MODELING AND CONTROL OF AN ENGINE FUEL INJECTION SYSTEM

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To my beloved father, mother and brothers.

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ABSTRACT

Control of automotive exhaust emission has become an important research area to meet the more stringent automotive emission regulations. Beside the modification on internal combustion engine, control engineering is seen as another approach to improve and meet these requirements. This project focuses on the design and development of a control system to reduce the harmful waste of automotive exhaust emission. The control system aims to regulate the amount of fuel injected into the combustion chamber such that the air to fuel ratio (AFR) is maintained within the allowable range. The control process in this project is demonstrated based on an analytical engine model that clearly describe engine's air and fuel dynamic with no loss of engine system performance. Since the dynamics of the internal combustion engine and fuel injection systems are highly nonlinear, a linear model is obtained in this project, based on a system identification approach to allow methodical application of linear control theories. Two types of control strategy are employed – the linear quadratic Gaussian (LQG) controller and the fuzzy logic controller (FLC). The LQG controller, designed based on the linear model of the engine system, results in good controlled output response but with large controller signal variation. The FLC, however, provides better controlled output response by reducing overshoot gain and transient effect occurred in LQG controller design.

ABSTRAK

Kajian dalam mengurangkan lepasan toksik dari ekzos semakin penting pada masa kini demi memenuhi peraturan yang semakin ketat. Pada hari ini, melibatkan sistem kawalan dalam enjin telah menjadi salah satu jalan penting dalam mengurangkan lepasan toksik selain menjalankan modifikasi pada enjin. Projek ini akan fokus pada penghasilan dan penciptaan system kawalan yang mampu mengurangkan pelepasan gas toksik dari enjin ekzos ke udara. Sistem kawalan yang dicipta bertujuan untuk mengawal jumlah kuantiti petrol yang dibenarkan untuk menyembuh ke dalam chamber enjin dan menetapkan AFR pada jumlah yang dibenarkan. Dalam projek ini, penghasilan sistem kawalan akan bergantung pada simulasi enjin model. Projek ini telah memilih enjin model berasaskan cara analisasi yang mampu menterjemaahkan petrol dan udara proses dalam enjin dengan kejituan yang tinggi. Akan tetapi, ciptatan sistem kawalan dalam simulasi gagal diterima disebabkan oleh enjin proses yang tidak linear. Oleh itu, teknik berasaskan sistem *identification* dipakai demi menghasilkan enjin model yang linear. Dua jenis sistem kawalan akan dibincang dalam projek ini iaitu *Linear Quadratic Gaussian* (LQG) dan *Fuzzy Logic Controller* (FLC). Sistem kawalan LQG dihasil berasaskan enjin model yang linear manakala FLC dihasil berasaskan model enjin yang tidak linear. Keseluruhnya, LQG mampu memberi bacaan AFR yang bagus. Akan tetapi, ia menyebabkan signal kawalan yang berulang alik. Sistem kawalan FLC pula, mampu member bacaan AFR yang lebih bagus daripada LQG. Kelemahan sistem kawalan LQG telah dibaiki sepenuhnya dalam implikasi sistem kawalan FLC.

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LIST OF ABBREVIATIONS

AFR	-	Air Fuel Ratio
FLC	-	Fuzzy Logic Control
CO	-	carbon monoxide
HC	-	Hydrocarbons
NOx	-	Nitrogen Oxides
CFD	-	Computational Fluid Dynamic
PI	-	Proportional Integral
LQG	-	Linear Quadratic Gaussian
LQR	-	Linear Quadratic Regulator
ze	-	estimated model
zv	-	validated model
A	-	an n-by-n system matrix
B	-	an n-by-m input matrix
C	-	an r-by-n output matrix
D	-	an r-by-m transmission matrix
Co	-	controllability
Ob	-	observability
H,Q, R	-	weighting matrix
Rk,Qk	-	noise covariance data
v	-	measurement noise
w	-	process noise
e	-	system error

