TECHNISCHE MECHANIK, Band 17, Heft 3 (1997), 167-178
Manuskripteingang: 19. Februar 1997

Speed Roughness Control of an SI Engine Using Fuzzy Self Tuning Method

M. Akhlaghi, F. Bakhtiari Nejad, S. Azadi

Reducing the exhaust emissions of a spark ignition engine by means of engine modifications requires consideration of the effects of these modifications on the variations of crankshaft torque and engine roughness respectively. Only if the roughness does not exceed a certain level does the vehicle not begin to surge. The present paper presents a method for controlling the engine roughness while exhaust emissions are reduced. A fuzzy self-tuning method has been applied for the improvement of the performance of an SI engine. Fuzzy rules and reasoning are utilized on-line to determine the control parameters. The main advantages of this method are simple structure and robust performance in a wide range of operating conditions. A non-linear model of an SI engine with an engine torque irregularity simulation is used in this study.

1 Introduction

Engine roughness is a measure of the irregularity of the angular velocity of the crankshaft which is caused by the variation in energy release from cycle to cycle as well as cylinder to cylinder. The variation of mean effective pressure causes torque changes and resulting angular speed changes of the crankshaft. The engine roughness corresponds to changes of the mean angular acceleration between successive crankshaft rotations. It is approximately proportional to the change of the mean torque or mean effective pressure during one rotation of the crankshaft (Latsch and Mausner, 1979). Figure 1 shows the crankshaft speed increasing the air-fuel ratio which increases the engine roughness. We can also see the optimal ignition point for smooth running in Figure 2 (Latsch and Mausner, 1979; Akhlaghi et al. 1979; Bamer et al. 1979; Akhlaghi, 1978).

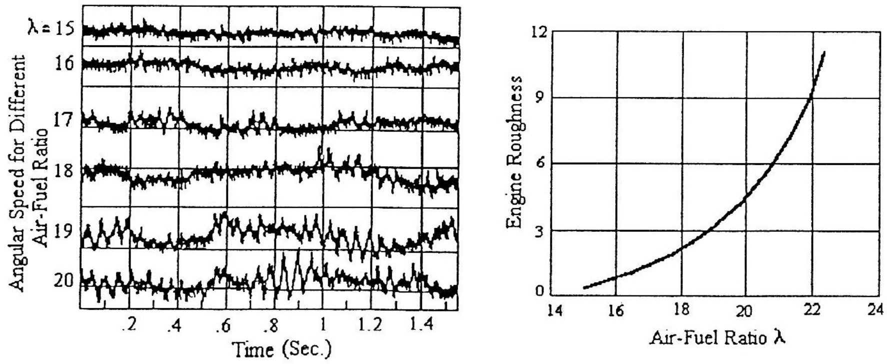

Figure 1. Variation of Engine Roughness with Respect to Air-fuel Ratio

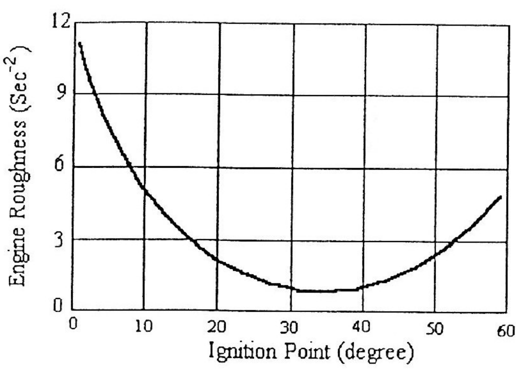

Figure 2. Engine Roughness as a Function of Ignition Point

Today fuzzy logic control (FLC) is used in several branches of science and technology. Simple control strategy for complex, uncertain and non-linear systems is an advantage of this method. FLCs are also relatively easy to construct and special purpose hardware is increasingly available for real time implementation. Most commercial products currently employ a constant look-up table type approach for implementing fuzzy control. Several researchers have been studying approaches to incorporate learning into the fuzzy control architecture (Wang, 1994; Lee, 1990).

The best known controllers used in industrial control processes are Proportional-Integral-Derivative (PID) controllers. The PID controllers are divided into two main categories in the literature. In the first category, the controller parameters are fixed during control after they have been tuned or chosen in a certain optimal way (Wang, 1994). The Ziegler-Nichols tuning formula is perhaps the most well known tuning method (Lee, 1990). Some other methods exist for PID tuning.

Controller tuning is a compromise between the desire for fast control and need for stable control (Lee, 1990; Astrom and Hagglund, 1995). Table 1 shows how stability and speed change when the PID controller parameters are changed.

