Speed Control System on Marine Diesel Engine Based on a Self-Tuning Fuzzy PID Controller

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Abstract: The degree of speed control of ship machinery effects on the economics and optimization of the machinery configuration and operation. All marine vessel ranging need some sort of speed control system to control and govern the speed of the marine diesel engines. This study presents a self-tuning fuzzy PID control system for speed control system of marine diesel engine. The system under consideration is a fourth-order plant with highly dynamic and uncertain environments. The current speed controllers for marine/traction diesel engines based on PID Controller cannot fully handle the uncertainties associated with such dynamic environments. A fuzzy logic control algorithm is used to estimate the PID coefficients in order to handle such uncertainties to produce a better control performance. Simulation tests were established using Simulink of MATLAB. The obtained results have demonstrated the feasibility and effectiveness of the proposed approach. Simulation results are represented in this study.

Key words: Marine diesel engine, self-tuning fuzzy PID controller, simulink

INTRODUCTION

Diesel engines have been widely used as power sources in practice. Diesel engine driven systems include automobiles, ships, and backup power generating units (Jiang, 1993). Marine propulsion and traction engines are large diesel engines which require accurate and robust speed control. The control of this large diesel engine is accomplished through several components: the camshaft, the fuel injector, and the governor. The camshaft provides the timing needed to properly inject the fuel, the fuel injector provides the component that meters and injects the fuel, and the governor regulates the amount of fuel that the injector is to inject. Together, these three major components ensure that the engine run at the desired speed (Zheng-Ming and Lee, 2003; Astrom and Hagglund, 2003).

As is well known, diesel engines are highly nonlinear devices, and their characteristics vary as a function of power output, speed, ambient temperature, etc. Such nonlinear behavior makes the design of engine control systems a very difficult task. Traditionally various forms of the PID controller have been used for speed control in diesel engines due to their simplicity. A great deal of research has also gone into providing more robust and optimal PID controllers through various tuning techniques including Zeigler Nichols, Cohen-Coon and the Chien, Hrones and Reswick (CHR) methods (Astrom and Hagglund, 1995), although in practice these techniques usually only provide a starting point for further manual tuning by experienced engineers (Lynch et al., 2005). Otherwise, AI researchers have shown that Fuzzy Logic and Fuzzy PID controllers can provide improved control and robustness over traditional PID (Astrom and Hagglund, 1995; Golob and Tovornik, 1999). As a result FLCs have found use in the speed control of various marine/traction engines (Amer et al., 2004; Bose et al., 1997).

The fuzzy control systems are rule based systems which are based on expert knowledge. The fuzzy theory based on fuzzy sets and fuzzy algorithms provides a general method of expressing linguistic rules so that they may be processed quickly by a computer. This study presents a development of speed and power control of marine diesel engine by using a self-tuning fuzzy PID controller to overcome the appearance of nonlinearities and uncertainties in the systems. The self-tuning fuzzy PID controller is the combination of a classical PID and fuzzy controller. The mathematical model of the diesel engine is also done by using System Identification technique.

METHODOLOGY

Mathematical model of marine diesel engine system: The actuator of marine diesel engine is a direct current servomotor which is used for the control of diesel engine governor, and it is a typical second order system. The transfer function is described as (Xu and He, 2008):

\[ H(S) = \frac{\omega^2_{nd}}{\omega^2_{nd} + 2\xi_{wd}\omega_{nd}S + S^2} \]

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Hg(S) is the link of given opening extent of fuel oil throttle. H(S) is link of actual opening extent of fuel oil throttle.

- \( \omega_n \) is the natural oscillation frequency of actuator.
- \( \xi_n \) is the damping coefficient of actuator. And its value is between 0.4 and 0.8.

The differential equation of marine diesel engine without turbocharger is:

\[
\frac{T_s}{\tau_c} \frac{dy(t)}{dt} - y(t) = \eta(t) - \lambda(t)
\]

(2)

where, \( y(t) \) is the rotation speed of marine diesel engine, \( \eta(t) \) is the link of opening extent of fuel oil throttle, \( \lambda(t) \) is disturbance, \( T_s \) is the time constant of marine diesel engine and \( \tau_c \) is the link of time delay of fuel throttle opening. And the corresponding Laplace’s equation is described as (Xu and He, 2008):

\[
\frac{Y(S)}{e^{-\alpha H(S)} - \lambda(S)} = \frac{1}{T_s S + 1}
\]

(3)

where, \( Y(S) \) is the Laplace transform of \( y(t) \), \( H(S) \) is the Laplace transform of \( \eta(t) \) and \( \lambda(S) \) is the Laplace transform of \( \lambda(S) \).

