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A Model reference adaptive speed control of marine diesel engine by fusion of PID controller and fuzzy controller

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Abstract : The aim of this paper is to design an adaptive speed control system of a marine diesel engine by fusion of hard computing based proportional integral derivative (PID) control and soft computing based fuzzy control methods. The model of a marine diesel engine is considered as a typical non oscillatory, second order system. When its model and the actual marine diesel engine are not matched, it is hard to control the speed of the marine diesel engine. Therefore, this paper proposes two methods in order to obtain the speed control characteristics of a marine diesel engine. One is an efficient method to determine the PID control parameters of the nominal model of a marine diesel engine. Second is a reference adaptive speed control method that uses a fuzzy controller and derivative operator for tracking the nominal model of the marine diesel engine. It was found that the proposed PID parameters adjustment method is better than the Ziegler& Nichols' method, and that a model reference adaptive control is superior to using only PID controller. The improved control method proposed here, could be applied to other systems when a model of a system does not match the actual system.

Key words : Marine diesel engine, PID control, Model reference adaptive control, Derivative controller, Fuzzy logic, Adaptive speed control system

1. Introduction

Recently, marine diesel engines have become low speed and long stroke devices in order to reduce the fuel consumption. But, these kinds of marine diesel engines have problems with severe frictional wear of operating parts of the fuel rack due to fuel index jiggling, and they also have the problem of the delay time related to fuel injection system. Furthermore, the values of parameters for a marine diesel engine vary widely according to the operating range, and it is very difficult to find out the exact parameter values for marine diesel engine[1]. In the past, a

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hydro mechanical governor had fixed parameter values for controller and a simple control algorithm such as proportional control. Therefore, the governors were unable to achieve the effective speed control of a marine diesel engine. As a counter measure to solve the above problem, digital governors using microcomputer were developed, and are now used in some marine vessels. So far, many digital governors use PID control algorithm[2] to regulate the speed of a marine diesel engine[3]-[5]. The performance characteristics of this kind of PID controller are changed remarkably by the adjustment of the parameters of the controller. Hence, the adjustment of parameters of the PID controller is very essential. Ziegler & Nichols' method[6] has been used in order to adjust the parameters of the PID controller, and a method that minimizes the value of the criterion function by the adjustment of PID parameters has been utilized[4]. In addition to the above, nowadays, several kinds of speed control method such as LQ (Linear quadratic) optimal control[7]-[12], adaptive speed control by the nominal tracking system model[13], speed control by the fuzzy PID controller or neural network PID controller[14],[15], are suggested.

In this paper, the model of a marine diesel engine is considered as a typical non-oscillatory, second-order system. A new parameter adjusting method is proposed for PID controller to be suitable for speed control. The system which consists of PID controller and marine diesel engine model is regarded as a nominal model. This also suggests that even when the model does not match the actual marine diesel engine, the adaptive speed controller based on fuzzy logic for tracking of the nominal model can control the speed of the marine diesel engine more effectively. The results of the unit step responses show that this proposed method has a superior response characteristics compared with Ziegler & Nichols' method. In addition, the proposed whole system which consists of the nominal system model and the tracking system for nominal model shows a better speed sensitivity in the unit step responses with no overshoot.

2. Modeling and control system of marine diesel engine

Generally, a marine diesel engine system consists of two parts: combustion part and rotating part. Therefore, the marine diesel engine model is considered as two first order systems with steady state gains (K_f, K_r) and time constants (T_f, T_r) as shown in Fig. 1.