		Speed	Stability
K	Increased	Increased	Reduced
Ti	Increased	Reduced	Increased
Td	Increased	Increased	Increased

Table 1. Rules of Thumb for the Effects of the Controller Parameters

The engineering problem treated here is in the development of a control scheme to reduce automobile exhaust emission rate and fuel consumption rate. Engine management basically involves the control of two functions: fuel injection and ignition. As a result, the trend today is very much towards the complete integration of the two functions into a single management system. The most complex of today's systems provide a range of outputs including the following as necessary (Inagak et al. 1990; Nam et al. 1994; Vachtsevanos et al. 1993; Feldkamp and Puskorius, 1993; Dingli et al. 1994; Tomizuka and Hedrick, 1995; Seiffert and Walzer, 1993):

- Throttle control
- Fuel injection timing (including emission control)
- Ignition timing (including knock protection)
- Idle speed stabilisation
- Maximum engine speed governing
- Variable valve timing control
- Cruise control
- Traction control via torque output

The majority of these functions involve control in real time, placing considerable demands on processing capacity.

2 Engine Modelling

Engine modelling efforts for control have been underway for less than 30 years (Powell, 1987). There have been many different formulations of engine models. In recent years, dynamic models for automotive engines have been developed that are accurate enough to be used for non-linear controllers, and simple enough to be computed in real time. Some of these models are based entirely on measurements and are often referred to as „input-output" models. The engine model which is presented here is for various parts of an automobile so any dynamic loads and other transients that affect exhaust emissions and fuel economy can be predicted. The vehicle system is divided into the following dynamic subsystems (Dobner, 1980; Coats and Fruechte, 1983; Hendricks and Sorenson, 1990):

- Intake manifold
- Engine inertia dynamic
- Vehicle inertia dynamic

Figure 3 represents the entire model in block diagram form.

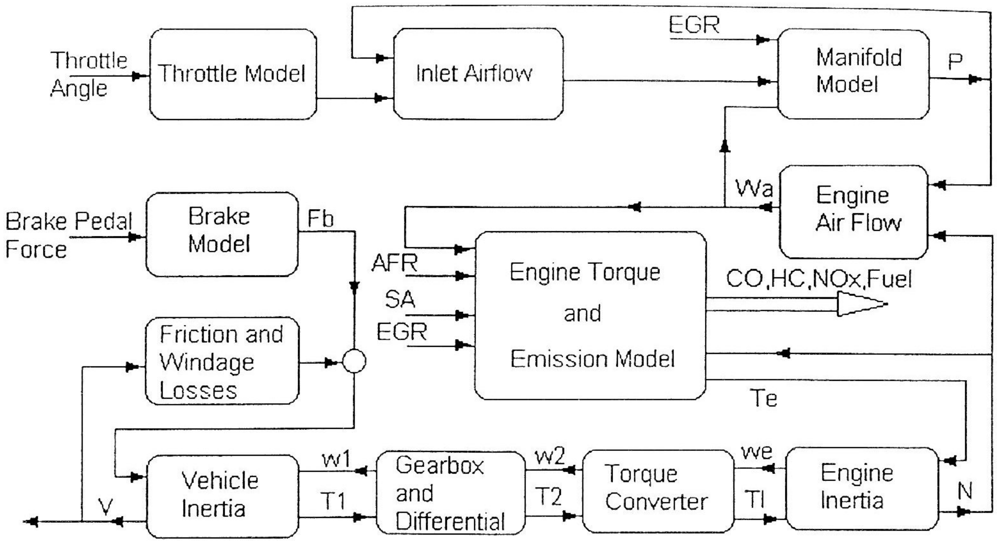

Figure 3. Schematic Block Diagram for a Vehicle System

The engine input variables are the throttle angle, the air-fuel ratio, the ignition timing and the exhaust gas recirculation (EGR). In this model the state variables are the crankshaft speed and the absolute manifold pressure. The engine output variables are the exhaust emissions and the engine roughness.

MANIFOLD PRESSURE STATE EQUATION - The state equation for manifold pressure is obtained by applying the conservation of mass. This can be expressed as (Coats and Fruechte, 1983; Handricks and Sorenson, 1990)

$$\frac{dp_m}{dt} + \frac{(1-\frac{EGR}{100})V\eta_v p_m}{V_m} = \frac{RT_m}{V_m} W_{th} \tag{1}$$

where

$$W_{th} = W_{Max} \; f_1 \; f_2 \; f_3 \; f_4 \tag{2}$$

$$W_{Max} = \frac{C_{dt} \, A_{tm} \, p}{3.85\sqrt{RT}} \tag{3}$$

$$f_1 = \left(\frac{p_m}{p}\right)^{\frac{1}{k}} (3.85) \left[\frac{2k}{k-1}\left(1-\left(\frac{p_m}{p}\right)^{\frac{k}{k-1}}\right)\right]^{\frac{1}{2}} \qquad \frac{p_m}{p} > 0.528 \tag{4}$$