ECU	-	Electronic control units
K	-	LQG controller gain

LIST OF SYMBOLS

$\dot{m}_a$	-	mass rate of air in the intake manifold
m_a	-	mass of air in the intake manifold
$\dot{m}_{ai}$	-	mass rate air entering the intake manifold
$\dot{m}_{ao}$	-	mass rate of air leaving the intake manifold and entering the combustion
MAX	-	the maximum flow rate corresponding to full open throttle
TC	-	Normalized throttle characteristic
PRI	-	Normalized pressure influence function
α	-	the throttle angle
P_m	-	intake manifold pressure
P_{atm}	-	atmosphere pressure
M_a	-	constant value
R	-	gas constant
T_m	-	gas temperature
V_m	-	intake manifold volume
ω_e	-	engine angular velocity
η_{vol}	-	volumetric efficiency
$\dot{m}_{fi}$	-	fuel rate entering the combustion chamber
$\dot{m}_{fc}$	-	command fuel rate
τ_f	-	effective fueling time constant
β	-	desired air fuel ratio
Δt_{it}	-	intake to torque production delay
Δt_{ct}	-	compression to torque production delay

AFI	-	normalized air fuel ratio influence function
CI	-	normalized compression influence function
c_T	-	the maximum torque production capacity of an engine given that AFI=CI=1
A/F	-	actual air fuel ratio of the mixture in the combustion chamber
CA	-	tuning parameter of cylinder advance at the Top Dead Center
MTB	-	minimum tuning such that best torque acquire
I_e	-	effective inertia of the engine
T_i	-	engine indicated torque
T_f	-	engine friction torque
T_a	-	accessories torque
J_{LQ}	-	Cost funtion
P^r	-	Ricatti gain
$\hat{x}$	-	expected states

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CHAPTER 1

INTRODUCTION

1.1 Control System Overview

Control is defined as maintaining desired conditions in a physical system by adjusting selected variable in the system (Stewart, 1995). There exist several reasons why control system is necessary to implement in human life. The major reason of control system application is to maintain desired output even when external disturbance is occurred. For example control of temperature in a room, water level in a tank, power supply of control room and etc while the second reason for control is to respond to change in the desired value. For example, if the fluid level in a tank is increased, percentage opening of control valve will be decreased in order to maintain desired value of fluid level (Stewart, 1995).

In general, there are two types of control system structure- open loop control and close loop control. For systems in which the output has no effect on the control action they are called open loop control systems. In this case, output of open loop control system is neither measured nor fedback for comparison with the input. On the other hand, a closed loop control system or commonly called feedback control is capable in feeding in an actuating error signal, which is the difference between the input signal and the feedback signal(from output) to a controller so as to reduce the error and bring output of the system to desired value (Lukáš, 2008). As a result, the controller design become an important part yet critical in control system since it determines whether performance of a system is good or poor.

1.2 Background of the Study

In the past decades, development of earth moving vehicle's engine was mainly focused on fuel efficiency and performance increment such as torque, horse power and revolution of vehicle without worry on emission legislation. However in today situation, emission legislation is no longer an easy challenge for vehicle manufacturer to pass through when the numbers of vehicle all around the world has reached 50 millions in 2007 and expected to increase by 5% every year and reach approximate 60 million at year 2010(Chang, 2007). The development of automotive market would bring many negative effects that require serious consideration by automotive industrial. For example, today, large quantity of earth moving vehicles has turned internal combustion engine exhaust emission one of the main contributors to environment pollution with harmful gases such as

- carbon monoxide(CO)
- Hydrocarbons(HC)
- Nitrogen Oxides(NOx)
- Particulate emission.

Carbon monoxide is a very toxic, colorless and odorless gas, which is generated in the exhaust gas, as the result of incomplete combustion of fuel. As engines operate at enclose spaces such as car park or tunnel, it can accumulate very quickly and reach concentration which could harm humans health by causing headaches, lethargy or dizziness. As well as carbon monoxide, hydrocarbons are also produced due to the incomplete combustion of fuel. Generally, it causes bad impact to environment by influencing earth ozone reactivity with contribution of smoke and has characteristic of nuisance smell. Nitrogen oxides on the other hand are generated from nitrogen and oxygen from air intake manifold of engine when air flow through the engine cylinder under high pressure and temperature. Nitrogen oxides is a reactive gas and very toxic to human. Emission of nitrogen oxides will also deteriorate ozone reactivity and cause smog formation, which is a serious environment concern in today situation.