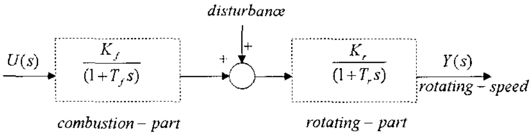


Fig. 1 Block diagram of a marine diesel engine

2.1 Adjustment of PID Parameters

Fig. 2 indicates a general block diagram for PID control system which is described by

$$G_p(s)=\frac{K}{(1+T_f s)(1+T_r s)},\ K=K_f\cdot K_r \qquad (1)$$

$$G_c(s)=K_p\left(1+\frac{1}{T_t s}+T_d s\right) \qquad (2)$$

$$G_m(s)=\frac{K_o}{(1+T_{fo}s)(1+T_{ro}s)} \qquad (3)$$

$$\frac{Y(s)}{Y_r(s)}=G(s)=\frac{G_c(s)G_m(s)}{1+G_c(s)G_m(s)} \qquad (4)$$

$$T_i=T_{fo}+T_{ro},\ T_d=\frac{T_{fo}T_{ro}}{T_i},\ K_p=\frac{T_i}{K_oT_m} \qquad (5)$$

$$G(s)=\frac{1}{(1+T_ms)} \qquad (6)$$

Here, $G_p(s)$ is the transfer function of an actual marine diesel engine. $G_c(s)$ is the transfer function of PID controller consisting of proportional gain (K_p), integral time (T_i) and derivative time (T_d). K in (1) indicates the steady state gain of the marine diesel engine.

Actually, it is difficult to determine the parameters of $G_p(s)$. Assuming that when finding out exactly the values of parameters of $G_p(s)$, the exact parameters of $G_p(s)$ are K_o , T_{fo} and T_{ro}, and $G_m(s)$ implies the model of $G_p(s)$. If $G_p(s)$ is replaced by $G_m(s)$ in Fig. 2, the overall closed transfer function $G(s)$ of this PID control system is given by (4). Furthermore, if the parameters of PID controller are adjusted according to (5), the overall transfer function $G(s)$ of this PID control system is rewritten as (6) that indicates a first order time delay system in which the steady state gain is one and the time constant is T_m.

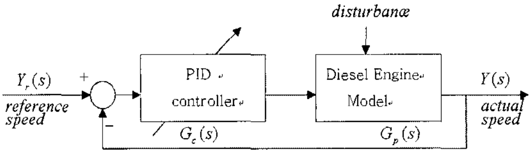
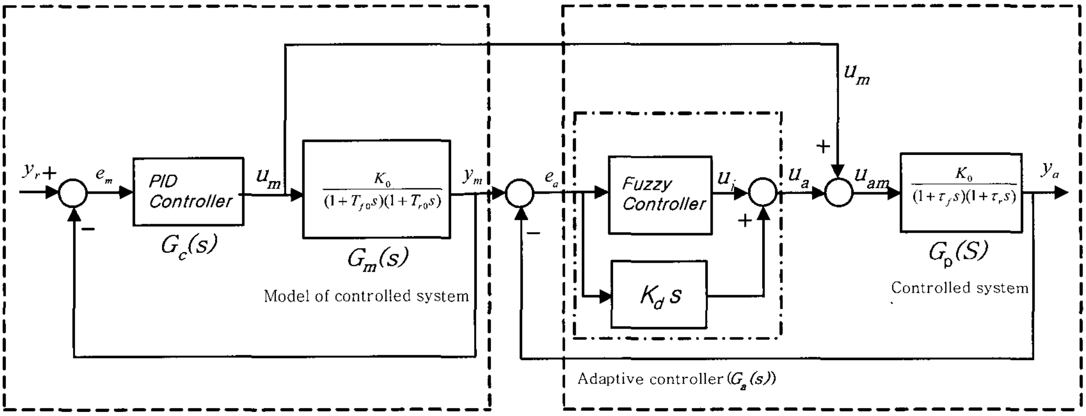


Fig. 2 PID control system

2.2. Nominal Model Adaptive Speed Control System

2.2.1. System Configuration

If $G_m(s)$ equals $G_p(s)$, the speed of a marine diesel engine will be effectively controlled by adjusting the PID parameters as shown earlier. But, $G_m(s)$ is rarely equivalent to $G_p(s)$ in the actual situation due to factors such as engine modeling error, variation of the operating



Nominal model　　Tracking system for nominal model

Fig. 3 Nominal model adaptive speed control system.

and environmental conditions and disturbances. In order to compensate for the differences between $G_m(s)$ and $G_p(s)$, a model reference adaptive control system (MRAC)[16], is added to PID feedback system as shown in Fig. 3. Tracking system for nominal model consists of the adaptive controller ($G_a(s)$) and controlled system ($G_p(s)$). The adaptive controller consists of a fuzzy controller and a derivative controller.