$$f_1 = 1 \qquad \frac{p_m}{p} \leq 0.528$$

$$f_2 = \sin\alpha \tag{5}$$

$$f_3 = \frac{p}{p_0} \tag{6}$$

$$f_4 = \sqrt{\frac{T_0}{T}} \tag{7}$$

In constructing the algebraic expression for volumetric efficiency some suggestive results are available in the literature. The function of the volumetric efficiency is (Nagao et al. 1969; Hava et al. 1985)

$$\eta_{vol} = \eta_{vb}\, k_p \tag{8}$$

where,

$$\eta_{vb} = 0.75 \qquad Z < 1 \tag{9}$$

$$\eta_{vb} = \frac{0.75}{Z} \qquad Z \geq 1$$

The dimensionless parameter Z is identical with „Inlet-Valve Mach Index" adapted by C. F. Taylor and can be written as (Hendrichs and Sorenson, 1990)

$$Z = \left(\frac{b}{d_c}\right)^2 \left(\frac{n_m}{C_{ia}}\right) \tag{10}$$

The functions k_p are given by

$$k_p = \frac{k-1}{k} + \frac{\varepsilon - \frac{p}{p_m}}{k(\varepsilon - 1)} \qquad \frac{p}{p_m} \leq 1.4\varepsilon - .4 \tag{11}$$

$$k_p = 0 \qquad \frac{p}{p_m} > 1.4\varepsilon - .4$$

VEHICLE DYNAMIC STATE EQUATION - In operation of the vehicle the engine develops a torque depending on air flow, air-fuel ratio, spark advance and other conditions. This torque is transmitted to the wheels through the torque converter, gear box and differential. When brakes are applied, the throttle is at its idle position and the brakes decelerate the vehicle dissipating the excess available energy in the form of heat. Physically the vehicle inertia equation is derived using Newton's law and can be expressed as

$$\frac{dv}{dt} = \frac{F_{in} - F_{out}}{M_{eq}} \tag{12}$$

where

$$M_{eq} = M + \frac{I_{ee} + I_e}{R_w^2} \tag{13}$$

$$I_{ee} = I_e(GR_t) \tag{14}$$

$$F_{in} = \frac{T_e \xi_t R_t G}{R_w} \tag{15}$$

$$F_{out} = F_r + C_w v^2 + F_b \tag{16}$$

where T_e is a function of throttle angle, spark ignition timing and other engine parameters such as air-fuel ratio. The torque irregularity from cycle to cycle is expressed by

$$\Delta \int_{j}^{j+1} T_e \, dt = -\delta_n \left(4\pi^2 I_e\right) \quad (17)$$

where δ_n is the engine roughness. In this study we have simulated the engine roughness as a disturbance on the engine torque. The characteristics of this signal is in the whole in agreement with experimental results of Latsch and Mausner (1979).

3 Modelling of Exhaust Emissions

Engine operating variables and design parameters have a significant influence on exhaust emissions. It is often difficult to isolate the effects of a single design variable or operating parameter. Any variable such as air-fuel ratio, spark timing, speed, load, EGR, valve overlap, intake manifold pressure, compression ratio and valve timing have a significant influence on the exhaust emissions and fuel economy. Many studies have shown that among the variables mentioned only the air-fuel ratio, spark advance and EGR can be controlled. Some research laboratories have used the steady state data from experimental studies and have reported the control strategies which sought to reduce emissions. Some approximate functional relationship between exhaust emissions, operating conditions and control variables can be established , then these empirical relationships can be directly used for determining exhaust emission rates at any operating condition. The following equations give the functional forms for the various emission rates. The functions f_1, f_2 and f_3 are determined by using empirical correlation techniques (Hassel et al. 1994).

$$\dot{Co} = f_1\left(W_{th}, AFR, \delta, EGR, T_e, n\right) \quad (18)$$

$$\dot{Hc} = f_2\left(W_{th}, AFR, \delta, EGR, T_e, n\right) \quad (19)$$

$$\dot{No} = f_3\left(W_{th}, AFR, \delta, EGR, T_e, n\right) \quad (20)$$

where $\dot{Co}$ is the CO exhaust emission rate, $\dot{Hc}$ is the HC exhaust emission rate, and $\dot{No}$ is the NOX exhaust emission rate.

Because steady state tests are used to obtain the experimental data, these equations are not valid for cold start and warm up periods.

4 Self Tuning Strategy

In this study the objective of the fuzzy controller is to keep the engine speed constant and to reduce the exhaust emission rates and the engine roughness. Thus, we require a composition of the optimal control and tracking control. In this paper we have developed a method which integrates these control strategies in a hierarchial parameter tuning controller. The controller requires only input and output data (it does not require the plant's model). This method is based on servo controller tuning with fuzzy logic adapted from Tseng and Hwang (1993).

