Application of Fuzzy Control to Internal Combustion Engines*

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The characteristics of engine~load systems are considerably nonlinear. Therefore, when feedback control is required in such a case as a diesel engine governor or cruise control for a gasoline engine, a countermeasure such as gain scheduling must be incorporated to compensate this nonlinearity. On the other hand, it is said that fuzzy control is very robust against nonlinearity. Thus, fuzzy control was applied to the governor of a diesel engine, and the level of robustness of fuzzy control was investigated in comparison with PI and LQI control methods. As a result, it was found that fuzzy control showed the highest level of robustness and a much faster control response compared with the two other methods of control.

Key Words: Diesel Engine, Computer Control, Fuzzy Control, Diesel Governor, Robustness

1. Introduction

The characteristics of engine~load systems change considerably with their operating conditions. Therefore, they are referred to as nonlinear characteristics. When feedback control is required in the system, a countermeasure such as gain scheduling, must be incorporated to compensate the nonlinearity⁽¹⁾.

On the other hand, it is said that fuzzy control is very robust against nonlinearity⁽²⁾. However, the level of robustness of fuzzy control in comparison with other conventional forms of control, especially in the case of internal combustion engines, is unclear.

In light of this, fuzzy control was applied to the governor of a diesel engine, that is, speed control of a diesel engine, and comparison of control performance and robustness between fuzzy control and PI and LQI control methods was performed.

The test rig for the experiments consists of a 1299

cc 3-cylinder diesel engine and a direct-coupled D.C. dynamometer. The rig is equipped with several sensors and actuators, such as a potentiometer for rack position, a speed detector, and a fuel rack actuator driven by a stepping motor. These devices are connected to an on-line computer so that the analysis can be carried out using software algorithms.

The following symbols are used. Others will be explained as they appear.

f : total friction of engine~load system	Nms
J : total moment of inertia of engine~load system	Nms ²
k : discrete time of control period	—
K_f : load coefficient of dynamometer	As
L_f : field inductance of dynamometer	H
n_e : engine speed	s ⁻¹
R : fuel rack position	mm
ΔR : manipulated displacement of R within a control period	mm
R_f : field resistance of dynamometer	Ω
T_e : engine torque	Nm
T_L : load torque	Nm
τ : control period	s
V : input voltage to dynamometer	V

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2. Model of Objective System

First, the model of the objective engine system, excluding its governor, was constructed, as shown in the area enclosed by a dotted line in Fig. 1. The model is very useful for simulating the behavior of the systems, tuning the controller's optimal gain, and comparing the performance and robustness of the above-mentioned three controllers.

It is well known that a diesel engine without its governor is an unstable system, as also recognized from the figure.

The model was converted into a discrete system by the use of the control period $\tau=0.125$ s. The transition matrixes of the discrete system, F_1 , F_2 , g_1 and g_2 are shown by the following equations.

$$F_1 = \exp[-(f/J)\tau], g_1 = (F_1 - 1)/f \quad (1)$$

$$F_2 = \exp[-(R_f/L_f)\tau], g_2 = (F_2 - 1)/R_f \quad (2)$$

The following is a description of the model shown in Fig. 1. The integrator drawn in the left side of the enclosed area is the actuator for the fuel rack. Engine torque T_e is obtained from this R and engine speed n_e . The generation of load torque T_L by the dynamometer circuit accompanies the time delay of the first-order system with the time constant (L_f/R_f) . The difference between the two, $(T_e - T_L)$, results in driving of the first-order systems with the time constant (J/f) by

mechanically movable parts of the engine and load.

The dead times, caused by the fuel pump, combustion chambers, and dynamometer, are represented by z^{-1} , drawn in the center of the figure, which is an expression approximated by equivalent conversion. The state equation and system matrixes are as follows.