2.2.2. Characteristics of the Tracking System for Nominal Model

Fig. 4 shows the equivalent transformation of the tracking system for nominal model between $Y_a(s)$ and $Y_m(s)$. Here,

$$G_r(s) = 1 + \frac{1}{G_a(s)G_m(s)} \tag{7}$$

where, $G_r(s)$ obtained from Fig. 3 corresponds to the set point for the tracking system for nominal model. Generally, $G_r(s)$ which includes the phase lead element, has the function of prediction. The overall transfer function, $G_T(s)$ in Fig. 4 is given by

$$G_T(s) = \frac{Y_a(s)}{Y_m(s)} = 1 + \left(\frac{1}{1+G_a(s)G_p(s)}\right)\left(\frac{G_p(s)-G_m(s)}{G_m(s)}\right) \tag{8}$$

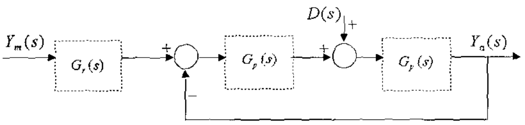


Fig. 4 Equivalent block diagram of tracking system for nominal model.

If the deviation between the input ($y_m(t)$) and output ($y_a(t)$) is defined as $e(t)$, the output of the nominal tracking system can be written as

$$y_a(t) = y_m(t) + e(t) \tag{9}$$

where, $e(t) = L^{-1}\left[Y_m(s)\left\{\frac{1}{1+G_a(s)G_p(s)}\right\}\left\{\frac{G_p(s)-G_m(s)}{G_m(s)}\right\}\right]$.

If $G_p(s)$ equals $G_m(s)$, $e(t)$ becomes zero, namely, $y_m(t)$ always equals $y_a(t)$. Although theoretically possible, $G_p(s)$ rarely equals $G_m(s)$ in the actual system, and the gain of adaptive controller cannot be infinite because perfect conditions cannot be met. Therefore, the adaptive controller needs to include the function of integrator to eliminate the offset in the nominal tracking system model.

2.2.3. Design of adaptive controller

A tracking system for nominal model is designed to perform two functions. One is the function of an integrator in order to eliminate the steady state error of system, the other is the function of a derivative controller to reduce the hunting of the tracking system for nominal model. The design method of the adaptive controller by H_∞ control theory was given in[11]. This method is superior in terms of the system stability and robustness. But, H_∞ control theory is not recommended in terms of the speed sensitivity and reduced overshoot. Hence, in this paper, an adaptive controller combining a fuzzy controller with a derivative controller is proposed as shown in Fig. 5. A relatively simple fuzzy controller[17] used in this study takes care of insufficient information of controlled system, and a derivative controller plays the role of reducing the hunting caused by the integral action of the fuzzy controller.

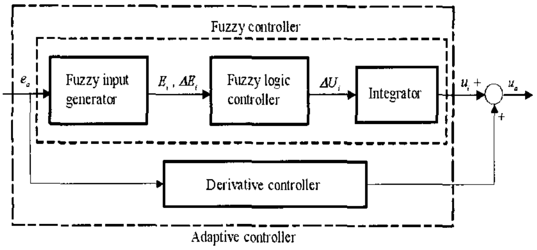


Fig. 5 Block diagram of adaptive controller.