For the same reason, the transfer function of marine diesel engine with turbocharger is described as:

\[
\frac{Y(S)}{e^{-\alpha H(S)} - \lambda(S)} = \frac{\sigma_{n}^2}{S^2 + 2 \xi_n \sigma_n S + \sigma_n^2}
\]

(4)

where, \( \sigma_n \) is the non-damping natural frequency of marine diesel engine, \( \xi_n \) is the damping factor of marine diesel engine.

Therefore, the transfer function of a whole marine diesel engine system without disturbance is obtained. Equation (5) is the transfer function of marine diesel engine with a turbocharger:

\[
\frac{Y(S)}{H(S)} = \frac{\sigma_{n}^2}{S^2 + 2 \xi_n \sigma_n S + \sigma_n^2}
\]

(5)

Design and structure of the self-tuning fuzzy PID controller:

**Proportional integral derivative (PID) controller:** The basic structure of the PID controller is described in the following equation.

\[
G(s) = K_p + K_i \frac{1}{s} + K_d s
\]

(6)

where, \( K_p \) is the proportional gain, \( K_i \) the integral gain, \( K_d \) the derivative gain.

The performance specifications of the systems such as rise time, overshoot, settling time and error steady state can be improved by tuning value of parameters \( K_p, K_i \) and \( K_d \) of the PID controller, because each component has it’s own special purposes.

The design algorithm of PID controller in this paper is to adjust the \( K_p, K_i \) and \( K_d \) parameters online through fuzzy inference based on the error \( e(t) \) between desired position set point and the output, and the derivation of error \( de(t) \) to make the controlled object attain the good dynamic and static performances.

**Self-tuning fuzzy PID controller design:** Figure 1 shows the basic configuration of a Fuzzy Logic Controller, which comprises four principal components: a fuzzification interface, a Knowledge base, decision making logic, and a defuzzification interface (Chuen, 1990).

The self-tuning of the PID controller refers to finding the fuzzy relationship between the three parameters of PID, \( K_p, K_i \) and \( K_d \), and "e" and "de", and according to the principle of fuzzy control modifying the three parameters in order to meet different requirements for control parameters when "e" and "de" are different and making the control object produce a good dynamic and static performance. The structure of the self-tuning fuzzy PID controller is shown in Fig. 2.

**Fuzzifier and rule-base formation:** The fuzzifier transforms the measured crisp input X to the fuzzy sets defines in \( V_x \), where \( V_x \) is characterized by a membership function \( \mu_x : V_x \rightarrow [0,1] \), and is labeled by a linguistic term such as “Negative Big (NB),” “Negative Medium (NM),” “Negative Small (NS),” “Zero (Z),” “Positive Small (PS),” “Positive Medium (PM),” and “Positive Big (PB).” Usually, the fuzzifier may transform the measured value into a fuzzy value (i.e., a fuzzy number) as an input fact.

Assume that all the control rules have the same form, each of which is given by:

IF situation THEN action

(7)

Stating a local relationship between the current control situation and the corresponding control action suggested by the expert.\( e(t) \) and \( de(t) \) are selected as input variables of the fuzzy inference and defined as two variables representing the situation. \( K'P, K'I \) and \( K'D \), respectively are selected as output of the fuzzy system and defined as a variable representing the action. Notice that variables for \( e(t) \), \( de(t) \), \( K'P \), \( K'I \) and \( K'D \), respectively assume linguistic terms as their values such as positive-big, negative-small, and zero, etc. Thus, rule (7) may be formally expressed for our fuzzy system by:

Rule i: If \( e(t) \) is \( A_i \) and \( de(t) \) is \( B_i \) then

\[
K'P = C_i \quad K'I = D_i \quad K'D = F_i
\]

(8)

where, \( A_i, B_i, C_i, D_i \) and \( F_i \), respectively are linguistic terms which in this study can be NL, NM, NS, Z, PS, PL and PB, respectively.
The rules designed are based on the characteristic of the marine diesel engine and properties of the PID controller. Therefore, based on these principles, a set of rules have been derived and are summarized in Table 1.

For simplicity, the same universe of discourse and the same fuzzy set are adopted for fuzzy input/output variables. The membership functions of isosceles triangles are used as the fuzzification function which is used to convert a crisp value into a fuzzy singleton within the universe of discourse.