Therefore, due to global warming effect and environment protection, a lot of attention has been focused on automotive industry and it started to become a hot topic in climate discussion. These has force cars manufacturer and their supplier to develop new engine control strategies within short time period instead of using traditional technology to meet strict and stricter emission legislation from government(Ericson, 2007).

There are different control methods available for reducing pollutant components, such as control of engine speed, engine torque, fuel injection timing, AFR and so on. Among all, control of AFR is related to fuel efficiency, emission reduction and drivability improvement, furthermore maintaining AFR at stoichiometric level can obtain best balance between power output and fuel consumption (Muske, 2008). Control of AFR also guarantee reduction of pollutant emission to atmosphere since variation of AFR greater than 1% below 14.7 can result in significant increase of CO and HC emission. An increase of more than 1% will produce more NOx up to 50% (Kenneth, 2006).

Figure 1.1 shows historical view of worldwide emission legislation. It shows that the allowable nitrogen oxide emission was reduce from 7 g/kWh in the year 1996 to less than 1 g/kWh in the year 2010. Emission legislation Euro III at year 2000 shows limits on allowable vehicle NOx emission, which reduce to less than 5 g /kWh, and this, has been achieved through application of higher injection pressure to result in low particulate emission and retarded injection. However, emission legislation Euro IV and Euro V are no longer achievable by using the technology applied in Euro III. Therefore, car manufacturers have introduced new technologies such as cooled Emission Gas Recirculation (EGR) and Selective Catalytic Reduction to reduce NOx emission in order to meet legislation requirement. Today, the technology of Selective Catalytic Reduction is still applied in most vehicles due to its simple, practical and cost effective benefits.

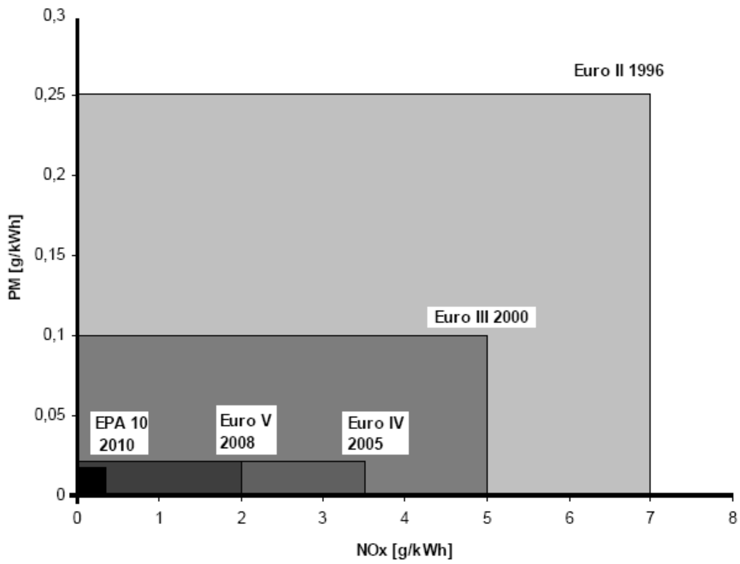

Figure 1.1: Historical view of emission legislation for vehicle
(Ericson, 2007)

In general, Selective Catalytic Reduction can be divided into two types-: Oxidation catalyst system and 3-way catalyst system. In this case, oxidation catalyst system is effective in reducing two major exhaust pollutants of carbon monoxide and hydrocarbons, through oxidation to carbon dioxide and water vapor (Tetsuji, 2004) as shown in Equation (1) and Equation (2).

$$CO + {}^{1}/_{2}\,O_2 \rightarrow CO_2 \qquad (1)$$

$$Hydrocarbon + O_2 \rightarrow CO_2 + H_2O \qquad (2)$$

However, this method is not longer used for emission control due to its low performance on reducing NOx components and meet stricter emission registration. Therefore, a newer catalyst technology, which is known as 3-way catalyst, was introduced (Tetsuji, 2004). In 3-way catalyst, three major pollutants, carbon monoxides, hydrocarbons and nitrogen oxides are simultaneously convert to carbon dioxide, oxygen and nitrogen. Equation 3 shows chemical conversion of pollutant within 3-way catalyst into environment friendly components.

$$(CO + HC) + NO_x \rightarrow CO_2 + N_2 + H_2O \quad (3)$$

The fundamental reaction in 3-way catalyst is between CO, HC and NOx. Therefore in order to achieve high percentage of conversions from all three environment pollutants- HC, CO and NOx into environmental friendly components, their concentration must be in stoischiometric ratio (Ali, 2008). This means that total amount of HC and CO should match the amount of NOx present in the system, in such a way exact equations of chemical reaction can be occurred in catalyst.