The input variables (E_i , ΔE_i), output (ΔU_i) of the fuzzy logic controller and the output (u_i) of the integrator are given by

$$E_i = e_a(i)/e_{max},\ \Delta E_i = \Delta e_a(i)/\Delta e_{max} \tag{11}$$

$$\Delta U_i = \Delta u(i)/\Delta u_{max},\ u_i = u_{i-1} + \Delta u_i,\ u_i = u(ih) \tag{12}$$

In equation(11), $e_a(i)$ means $e_a(ih)$, and h is sampling time and $\Delta e_a(i)$ equals $\dfrac{e_a(i)-e_a(i-1)}{h}$. Also, $e_a(t)$ is the deviation between ideal response of the nominal engine model $y_m(t)$ and controlled object output $y_a(t)$. In addition, e_{max} , Δe_{max} and Δu_{max} take the maximum estimated values used for normalization. Here, fuzzy input space is divided into two simple control rules:

Control rule 1 : R^1 = *If* E_i *is P and* ΔE_i *is P then* ΔU_i *is* P', (13)

Control rule 2 : R^2 = *If* E_i *is N and* ΔE_i *is N then* ΔU_i *is* N'. (14)

P and P' indicate the positive fuzzy variables, and N and N' indicate negative fuzzy variables. Fig. 6 shows the response that fuzzy controller will follow according to the IF-THEN type control rules (R^1, R^2). R^1 is the control rule for region D. and R^2 is the control rule for region B. Also, control rule R^1 and R^2 act complementarily within the region A and C [9]-[13].

The simple membership functions for the antecedent portion (P and P') and consequent portion (N and N') are given by

$$\text{Antecedent : } P(x) = (1+x)/2,\ N(x) = P(-x) \tag{15}$$

$$\text{Consequent : } P'(x) = x,\ N'(x) = P'(-x) \tag{16}$$

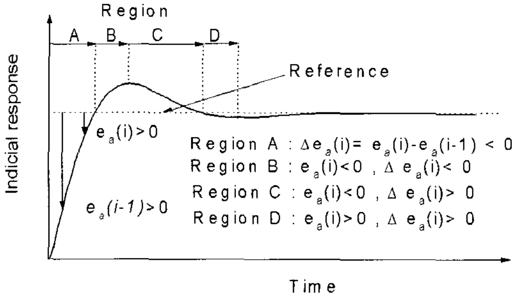


Fig. 6 Control logic according to the region

Fig. 7 illustrates the membership functions. The output of fuzzy controller is given by

$$\omega_1 = P(E_i^0) \wedge P(\Delta E_i^0),\ \omega_2 = N(E_i^0) \wedge P(\Delta E_i^0) \tag{17}$$

$$\Delta U_i = (\omega_1 P'(\omega_1) + \omega_2 N'(\omega_2))/(\omega_1 + \omega_2) \tag{18}$$

These equations are obtained by simplifying the fuzzy inference suggested by Tsukamoto[18].

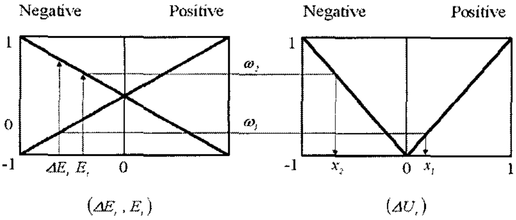


Fig. 7 Membership functions

In (17), $\omega_1$and ω_2 denote the grades to control rule R^1, R^2 and Λ denotes minimum operator, E_i^0 and ΔE_i^0 denote the crisp information to be obtained from the control object. Equation (18) shows the output of the fuzzy logic controller. In equation (18), $P'(\omega_1)$ equals x_1 and $N'(\omega_2)$ equals x_2. Accordingly, the input of actual controlled object can be expressed as

$$u_{am}(i)=u_a(i)+u_m(i)=u(i)+K_d\Delta e_a(i)/h+u_m(i) \qquad (19)$$

where, K_d is a gain of derivative controller, u_a is the output of adaptive controller, and u_m is the output of PID controller.