Figure 4 shows a block diagram of the self tuning fuzzy control. U is the plant input vector, y is the output vector, $y_d(t)$ is the desired output vector and e is the error vector.

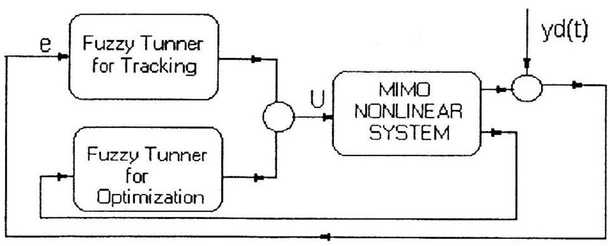

Figure 4. The Block Diagram of Integrated Controller

The process model is given by

$$\dot{x}(t) = f(x(t), u(t), t) \tag{21}$$

$$y(t) = g(\dot{x}(t), x(t), t) \tag{22}$$

$$e(t) = y(t) - y_d(t) \qquad \text{for tracking} \tag{23}$$

$$y_d(t) = y(t) + \delta_y \qquad \text{for maximisation} \tag{24}$$

$$y_d(t) = y(t) - \delta_y \qquad \text{for minimisation} \tag{25}$$

$$u(t) = Ke(t) \tag{26}$$

where, $x \in R^n$, $u \in R^m$, $y \in R^r$, $e \in R^r$ and $\delta_y \in R^r$.

The specified variable δ_y is the small variation from the instantaneous value of y. The tracking tuner causes that

$$e(t) \to 0$$

when for an optimal tuner we have

$$y(t) \to y_{extremum}$$

5 Fuzzy Rules

The control variable $U(t)$ is proportional to the error $E(t)$ and given by

$$U(t) = K(t)\,E(t) \tag{27}$$

The objective of the fuzzy tuner is to evaluate the incremental changes of K, in other words we have

$$K(t_{k+1}) = K(t_k) + \Delta K(t_{k+1}) \tag{28}$$

FUZZY RULES FOR TRACKING - Based on the servo controller tuning whose complete technique can be found in Tseng and Hwang (1993), we have used the method for fuzzy rules generation based on the Lyapunov function as a performance index. Consider the following Lyapunov function candidate for deriving a stable fuzzy rule set (Wang, 1993):

$$V(e, \dot{e}) = e^T e + \dot{e}^T \dot{e} \tag{29}$$

The rate of change $\dot{V}$ of V with respect to time can be approximated by

$$\dot{V} \approx \frac{\Delta V}{\Delta t} \tag{30}$$

where

$$\Delta V(t_k) = V(t_k) - V(t_{k-1})$$

In order to derive $y_{id}(t)$ we require $d|e_i|/dt < 0$. To satisfy the condition $d|e|/dt < 0$ or $\Delta|e| < 0$ by tuning K, one must find an expression that relates $\Delta|e|$ to the desired changes in K. This expression can be obtained through the introduction of a sensitivity function

$$S_{ij} = \frac{\partial|e_i|}{\partial K_{ij}} \tag{31}$$

which leads to

$$\Delta|e_i| = \sum_{j=1}^{m} S_{ij}\Delta K_{ij} \tag{32}$$

and for a stable control, to

$$\Delta V \approx \Delta\left(e^T e + \dot{e}^T \dot{e}\right) \leq 0 \tag{33}$$

The idea of deriving the fuzzy rules is to have $\Delta|e_i|$ such that it converges at a constant rate $\Delta|e_i| = -\eta_i$, where η_i is positive and defining the convergence rate. To guarantee this convergence condition, one can use the principle of superposition to determine the sign of each ΔK_{ij}, such that $\Delta|e_i|$ is always negative. One way to fuzzify the variables, Δe_i, ΔK_{ij} and S_{ij} is to introduce a linguistic term (membership function) for each of them in form of triangular arrangement as shown in Figure 5.

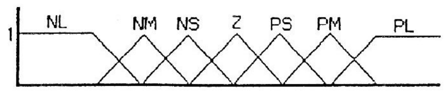

Figure 5. Membership Function for the Fuzzy Term Sets

6 Fuzzy Rules for Optimization

The idea for generating the fuzzy rules in an optimal fashion is to lead $f(t)$ toward $f_{extremum}$ by using $f_d(t) = f(t) \pm \delta f$ as a target, because the extremum value of f is unknown. As error statement we have

$$e(t) = \pm\delta f \tag{34}$$

We can use the steepest descent technique for optimization. In this method, for function f, which is a function of variables $y_1, y_2, \ldots$ and y_n, we have

$$df(y_1, y_2, \ldots, y_n) = \left[\frac{\partial f(y)}{\partial y}\right]^T \Delta y = 0 \tag{35}$$

for obtaining the extrimum of f, the gradient of f in optimum point y^* must be zero. In the other words, one can write

$$\frac{\partial f}{\partial y}\left(y^*\right) = 0 \tag{36}$$

The optimum result is obtained when f leads to $f_{extremum}$ in steepest descent. Figure 6 shows this technique in the phase plane and the time domain.