However, there is no way both of the components can meet stoichiometric ratio all the time, since concentrations of pollutants in the exhaust gas are highly depend on the fuel mixture composition. For example, at lean fuel mixtures the exhaust gases contain little carbon monoxide and hydrocarbons but high concentrations of NOx. On the other hand, at rich fuel mixtures the exhaust gas contains high concentrations of carbon monoxide and hydrocarbons but low concentration of NOx. Therefore, amount of engine’s fuel injection should be controlled in such a way so that engine’s air fuel ratio (AFR) is at the stoischiometric value of 14.7 and achieve full conversion of pollutant components as shown in Figure 1.2.

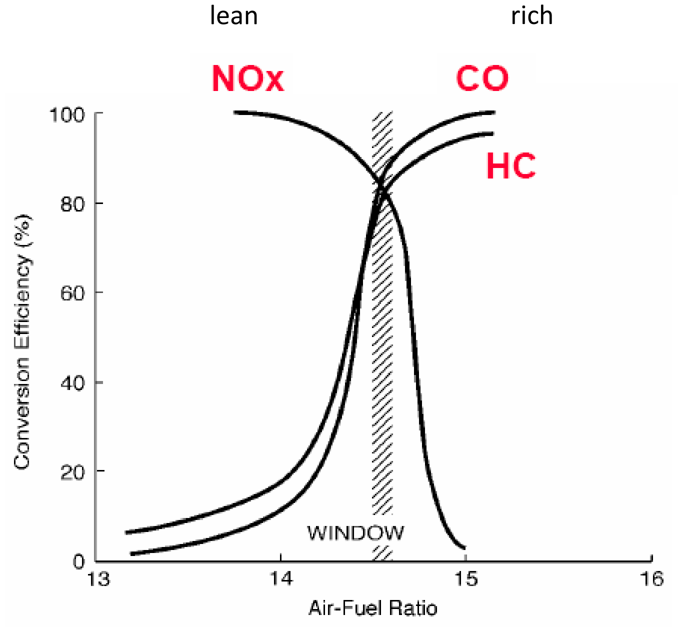

Figure 1.2 Percentage of pollutant conversion due to engine air fuel ratio

(Ali Ghaffari, 2008)

As a result, a compatible and suitable controller is required to be applied into engine's system such that engine's AFR can be maintained at stoischiometric range, thus resulting in high conversion efficiency of pollutant components.

1.3 Objectives of the Research

Based on the issue that variation of AFR deviating away from stoichimetric ratio can result in high concentration of pollutant from exhaust emission as discussed in the previous section (section 1.2), the project objective is therefore to maintain the engine's Air Fuel Ratio at stoischiometric level. This objective can be achieved through the following efforts:

i) To identified suitable mathematical engine model for AFR controller design purpose.

ii) To design and develop FLC and LQG control system for AFR control purpose in MATLAB-SIMULINK

iii) To ascertain the performance of the developed control system

1.4 Organization of the Report

The scope of work in this project concentrates on the engine and control system modeling follows by ascertain of control system performance using MATLAB-SIMULINK. This report will be build up by five chapters, which are introduction in chapter one, methodology in chapter two, literature review in chapter three, result and discussion in chapter four, last but not least conclusion and future work in chapter five. Following are important content and description of each chapter.

Chapter two will concentrate on literature review of engine and controller modeling method. In this project, mean value method been applied for engine modeling. Besides that, there are several available engine modeling method existed. For example, CFD method, Filling and Emptying method, Polynomial method and so on. Advantages and disadvantages of each method also application method of each method will be explained in this chapter. For controller modeling, several types of controller shall be reviewed. Performance and advantages of each controller will be discussed for decide and decision making purpose on suitable controller.