3. SIMULATION and RESULTS

3.1 Controlled System

The B&W4L80MC marine diesel engine with the specifications in Table 1 is selected for our present study. Fig. 8 shows the parameters ($K=K_fK_r$, T_f , T_r) of the marine diesel engine to be obtained by the calculation method of NORCON company[19] using the data of a no-load (e.g., a vessel without cargo) sea trial test of the marine diesel engine described below.

Table 1 Specification of B&W4L80MC Marine Diesel Engine

Bore × Stroke × Cycle	800×2592mm×2cycle
P_{mean}	18.11 kg/cm^2
BHP(MCR)	15,880BHP(at 83RPM)
Moment of inertia	27,130.27 kg · m · sec^2
F.O. consumption	125g/BHP · hr

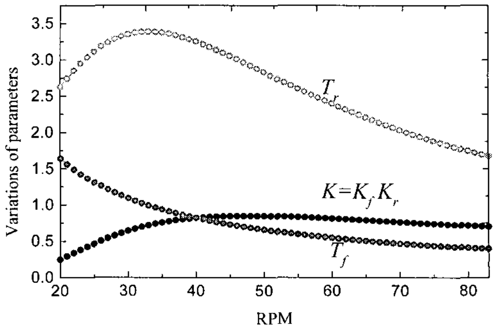


Fig. 8 Variations of parameters of B&W4L80MC marine diesel engine (under no load).

3.2 Simulation and Results

First, when a model of controlled system and an actual controlled system do not agree, the simulation for the unit step response of the nominal model adaptive speed control system is carried out. The sampling time for simulation is 0.05 second and the usual operation range of the marine diesel engine is 20 rpm to 83 rpm. Fig. 9 illustrates the comparison of the unit step responses by the Ziegler&Nichols' PID parameter adjustment method and a proposed PID parameter adjustment when excluding the adaptive controller in the Fig. 3. In Fig. 9, C83 means that the parameters of the PID controller are determined when the marine diesel engine is operating at 83 rpm, and E20 means that the marine diesel engine is running at 20 rpm. C83+E20 means that the parameters of the PID controller are the values at 83 rpm but the engine operating at 20 rpm. T is the ideal time constant of closed-loop nominal model when the proposed PID parameters adjustment is adopted. Fig. 10 shows the comparison of unit step responses by the Ziegler&Nichols' PID method and a proposed PID parameter adjustment when including the tracking system for nominal model in the Fig. 3.

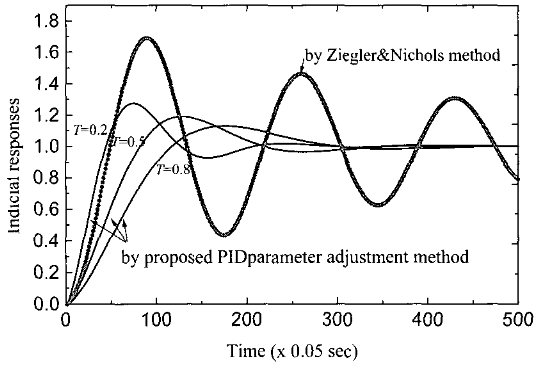


Fig. 9 Comparisons of unit step responses excluding the tracking system for nominal model at C83+E20.

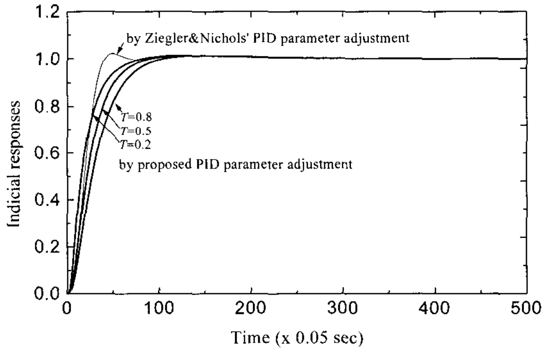


Fig. 10 Comparisons of unit step responses including the tracking system for nominal model at C83+E20.