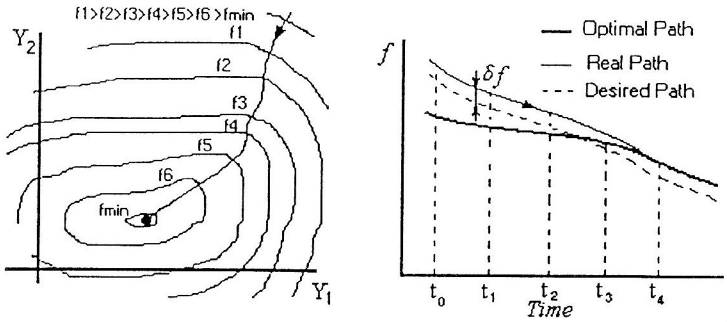

Figure 6. The Optimization Technique in Phase Plane and Time Domain

The sample rules for choosing ΔK are as follows:

If $\Delta|e_i(t_k)|$ is NM and $S_{ij}(t_k)$ is PS then $\Delta K_{ij}(t_{k+1})$ will be NL. (The product of PS and NL is large, in order to obtain the steepest variation in the performance index.)

If $\Delta|e_i(t_k)|$ is PM and $S_{ij}(t_k)$ is PS then $\Delta K_{ij}(t_{k+1})$ will be NL. (The product of PS and NL is a large action, in order to bring the system back to the desired condition $\Delta|e| < 0$ quickly.)

If $\Delta|e_i(t_k)|$ is PM and $S_{ij}(t_k)$ is Z then $\Delta K_{ij}(t_{k+1})$ will be Z. (The reasoning is that if $S_{ij}(t_k)$ is near zero, then the system will reach the extremum point and the optimality condition of equation (36) would be satisfied.)

The complete fuzzy decision table for the matrix K is as shown in Table 2.

$\Delta\|e\|$ Sij	NL	NM	NS	Z	PS	PM	PL
NL	PS	PS	PS	Z	PS	PM	PM
NM	PM	PM	PS	PS	PM	PM	PL
NS	PL	PM	PM	PS	PM	PL	PL
Z	Z	Z	Z	Z	Z	Z	Z
PS	NL	NM	NM	NM	NL	NL	NL
PM	NM	NM	NS	NS	NM	NM	NL
PL	NS	NS	NS	Z	NS	NS	NM

(a)

$\Delta\|e\|$ Sij	NL	NM	NS	Z	PS	PM	PL
NL	PL	PL	PM	Z	PM	PL	PL
NM	PL	PL	PM	Z	PM	PL	PL
NS	PM	PM	PS	Z	PS	PM	PM
Z	Z	Z	Z	Z	Z	Z	Z
PS	NM	NM	NS	Z	NS	NM	NM
PM	NL	NM	NM	Z	NM	NM	NL
PL	NL	NL	NM	Z	NM	NL	NL

(b)

Table 2. Fuzzy Decision Table for Matrix ΔK a) Tracking Control b) Optimal Control

In this paper the quadratic performance index is as follows:

$$J = e^T Q e + \dot{e}^T P \dot{e} \quad (37)$$

where e is the output error vector and Q and P are weighting matrices for selecting the most important outputs.

7 The Adaptive Fuzzy Control Applied to SI Engine

In this paper computer simulations of the vehicle dynamics and of an SI engine with engine roughness simulation have been accomplished. The large non-linearities of the intake manifold state equation are preserved in this simulation. The results of the MIMO closed loop simulation are shown in Figures 8 to 17. In order to check the performance of the algorithms, we have specified a torque disturbance with characteristics similar to experimental results. The engine speed is approximately constant. The engine outputs are given for three gains. Table 3 shows the gains.

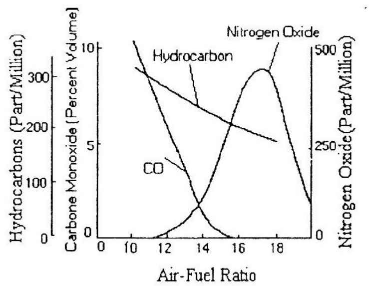

Figure 7. Effects of Air-fuel Ratio on the Exhaust Emissions

The exhaust emission experimental tests have shown that increasing the value of air-fuel ratio reduces the CO gas emission (Newton et. al., 1991), as illustrated in Figure 7. In this simulation the CO emission is reduced by applying the exceed air-fuel ratio until the air-fuel ratio reaches 20. We can also control the other emissions and engine roughness by choosing proportional weighting factors. Because of gain adjusting capability, the engine speed remains constant only by throttle angle, while the engine roughness and exhaust emission are minimized by other controllers.

