error of heading and keep the ship in a predetermined direction.

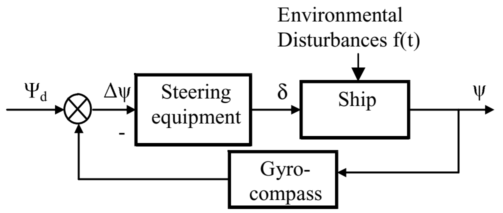

Fig. 1 General structure of ship steering systems

2.2 Mathematical description

Corresponding to the general structure of a steering system shown in Figure 1, steering equipment can be divided into a controller and a rudder angle regulator (that is a amplifier with boundary limitation). The ship is usually expressed by a transmission function (between heading angle ψ and rudder deflection angle δ) for both course-stable and course-unstable cases are expressed as following (plus for course-stable case and minus for course-unstable case):

$$W_\delta(p) = \frac{\psi(p)}{\delta(p)} = \frac{k_c(1+\tau_1 p)}{p(T_2 p^2 + T_1 p \pm 1)} \quad \text{(3-order)} \quad (2)$$

$$W_\delta(p) = \frac{\psi(p)}{\delta(p)} = \frac{k_c}{p(T_1 p \pm 1)} \quad \text{(2-order)} \quad (3)$$

Then, block diagram of a simple autopilot can be drawn as shown in Figure 2.

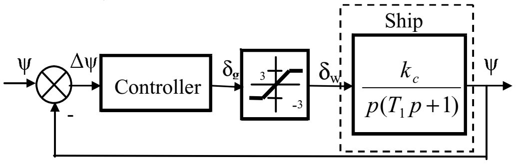

Fig. 2 Block diagram of a simple autopilot

2.3 Control method based on PID controller

In this method, rudder deflection angle $\delta(t)$ is controlled by PID control law based on error of heading angle $e(t) = \psi_r(t) - \psi(t)$, here ψ_r reference (desired) heading angle, as expressed by following equation:

$$\delta(t) = K_p e(t) + K_d \frac{de(t)}{dt} + K_i \int e(t)dt \quad (4)$$

, and the transmission function is as follows:

$$w_c(p) = \frac{\delta(p)}{e(p)} = K_p + K_d p + \frac{K_i}{p} \quad (5)$$

Parameters K_p, K_i, K_d of the PID controller can be estimated using Routh-Hurwitz methodology [12]. Usually, only 2 equations can be established, where as the number of parameters is 3, then 1 parameter is chosen to satisfy some criteria and the others then calculated accordingly. In the case of 2-order system, the PID parameters can be chosen to satisfy control quality criteria such as overshoot, time of stable and so on. With a chosen K_i, K_p, K_d are calculated by:

$$K_p = \frac{-\sin(\beta+\varphi)}{|w_p(s_1)w_c(s_1)|\sin\beta} - \frac{2K_i\cos\beta}{|s_1|} \quad (6)$$

$$K_d = \frac{\sin(\varphi)}{|s_1||w_p(s_1)w_c(s_1)|\sin\beta} + \frac{K_i}{|s_1|^2} \quad (7)$$

, here s_1 is the pole of closed-loop control system, β and φ are parameters defined by:

$$s_1 = |s_1| e^{j\beta} \quad (8)$$

$$w_p(s_1)w_c(s_1) = |w_p(s_1)w_c(s_1)| e^{j\psi} \quad (9)$$

2.4 The FPID controller

Fuzzy logic controllers (FLC) have good characteristics on the zones with large error of control, where the controllers can produce quick dynamic responses due to non-linear characteristics. Besides, when the controllers work near stable points, the role of FLC is not sufficient, and a PID controller may have better effectiveness.

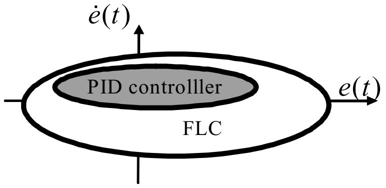

Fig. 3 FLC and PID controllers' effective zones

Changing from FLC to PID and vise versa is done by following simple laws:

if $|e(t)|$ **is** PB **and** $|\dot{e}(t)|$ PB **then** u **is** FLC (10)

if $|e(t)|$ **is** PS **and** $|\dot{e}(t)|$ PS **then** u **is** PID (11)

, where PS, PB are condition expressions. This can be applied for cases when several PID controllers are used and each of them has a pre-determined working zone. In these cases, changing laws has the following form:

Ru(i): **if** ER **is** E^p **and** CER **is** CE^q **then**

$$u_i = K_{Pi} e + K_{Ii} \int_0^t e(\tau)d\tau + K_{Di} \frac{de}{dt} \quad (12)$$

i = 1, 2, ..., n

, where u_i is the working results of the i^{th} PID controller. If define:

$$\sigma_i(t) = \frac{(\mu_i(e(t)) \times \mu_i(\dot{e}(t)))}{\sum_{i=1}^{n} \mu_i(e(t)) \times \mu_i(\dot{e}(t))} \tag{13}$$

with $\mu_i(.)$ is the membership functions, then results of the FPID controller according to the system of laws (12) can be drawn as follows:

$$u(t) = K_{PN} e + K_{IN} \int_0^t e\, dt + K_{DN} \frac{de}{dt} \tag{14}$$

$$\begin{cases} K_{PN} = \left(\sum_{i=1}^{n} \sigma_i(t) K_{Pi} \right) \\ K_{DN} = \left(\sum_{i=1}^{n} \sigma_i(t) K_{Di} \right) \\ K_{IN} = \left(\sum_{i=1}^{n} \sigma_i(t) K_{Ii} \right) \end{cases} \tag{15}$$

3. SIMULATION RESULTS AND EVALUATION

The FPID controller was designed for a 16.500 T named Kabec (a Russian flag ship) with following parameters:

$$k_c = (0{,}0311 \div 0{,}057)\, \sec^{-1};\ T_1 = (14 \div 19)\, \sec \tag{16}$$

Parameters of the PID controller are shown in Table 1.