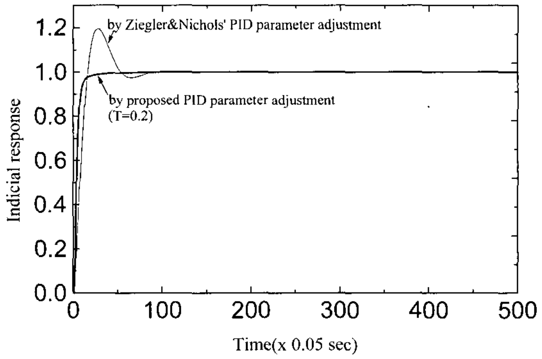


Fig. 11 Comparisons of unit step responses when the model of controlled system coincides with the actual controlled system at C83+E83.

Second, when a model of controlled system coincides with an actual system, the simulation for the unit step response of the nominal model adaptive speed control system is shown in Fig. 11.

Fig. 12 shows that when a model of controlled system and an actual controlled system do not agree, the unit step responses are improved by the adaptive control.

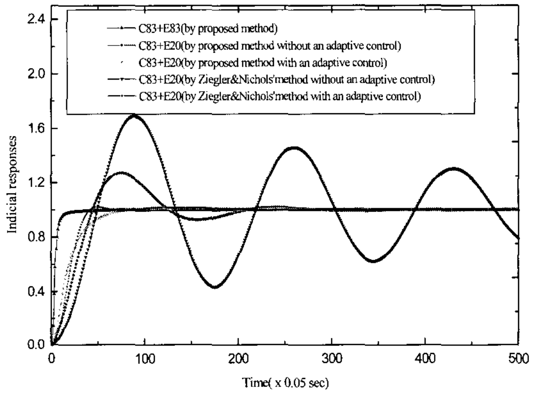


Fig. 12 Comparisons of unit step responses when the adaptive control is adopted.

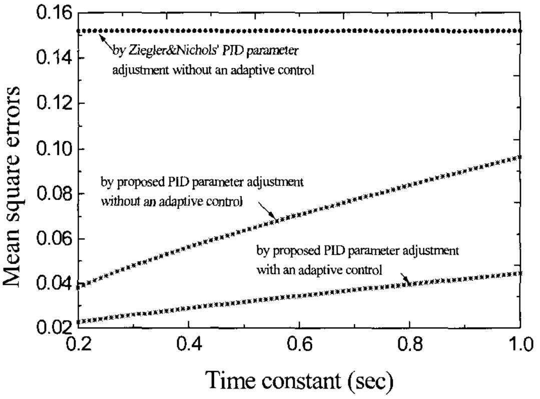


Fig. 13 Comparisons of mean square errors (at C83+E20).

Fig. 13 illustrates the comparison of the mean square errors when the model of controlled system does not match the actual controlled system. Fig. 14 indicates the comparison of the mean square control input when the model of controlled object and the actual controlled object do not match.

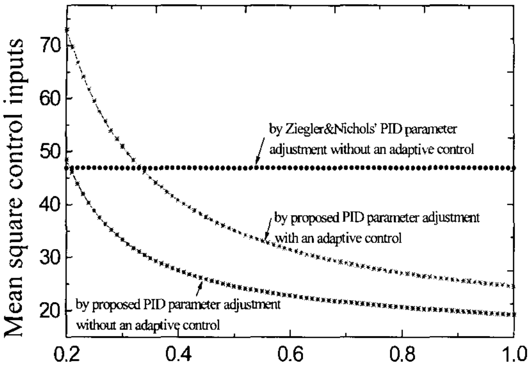


Fig. 14 Comparisons of mean square control inputs (at C83+E20).

Fig. 13 indicates that when the adaptive control and the proposed PID parameters adjustment are used, the errors are smaller than the cases excluding the adaptive control. Fig. 14 indicates that when the adaptive control and the proposed PID parameter adjustment are used, the control energy inputs needed are more than the case excluding an adaptive control. Furthermore, when the Ziegler& Nichols's method excluding an adaptive control is adopted, the control energy inputs needed are more than the case including an adaptive control in the region of time constant 0.33 above.