Gain Series	Engine roughness	CO Emission
1	High	Low
2	Low	High
3	Medium	Medium

Table 3. The Gain Series

8 Conclusion

In this paper, it has been shown that it is possible to find the best engine adjustment compromise regarding emissions and engine roughness. A vehicle model has been used for simulation. The model contains non-linear elements of the engine, specially the engine torque irregularities. The control is done by the regulating of multidimensional proportional fuzzy controller gains. These simulation results show the applicability of self tuning fuzzy control for engine roughness and emissions control.

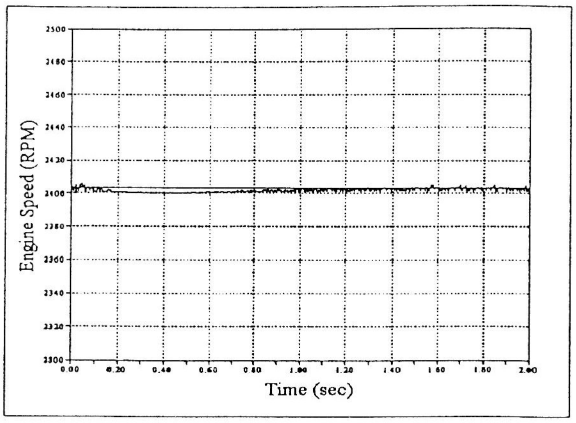

Figure 8. The Engine Speed Control for First Gain Series

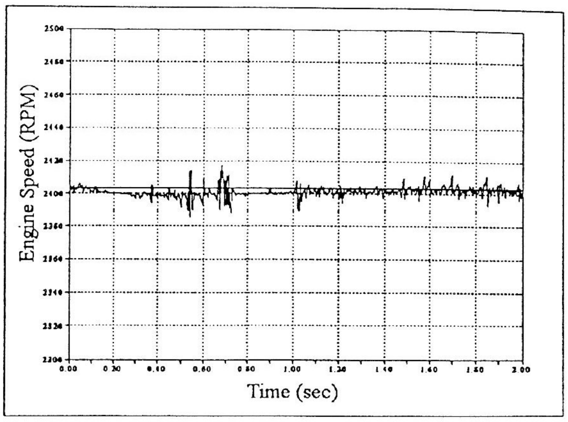

Figure 9. The Engine Speed Control for Second Gain Series

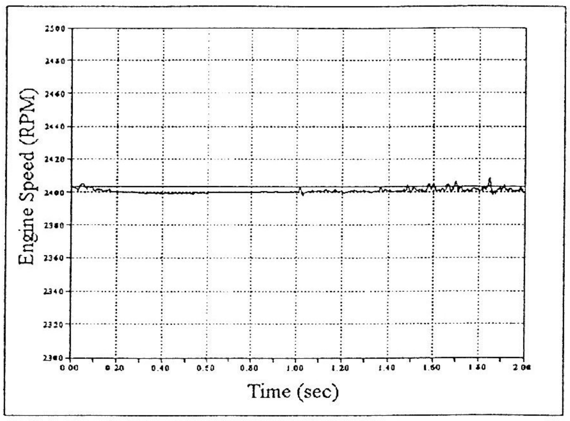