**Fuzzy inference engine and defuzzifier:** In a fuzzy inference engine, fuzzy logic principles are used to synthesize the fuzzy IF-THEN rules in the rule base into a mapping from the family of fuzzy subsets in $V$ to the family of fuzzy subsets in $W$. Mamdani model is applied as structure of fuzzy inference with some modification to obtain the best value for $K_p$, $K_i$, and $K_d$, respectively. Fuzzy inference block of the controller design is shown in Fig. 3.

In the approximate reasoning, the max-min compositional operators are often adopted. The defuzzifier performs a mapping from fuzzy subsets in $W$ to a crisp point $y$. Here, the center average method is used as the defuzzifier, which is defined as:

$$T_i = \frac{\sum_{i=1}^{N} T_i^j \mu_{y_i}(T_i^j)}{\sum_{i=1}^{N} \mu_{y_i}(T_i^j)}$$

where, $T_i^j$ is the center of the fuzzy subset and $\mu_{y_i}$ is the membership function of the output variable.

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**Table 1: Rule base of the fuzzy logic controller ($k_p$, $k_i$, and $k_d$)**

![Fig. 1: Basic configuration of Fuzzy Logic Controller (FLC)](image1)

![Fig. 2: Self-tuning fuzzy PID controller](image2)

![Fig. 3: Fuzzy inference block](image3)
Fig. 4: Simulink model of marine diesel engine

Fig. 5: Simulink block of fuzzy tuning of $K_p$, $K_i$, $K_d$

Fig. 6: Simulink block of the system and controller

**SIMULATION RESULTS AND DISCUSSION**

The Simulink of MATLAB software is used to the whole system simulation. The parameters of marine diesel engine model are $\omega_n = 35.4$, $\xi_n = 0.707$, $\alpha_n = 1.324$, $\xi_n = 1.75$ and $\tau = 0.24s$ so the model of our diesel engine become as in Eq. (10):

![Image](image1)

![Image](image2)

![Image](image3)

So the closed loop controller for speed control of diesel engine, after ignoring $e^{-0.24s}$, is as shown in Fig. 4.

In this simulation, we investigate the performance of the proposed Self-Tuning Fuzzy PID Controller and compare it with the conventional PID controller. The fuzzy tuning of $K_p$, $K_i$ and $K_d$, respectively subsystem block as shown in Fig. 5, consists of Fuzzy logic block set and some modification refers to the formula which is applied to calibrate the value of $K'_p$, $K'_i$ and $K'_d$, respectively from fuzzy block to obtain the value of $K_p$, $K_i$, and $K_d$. 

$$\frac{Y(s)}{H(s)} = \frac{1250}{s^2 + 50s + 1250} \frac{1}{0.57s^2 + 2.64s + 1} e^{-0.24s} \quad (10)$$

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The results of the simulation investigating speed performance of the diesel engine system are shown in Fig. 7, for the self-tuning Fuzzy PID Controller and the conventional PID controller. These step responses performances show that the response is still slow with insignificant overshoots when the conventional PID controller is applied on the system. In the other hand, when the self-tuning fuzzy PID controller is applied into the system, the response become significantly faster without overshoot.

In order to see the disturbance rejection aptitude of the proposed controller, small disturbances were chosen, causing a speed perturbation. The injected disturbance was a pulse of 10 rev/min amplitude and 1s duration. The comparisons of the disturbances rejection between the proposed approach and the conventional PID approach are plotted in Fig. 8. They show that there is not significant difference between both methods. However, comparing the step responses, which are shown in Fig. 7, the performance of the proposed approach is better than that of the conventional approach in terms of rise time and settling time. In summary, the simulation results show that the proposed controller is stable and it results in a satisfactory speed regulation performance.

CONCLUSION

This study has considered the problem of speed control of the marine diesel engine. Modeling was done on the marine diesel engine and was proposed successfully. Then, a self-tuning fuzzy PID controller has been proposed, and by comparing it with the conventional PID controller, it has been shown in the paper that uniformly stable operation is achieved.

In the study, simulation results in applying the proposed self-tuning fuzzy PID controller to speed control of marine diesel engine have been presented which demonstrates the effectiveness of the combined controller. Future work is directed to the application of genetic algorithm for PID coefficients tuning and compare it with the fuzzy tuning.

REFERENCES