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{b}u(k) \quad (3)$$

$$y(k) = \mathbf{c}\mathbf{x}(k), u(k) = \Delta R(k) \quad (4)$$

$$\mathbf{x}^T = [n_e(k), V(k), T_v(k), R(k)] \quad (5)$$

$$\mathbf{A} = \begin{bmatrix} -F_1 & 0 & g_1 & 0 \\ g_2 & -F_2 & 0 & 0 \\ \frac{\partial T_e}{\partial n_e} & \frac{\partial T_e}{\partial V} & 0 & \frac{\partial T_e}{\partial R} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

$$\mathbf{b}^T = [0 \ 0 \ 0 \ 1] \quad (7)$$

$$\mathbf{c} = [1 \ 0 \ 0 \ 0] \quad (8)$$

Table 1(a) shows the parameter values of gain constants of the system. The range of speed of the experimental engine operation is relatively narrow, as shown in Fig. 3, due to the limitations of the D.C. dynamometer. Therefore, $\partial T_e/\partial n_e$, $\partial T_L/\partial V$ and $\partial T_e/\partial R$ are easily approximated as constant values. However, it is necessary to treat $\partial T_L/\partial V$ similarly as the variables listed in Table 1(b) even in such a narrow range. Under these conditions, the objective engine system is suitable for use in examination of the robustness of fuzzy control.

Next, for identification of the model in Fig. 1, experimental engine operation and simulations of the model were conducted under similar conditions.

Needless to say, both systems are unstable without their governors, thus, they were equipped with an electronic PI governor or the numerical PI governor model (controller), shown outside of the dotted line in Fig. 1.

One example of the results is shown in Fig. 2. The optimal gain values of this PI governor were determined from simulation results which had been obtained beforehand. It is recognized that relatively

Table 1 (a) Parameter values of the system

$\partial T_e/\partial n_e$	1.764	$\partial T_e/\partial R$	26.46
J	10.584	f	1.117
L_f	83.7	R_f	83.7

(b) Values of $\partial T_L/\partial V$

	n_e		
T_L	21~22	22~23	23~24
0~30	0	0	0.001
30~60	0.06	0.07	0.08
60~80	0.09	0.1	0.12

Fig. 1 Block diagram of the objective system

good agreement was obtained except in the case of high-frequency vibration, which is not considered in the model.

Finally, the design of the LQI controller and the performance and robustness of all three controllers are investigated using this model.

3. Fuzzy Controller

The rules of fuzzy control in this study are very simple and explicit, as seen in Eqs. (9) and (10).

R^1 : if E is P and ΔE is P , then ΔR is P' (9)

Fig. 2 Results of identification

Fig. 3 Range and conditions of engine operation

R^2 : if E is N and ΔE is N , then ΔR is N' (10)

Here, E is the difference between the engine speed and its command value, and ΔE is the difference between $E(k+1)$ and $E(k)$, where k is the discrete time of one control period. P and N are fuzzy variables which express the degree of positivity and negativity, respectively.

The rules, R^1 and R^2 , express the actions in the "if~ then~" format at points R^1 and R^2 in Fig. 4. It is easily understood by applying the rules to the corresponding points in the figure that the actions are reasonable (at other points, the rules, R^1 and R^2 , supplement each other, and suitable actions are determined).

P and N of the precondition (if~) are membership functions of Eq. (11) which express the degree of positivity and negativity, respectively, and P' and N' of the postcondition (then~) are the same as in Eq. (12), respectively.

$$P(x) = \frac{1}{1 + \exp(-ax)}, N(x) = P(-x) \quad (11)$$

$$P'(x) = b(x-1)+1, N'(x) = P'(-x) \quad (12)$$

Here, a and b are positive values. In Fig. 5, which shows the functions, E , ΔE , and ΔR are normalized within the range $[-1, 1]$ by standardization constants K_E , $K_{\Delta E}$, and $K_{\Delta R}$. Tsukamoto's simplified method⁽⁹⁾ was adopted as the fuzzy reasoning method for

Fig. 4 Rules of fuzzy control and definitions of J_i

Fig. 5 Membership functions

obtaining concrete output values. Namely, as shown in Eq. (13), the output of the smaller membership function is denoted as w_1 , and then the control output $y^0 (\propto \Delta R)$ is calculated using Eq. (15).

$$w_1 = P(E) \wedge P(\Delta E), w_2 = N(E) \wedge N(\Delta E) \quad (13)$$

$$y_1 = P'^{-1}(w_1), y_2 = N'^{-1}(w_2) \quad (14)$$

$$y^0 = \frac{w_1 y_1 + w_2 y_2}{w_1 + w_2} \quad (15)$$

Figure 6 shows the relationship between input and output obtained using this reasoning method. Such a relationship obtained by means of a conventional linear control theory is planar, as is well known. In contrast, fuzzy theory yields a curved surface which is thought to result in robustness.