Figure 10. The Engine Speed Control for Third Gain Series

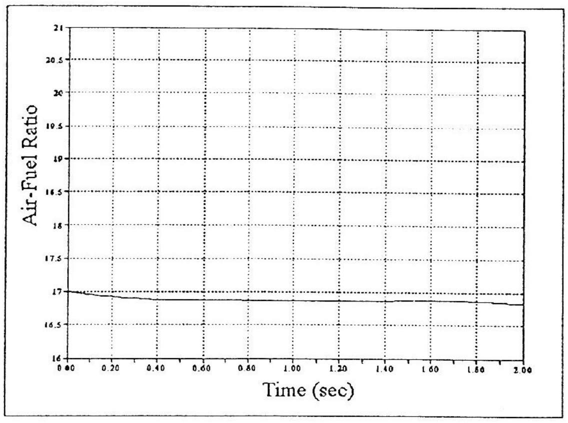

Figure 11. Air-fuel Ratio for First Gain Series

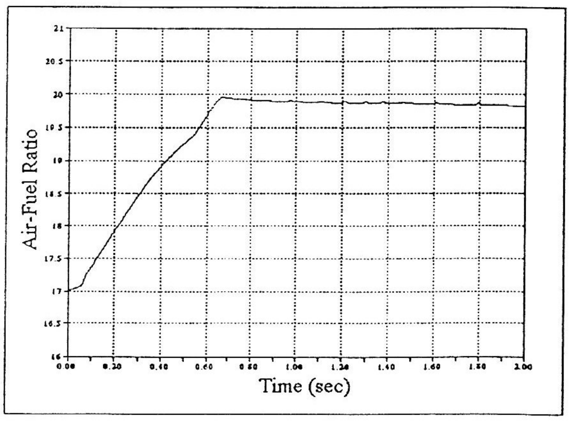

Figure 12. Air-fuel Ratio for Second Gain Series

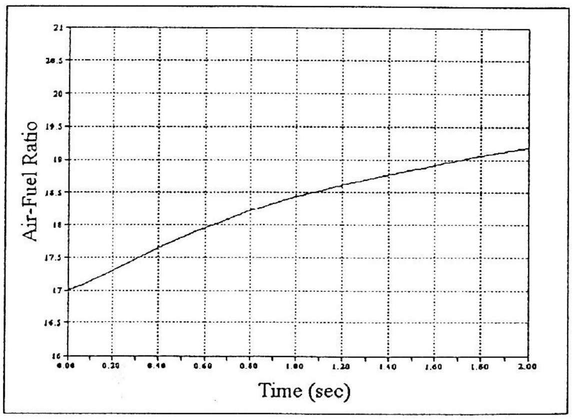

Figure 13. Air-fuel for Third Gain Series

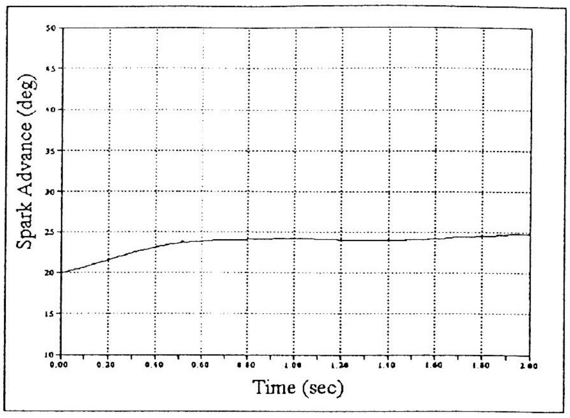

Figure 14. Spark Ignition Point for First Gain Series

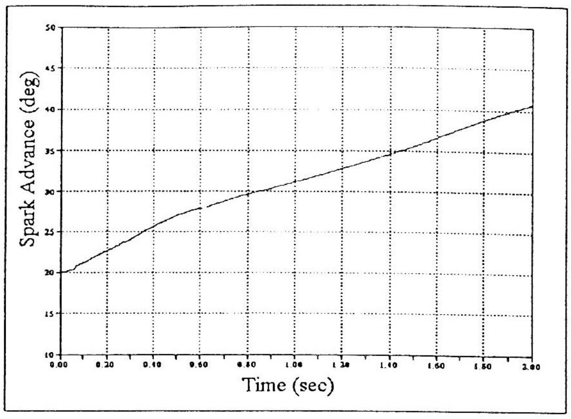

Figure 15. Spark Ignition Point for Second Gain Series

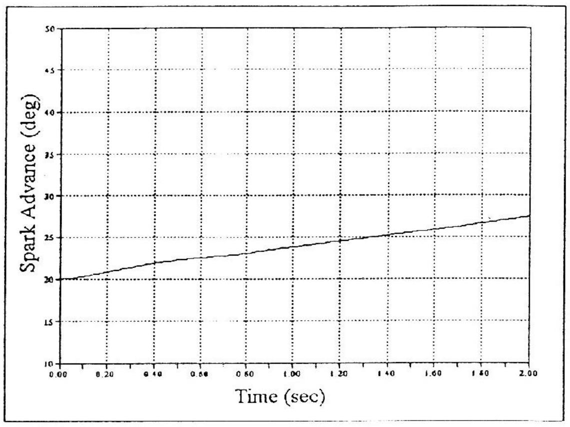

Figure 16. Spark Ignition Point for Third Gain Series

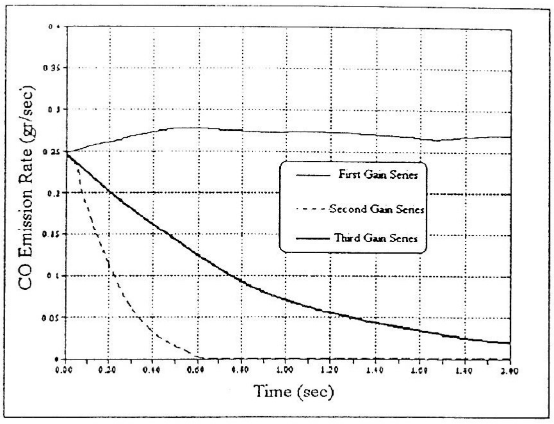

Figure 17. CO Emission Rate for Three Gain Series

Literature

1. Akhlaghi, M.: Laufunruhe, Abgasemissionen und Verbrauch eines Ottomotors bei Magerbetrieb und Möglichkeiten zur Ausweitung des mageren Betriebsbereiches, VWGO, Wien, (1978)