Table 1: Parameters of the PID autopilot for the Kabec

K_P	K_I	K_D
90	40	400
150	55	380
205	75	250
98	95	180
335	125	130

If inputs and output are defined as follows:

$$\begin{cases} |e(t)| \doteq \{\text{VPS, PS, PM, PB, VPB}\} \\ |\dot{e}(t)| \doteq \{\text{PS, PM, PB}\} \\ u(PID_i) \doteq \{\text{PID}_1, \text{PID}_2, \text{PID}_3, \text{PID}_4, \text{PID}_5\} \end{cases} \tag{17}$$

, and the de-fuzzification laws are chosen as shown in Table 2.

Table 2: De-fuzzification laws for FPID autopilot

$|e(t)|$ $|\dot{e}(t)|$	**VPS**	**PS**	**PM**	**PB**	**VPB**
PS	PID_5	PID_4	PID_3	PID_2	PID_1
PM	PID_5	PID_4	PID_3	PID_2	PID_1
PB	PID_5	PID_4	PID_3	PID_2	PID_1

Membership functions for $|e(t)|$, $|\dot{e}(t)|$ were chosen using Gaussian distribution form in [0, 1] interval as shown in Figures 4a, 4b.

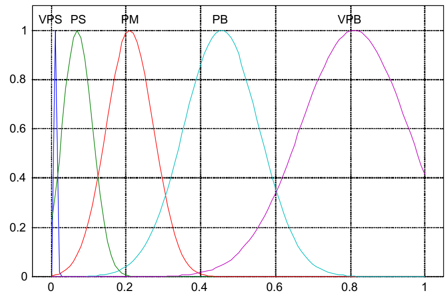

Fig. 4a: Membership function for heading angle error

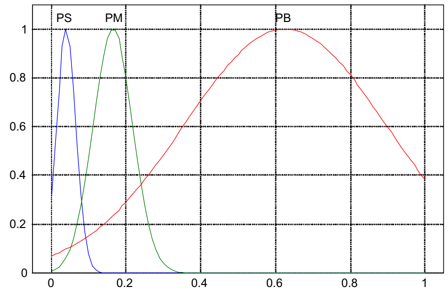

Fig. 4b: Membership function for ship turning rate

MATLAB simulation results of the PID autopilot and FPID autopilot are shown in Figures 5a, 5b, 5c.

It is clearly seen that, in comparison with the PID autopilot, the new FPID autopilot has several important features:

- In general ship heading error (or deflection of ship heading angle from reference values) of FPID autopilot is smaller than that of PID autopilot;
- Times of over-correction and maximum values of overshoot of heading angle for FPID autopilot are much more smaller than that of the PID autopilot;

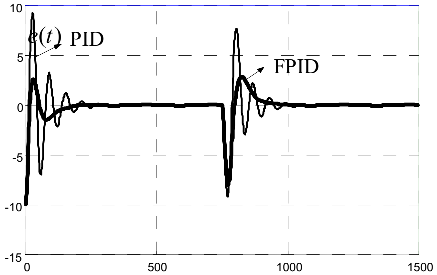

Fig. 5a Ship heading error according to PID and FPID autopilots

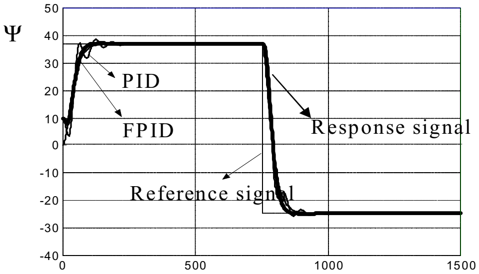

Fig. 5b Ship heading angle according to PID and FPID autopilots

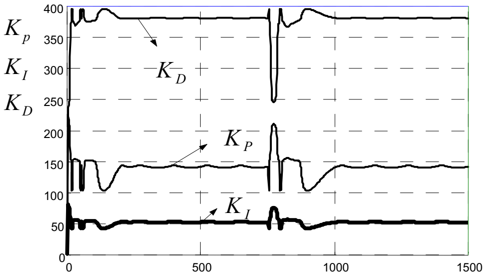

Fig. 5c PID and FPID autopilots' parameters during maneuvers

4. CONCLUSIONS AND FUTURE WORKS

A new method for constructing Ship Autopilots based on the combination of Fuzzy Logic Control (FLC) and Linear Control Theory (PID control) has been presented. The new Ship Autopilot has the advantages of both the PID and FLC control methodologies: easy to construct, and optimal control laws can be established based on ship masters' knowledge. Simulation using MATLAB software for a ship with real parameters shows that the FPID autopilot has several important features in comparison with the corresponding PID autopilot. The new autopilot is much more effective than PID autopilot in course keeping and course changing manoeuvres.

However, in order to be able to use the FPID autopilot in practice, several problems should be solved, among them are: what is most suitable form for membership functions of the FPID controller, how to automatically design the membership functions and de-fuzzification laws for the autopilot, what criteria should be chosen for the optimal autopilot, consideration of real aspects of the autopilot, and so on.

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