The simulation and experimental engine operation were performed using this fuzzy controller. The operating conditions for the design of the controller are denoted by point ① in Fig. 3.

Specifically,

$$n_e = 21 \text{ [s}^{-1}\text{]}, \frac{\partial T_e}{\partial R} = 26.46 \text{ [Nm/mm]},$$

$$\text{and } \frac{\partial T_l}{\partial V} = 0 \text{ [Nm/V]}.$$

It was previously confirmed that the use of $K_E = 1.167$, $K_{\Delta E} = 0.133$, and $K_{\Delta R} = 0.104$ as standardization constants, and $a=3$ and $b=1.5$ as constants of the membership functions, yields the best control performance under the operating conditions of point ①.

Figure 7 shows an example of the results. It is recognized that considerable improvement in the response speed has been achieved in comparison with the case of optimally tuned PI control in Fig. 2. Furthermore, good agreement between the simulation and experiment is obtained.

4. Assessment of Robustness

The optimal method of control was determined by examining the robustness of each control method, i.e., fuzzy, PI and LQI. Each controller has been tuned

Fig. 6 Input-output relationship of the fuzzy controller

to the optimal states, as derived above. The examination was carried out by comparing the effectiveness or ineffectiveness of each controller, when the parameter values of the objective system were varied from those of the conditions at point ①.

4.1 LQI control⁽⁴⁾

Below, an outline and a description of the procedure of LQI control are given. First, the new state variable s is introduced for an extended system of P , q , and x_c .

$$s(k) = x(k) - x(k-1) \quad (16)$$

$$\underbrace{\begin{bmatrix} y(k+1) \\ s(k+1) \end{bmatrix}}_{x_c} = \underbrace{\begin{bmatrix} 1 & cA \\ 0 & A \end{bmatrix}}_P \underbrace{\begin{bmatrix} y(k) \\ s(k) \end{bmatrix}}_s + \underbrace{\begin{bmatrix} cb \\ b \end{bmatrix}}_q d(k) \quad (17)$$

Here, $d(k) = u(k) - u(k-1)$. The output of the extended system, y_c , is

$$y_c = r x_c(k), r = [1, 0, 0, 0]. \quad (18)$$

Next, the performance index function of the assessment for the extended system is determined to be

$$J = \sum_{k=0}^{\infty} \{y_c^2(k+1) + w d^2(k)\}, \quad (19)$$

where w is a weight constant. As is well known, optimum gain vector K which minimizes J can be obtained by solving Eq. (20) analytically.

$$K = (w + q^T H q)^{-1} q^T H P \quad (20)$$

Here, H is a steady-state solution of the discrete Riccati equation (21).

$$H(k+1) = P^T H(k) P - P^T H(k) q [w + q^T H(k) q]^{-1} q^T H(k) P + W_x \quad (21)$$

$$W_x = H(0) = r^T r \quad (22)$$

4.2 PI control

The manipulated variable is obtained from Eq. (23).

$$u(k) = K_p(n_e(k-1) - n_e(k)) + K_i(\bar{n}_e(k) - n_e(k)) \quad (23)$$

Fig. 7 Results of engine operation using fuzzy control

In the equation, $\tilde{n}_e(k)$ is a reference value of n_e , and $u(k)$ is $\Delta R(k)$ in the present case of a diesel engine. The optimal values of PI gain, K_p and K_i , were determined to be $K_p=0.312$ and $K_i=0.012$ from trial simulation results. The simulation result obtained using these optimal values is shown in Fig. 2 which was previously given for the identification.

4.3 Performance indices

In order to assess the performance of these three controllers numerically, $J_1 \sim J_4$ described in Fig. 4 were adopted.