4. Conclusion

This paper proposed two methods to investigate the speed control characteristics of a marine diesel engine. One is an efficient method to determine the PID control parameters. Second is a combination of soft and hard computing methods such as a reference adaptive speed control method that adopts the fuzzy controller and derivative operator for tracking the nominal model of the marine diesel engine. It was found that the proposed PID parameters adjustment method is better than the Ziegler& Nichols' method, and that a model reference adaptive control is superior to using only PID controller. The improved control method proposed here, could be applied to other systems when a model of a system does not match the actual system.

References

[1] H.H. Yoo and J.S. Ha, "An adaptive speed control of diesel engine by the estimation of the on-line parameters", The Korean Society of Marine Engineers, 20, pp. 342-348, 1996.

[2] Toshiyuki Kitamori, "Design of PID control system", Measurement and Control, 19, pp.382-391, 1980.

[3] G.E. Halang and K.F. Gill, "Design of a model reference adaptive control for an internal combustion engine", Measurement and Control, 6, pp.173-176, 1973.

[4] S. M. Shinner, Modern Control System Theory and Application, Addison Wesley, Boston, 1978.

[5] W.C. Lam, T. Katagi, and T. Hashimoto, "Design of an adaptive electronic governor for better control of marine diesel engine", Maritime Technology 21st century, 2, pp. 1-12, 1993.

[6] J.G. Ziegler and N.B. Nichols,

"Optimal settings for automatic controllers", Transactions of A.S.M.E., 14, pp. 759-768, 1942.

[7] Y.H. Yoo, "A study on Speed Control of Marine Diesel Engine", Ph.D. Thesis, Korea Maritime University, Busan, Korea, 1990.

[8] J.H. Yang, "A study on marine diesel engine control by application of self-tuning control", The Korean Society of Fisheries Technology, 28, pp.262-273, 1992.

[9] Hisashi Matsumoto and Shigeyuki Morita, "Fuzzy diesel governor and its designing expert system", Internal Combustion Engine", 31, pp.53-62, 1992.

[10] J.H.Yang and B.Y. Jeoung, "The Speed control of low speed diesel engine by H8 control method", The Korean Society of Marine Engineers, 17, pp. 409-416, 1993.

[11] Seiichi Shin, "Adaptive control and industrial application", Denki Gakkai Ronbunshi D, 114-D, pp. 939-942, 1994.

[12] B.D. Kim, "AStudy on the Improvement of Speed Control Performance of Diesel Engine", Ph.D. Thesis, Korea Maritime University, Busan, Korea, 1994.

[13] M.H. Song, "A Study on Adaptive Speed Control of the Rotational System by the Nominal Model Tracking System", Ph.D. Thesis, Korea Maritime University, Busan, Korea, 1996.

[14] B.G. Hu, George K.I. Mann, and R.G. Gosine, A systematic study of fuzzy PID controllers, IEEE Trans. on fuzzy systems, 9(5), pp.699-712, 2001.

[15] W.S. Park, I.H. Ryu and S.S. Lee, A study on the DC motor speed control using neural network-PID controller, Journal of the research institute of technology development, Wonkwang University, 23, pp.41-45, 2003.

[16] H. Butler, Model Reference Adaptive Control, Upper Saddle River, NJ : Prentice-Hall, June 1992.

[17] K. M. Passino and S. Yurkovich, Fuzzy Control, Addison Wesley Longman, Menlo Park, CA, 1998.

[18] Y. Tsukamoto, "An approach to fuzzy reasoning method", in M.M. Gupta, R.K. Ragade, R.R. Yager, eds., Advanced in Fuzzy Set Theory and Applications, North-Holland, Amsterdam, pp.137-149, 1979. .

[19] Norcontrol, Digital governor DGS8800 system information, Norway, 1985.

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