Chapter three is descript the methodology of engine plant and control system modeling. The simulated engine model is modeled by three blocks: Fuel dynamic, Air dynamic and rotation torque dynamic. Each block is correlating between each other.

Sets of model equation and formula which contribute to each block will be explain and descript in this chapter. Two types of controller will be discussed in this report:-fuzzy logic controller (FLC) and linear quadratic Gaussian (LQG) controller. In chapter three, the control algorithm and theory from each controller will be explained.

Chapter four will discuss FLC and LQG controller performance in controlling engine model's AFR. Simulation result from FLC and LQG controller will be compared and investigated to determine suitable controller, which work well with engine plant. Last but not least, chapter five is the project conclusion and future work description.

REFERENCE

Ali, G, Shamekhi, A. H, Saki, A and Kamrani, E (2008), Adaptive Fuzzy Control for Air-Fuel Ratio of Automobile Spark Ignition Engine, *proceedings of world academy of science, engineering and technology* ,volume 36, December 2008,1064-1072

ANDERSSON, H. (2008). *Model based control of air and EGR into a diesel engine*. Master Thesis. Chalmers University Of Technology.

Burl, J.B. (1999). *Linear optimal control H_2 and $H_\propto$ methods.* Menlo Park, California: Addison Wesley Longman Inc.

Chang, I. P.,Lin,G. Y. (2007), Fuzzy Logic Design of the SI Engine Air-Fuel Ratio Controller, *Proceedings of 2007 CACS International Automatic Control Conference ,* Nov. 9-11, 2007, 1072-1078

Chen, L. L. & Wei, M. X. (2008). On transient air/fuel ratio control for gasoline engine on the basis of model identification. *Proceedings of the 27th Chinese Control Conference.* Nanjing University of Aeronautics and Astronautics, China, July 16-18, 2008. 355-359

Copp, D.G. , Burnham, K.J. and Lockett, F.P. (1998). Fuzzy modelling techniques applied to *an* air/euel ratio control system. , *1998 The Institution of Electrical Engineers Control Theory and Applications Centre (CTAC).* Coventry University..3/1-3/7

Eko, A. P.(2001), *Modeling and control design of a powertrain simulation testbed for earthmoving vehicles*, the degree of master of science in Mechanical and Industrial Engineering Department, B.S., Texas A&M University

Ericson, C. (2007), *NOx Modeling of a Complete Diesel Engine/SCR System*, Licentiate Thesis, Lund Institute of Technology, Lund University

Gawronski, W. K., Racho, C. S. and Mellstrom, J. A. (1994). Linear quadratic gaussian and feedforward controllers for the dss-13 antenna. *TDA Progress Report 42-118*, August 15, 1994.37-56

HOU, Z. X. & WU,Y. H.(2007). The research on air fuel ratio predictive model of gasoline engine during transient condition. *Proceedings of the 2007 IEEE. International Conference on Mechatronics and Automation.*932-937

Hou, Z. X.& Wu, Y.H. (2006). Air fuel ratio identification of gasoline engine during transient conditions based on Elman neural networks. *Proceedings of the sixth international conference on intelligent systems design and applications (isda'06)*, IEEE.932-936

HOU, Z.X., WU, Y.H (2007), Multi-step predictive model of air fuel ratio for gasoline engine based on neural network, *International Technology and Innovation Conference 2007,*2028-2030

Huang, T. (2006). *Neural Network modeling and feedback Error Learning Control for Automotive Fuel injection System.* Master Thesis. University of Illinois at Chicago.

Jan Jantzen, (1998) Design Of Fuzzy Controllers,. *Tech. report no 98-E 864 (design)*, Technical University of Denmark, Department of Automation, DENMARK, 19 Aug 1998.

Jan Jantzen, (1998) Tutorial Of Fuzzy Controllers,. *Tech. report no 98-E 864 (design)*, Technical University of Denmark, Department of Automation, DENMARK, 19 Aug 1998.