Fig. 8 Simulation results of fuzzy control, LQI control and PI control

5. Results

An example of the indicial response is shown in Fig. 8. As previously mentioned, the gain and other variables were tuned optimally at the operating conditions of point ①, and they are shown in Fig. 8(a).

In contrast to Fig. 8(a), Fig. 8(b) shows the simulation results of operating conditions of point ③, which are as follows.

$$n_e = 23 \text{ [s}^{-1}\text{]}, \frac{\partial T_e}{\partial R} = 26.46 \text{ [Nm/mm]},$$

$$\frac{\partial T_L}{\partial V} = 0.1 \text{ [Nm/V]}$$

Thus, the operating conditions were shifted intentionally for examination of robustness. The superior robustness of fuzzy control is clearly recognized in the comparison with PI and LQI results.

In order to calculate the robustness, the values of system parameters in the objective model were changed as described below, maintaining the engine operating conditions of point ①.

(a) Nine combinations of the following 6 parameter values, including the conditions of point ①(*), were observed. Any change of the operating conditions was for the convenience of observation.

$$\begin{cases} \frac{\partial T_e}{\partial R} = 9.8, 26.46^*, 49 \text{ [Nm/mm]} \\ \frac{\partial T_L}{\partial V} = 0^*, 0.0098, 0.098 \text{ [Nm/V]} \end{cases}$$

(b) Nine combinations of the following 6 parameter values including the conditions of point ①(**) were observed. Any change in the system, namely, the engine-load system itself, was for the convenience of

Fig. 9 Comparison of performance indices

Table 2 (a) Comparison of JJ (in the case of (a))

	Maximum	Minimum	Variance
FC	1	1	1
LQI	1.233	2.311	1.035
PI	2.072	2.209	2.047

(b) Comparison of JJ (in the case of (b))

	Maximum	Minimum	Variance
FC	1	1	1
LQI	3.208	0.485	5.122
PI	1.567	1.043	1.932

observation.

$$\begin{cases} J=5.0, & 10.584^{**}, 20 \text{ [Nms}^2\text{]} \\ f=0.117, 1.117^{**}, 11.17 \text{ [Nms]} \end{cases}$$

The simulations of indicial response were performed with each set of parameter values, (a) and (b), and performance indices $J_1 \sim J_4$ were calculated. Results are shown in Fig. 9: (a) in the upper part of the figure denotes combination set (a), and (b) denotes combination set (b). The abscissa shows the three control methods (FC is the abbreviation of fuzzy control), and the ordinate shows the performance indices J_i ($i=1 \sim 4$).

For example, J_1 , which is drawn on the left side of the figure, represents the performance with respect to rise time, as explained in Fig. 4. Therefore, it is recognized that LQI control is superior to the other two control methods in both (a) and (b). (There are 9 J_i data values on the vertical line for each control method. The best control method shows the smallest variation as well as the smallest value.)

On the right side, JJ represent the overall performance of these four J_i values in the simulation based on the definition of Eq. (24).

$$JJ = \sum_{i=1}^4 (J_i/a_i) \quad (24)$$

In the case of (a): $a_i = \{240, 0.61, 240, 64\}$ (25)

In the case of (b): $a_i = \{240, 0.805, 240, 60.54\}$

The four values of a_i show minimum values of $J_1 \sim J_4$, as recognized from the respective figures. Hence, Eq. (24) indicates that the performance indices were treated equally, i.e., with the same weight.

It is indicated by the JJ results that fuzzy control is excellent in both cases (a) and (b).

For numerical estimation, (a) and (b) of Table 2 are the lists of calculation results of the maximum, minimum, and variance values of JJ , which were standardized as FC=1 in both cases (a) and (b).

6. Conclusions

Fuzzy control was applied to speed control of a diesel engine, and the following conclusions were obtained.

(1) From the experimental operation of a diesel engine, it was confirmed that fuzzy control is very robust, i.e., it is applicable to nonlinear systems.

(2) From the simulation studies, it was shown that fuzzy control was more robust than PI and LQI control methods.

(3) With respect to rapid control response, fuzzy control showed the best performance.

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