2. Akhlaghi, M.; Bamer, F.; Lenz, H.P.: Experimental Studies on Lean Run Spark Ignition Engines with Intensive Micro Turbulence, ISATA, Graz, Vol. 2, pp. 113-121, (1979)

3. Astrom, K.J.; Hagglung, T.: PID Controllers, 2nd Edition, Instrument Society of America, (1995)

4. Bamer, F.; Lenz, H.P.; Akhlaghi, M.: The Effect of Mean Pressure Variations on the Angular Velocity, on the Running Disturbance and on other Possible Measured Quantities, ISATA, vol. 1, pp. 502-518, (1979)

5. Coats, F.E.; Fruechte, R.D.: Dynamic Engine Models for Control Development - Part II, Int. J. of Vehicle Design, (1983)

6. Dingli, R.J.; Watson, H.C.; Palaniswami, M.; Milkins, E.E.: Adaptive Control of Air-fuel Ratio for Optimising the Fuel Efficiency of a Lean Burn Natural Gas Engine, Fisita Paper No. 945150, (1994)

7. Dobner, D.J.: A Mathematical Engine Model for Development of Dynamic Engine Control, SAE Paper No. 800054, (1980)

8. Feldkamp, L.A.; Puskorius, G.V.: Trainable Fuzzy and Neural Fuzzy Systems for Idle Speed Control, IEEE (1993)

9. Hara, S.; Nakajima, Y.; Nagumo, S.: Effects of Intake-valve Closing Timing on Spark Ignition Engine Combustion, SAE Paper No. 850074, (1985)

10. Hassel, P.J.D.; Joumard, R.; Hickman, A.J.: Vehicle Emissions and Fuel Consumption Modelling Based on Continuous Measurements, Fisita Paper No. 945127, (1994)

11. Hendricks, E.; Sorenson, S.C.: Mean Value Modelling of Spark Ignition Engines, SAE Paper No. 900616, (1990)

12. Inagak, H.; Ohata, A.; Inoue, T.: An Adaptive Fuel Injection Control with Internal Model in Automotive Engine, IEEE, (1990)

13. Latsch, R.; Mausner, E.: Experiences with a New Method for Measuring the Engine Roughness, ISATA, Vol. 2, pp. 306-319, (1979)

14. Lee, C.C.: Fuzzy Logic in Control Systems, Part I and II, IEEE, Vol. 20, No. 2, (1990), 17. G.E.

15. Nagao, F.; Nishiwaki, K.; Yokoyama, F.: Relation Between Inlet Valve Closing Angle and Volumetric Efficiency of a Four Stroke Engine, Bulletin JSME, Vol. 12, No. 52, (1969)

16. Nam, S.K.; Kim, J.S.; Yoo, W.S.: Fuzzy Sliding-mode Control of Gasoline Fuel-injection System with Oxygen Sensor, JSME International Journal, Vol. 37, No. 1, (1994)

17. Newton, K.; Steeds, W.; Garrett, T.K.: The Motor Vehicle, Butter Worth-Heinemann, (1991)

18. Powell, J.D.: A Review of IC Engine Models for Control System Design, IFAC 10th Triennial Word Congress, Munich, FRG, (1987)

19. Seiffert, U.; Walzer, P.: Automotive Technology of the Future, SAE Pub., (1993)

20. Tomizuka, M.; Hedrick, J.K.: Advanced Control Methods for Automotive Application, Vehicle System Dynamics, 24, pp. 449-468, (1995)

21. Tseng, Ch.H.; Hwang, V.H.: Servocontroller Tuning with Fuzzy Logic, IEEE Transactions on Control Systems Technology, Vol. 1, No. 4, (1993)

22. Vachtsevanos, G.; Farinwata, S.S.; Pirovolou, D.K.: Fuzzy Logic Control of an Automotive Engine, IEEE Control Systems, (1993)

23. Wang, Li-Xin: Stable Adaptive Fuzzy Control of Nonlinear Systems, IEEE Transactions of Fuzzy Systems, Vol. 1, No. 2, (1993)

24. Wang, Li-Xin: Adaptive Fuzzy Systems and Control, Design and Stability Analysis, PTR Prentice Hall, (1994)

Addresses: Dr. M. Akhlaghi, Dr. F. Bakhtiari Nejad and Ph. D. Candidate S. Azadi, Mechanical Engineering Department, Amirkabir University of Technology, P.O. Box: 15875-4413 Teheran, IRAN, Fax: (009821)-6419736