Jiang, J. (1994). Optimal gain scheduling controller for a diesel engine. *Procs of IEEE Control Systems*. The University of New Brunswick,, Canada. August 1994.42-49

Joao P. Hespanha (2007). *Undergraduate Lecture Notes on LQG/LQR controller design*, Copyright to Joao Hespanha. April 1, 2007

Kenneth, R. M. & James, C. P. J. A (2006). Model-based SI engine air fuel ratio controller. *Proceedings of the 2006 American Control Conference.* Minneapolis, Minnesota, USA, June 14-16, 2006. 3284-3289

Kyung, W. M. , Lan, C. (2004). Design of frequency- dependent weighting function for H2 control of seismic-excited structures. *Journel of vibration and control, 112005*. 137-157

Li, Y. C., Liu, G. J. and Zhou, X. (2003). Fuel-injection control system design and experiments of a diesel engine. *IEEE transactions on control systems technology*, vol. 11, no. 4, july 2003.565-570

Liu, L. H., Wei, X. K., Liu, X. H.(2007). LPV control for the air path system of diesel engines. *IEEE International Conference on Control and Automation ThA3-4.* Guangzhou, CHINA - May 30 to June 1, 2007.1345-1351

Ljung, L. (1999). *System Identification : Theory for the User*, Prentice Hall, Upper Saddle River, N.J.

Lukáš Lanský (2008). *Diesel engine modeling and control*. Master Thesis. Czech Technical University in Prague

Muske, K. R., Jones, J. C., & Schallock, R. W. (2008). Application of an adaptive delay-compensated PI controller. *Proc. 17th IEEE International Conference on Control Applications*, San Antonio, Texas, USA, September 3-5, 781-785

Pieper, J. K. and Mehrotra, R (1999), Airfuel ratio control using sliding mode methods, *Proc. of the American Control Conference*, San Diego, California, June 1999, 1027-1031

Powell, J. D., Fekete, N. P. and Chang, C. F. (1998). Observer-based air fuel ratio control, *IEEE control system, SAE Paper 0272-1708/98*, Octorber 1998, 72-83

RACHID, A., LIAZID, A. & CHAMPOUSSIN, J. C.(1994). Nonlinear Modelling of a Turbocharged Diesel Engiric. *Procs of control system IEEE France* 1994.133-136

Segismundo, I. M., Cesáreo, H. I., Javier, P. G. (2004) State space modelling of cointegrated systems using subspace algorithms, *the International Conference on Modelling & Simulation - ICMS'04 Valladolid (Spain), s/n. 47011* , 22, 23 and 24 September 2004

Stewart, P. P.(1995).*Development of a Transient Air Fuel Controller for an Internal Combustion Engine*. Master Thesis California State University, Northridge Northridge, CA

Sun, J. S. & Liu, L. P.(2007) Determination of optimal air/fuel ratio and its control using CBR methodology. *The Eighth International Conference on Electronic Measurement and Instruments, ICEMI'2007.* 1-209-214

System Identification Toolbox User's Guide © COPYRIGHT 1988 – 2009 by The MathWorks, Inc

.

Tetsuji Watanabe, Takashi Watanabe, Kenichi Abe Hidekazu Yoshizawa (2004). Parameter identification of 3-way catalytic converter for use in air fuel ratio control. *SICE Annual Conference in Sapporo*, August 4-6,2004.1134-1138

Yao, J. B.,Wu, B., Zhou, D. S. (2009), Simulation on air fuel ratio control based on neural network, *SAEPaper 200500244,* College of Environmental and Energy Engineering Beijing, University of Technology, ,2009

Yazdanpanah, M. J. & Kalhor, A. (2003). Air/Fuel Ratio control in SI1 engines using a combined neural network & estimator. *Procs of 2007 Intelligent Control & Processing Center of Excellence*. University Of Tehran,2003 IEEE. 347-353

Yildiz, Y., *Student Member, IEEE*, Annaswamy, A. *Fellow, IEEE,* Yanakiev, D. *Member, IEEE,* Kolmanovsky, I. *Fellow, IEEE*. (2008). Adaptive Air Fuel Ratio Control for Internal Combustion Engines. *American Control Conference Westin Seattle Hotel, Seattle, Washington, USA June 11-13*. 2058-2063

Zhang, W. G., Jiang, J. H., Xia, Y., Zhou, X. D.(2002). CNG engine air-fuel ratio control using fuzzy neural networks. *Proceedings of the 2nd International Workshop on Autonomous Decentralized System*,2002 IEEE.156-162