DYNAMIC MODELLING AND ADAPTIVE PID CONTROL OF PALM OIL BIODIESEL ENGINE

by

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LIST OF ABBREVIATIONS

AFC	Active Force Control
AMM	Agilent Measurement Manager
ANN	Artificial Neural Network
ARX	AutoRegresive model with eXternal input
ARMAX	Autoregressive Moving Average with eXogenous
B2	two percent biofuel
B5	five percent biofuel
B10	ten percent biofuel
B100	One-hundred percent biofuel
BDC	BDC
BPO	Bleach Palm Oil
CPO	Crude Palm Oil
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
ERR	Error Reduction Ratio
DAQ	Data Acquisition
DE	Differential Evolution
DOHC	Double Overhead Camshaft
DSQRT	Discrete Square Root
GA	Genetic Algorithms
GDP	Gross Domestic Product
GPC	General Predictive Controller
HCCI	Homogeneous Charge Compression Ignition
ICE	Internal Combustion Engine
IFT	Iterative Feedback Tuning
LQG	Linear-Quadratic-Gaussian
MIMO	Multi-Input-Multi-Output
MLS	Maximum Length Sequences
MPC	Model Predictive Controller
MPOB	Malaysian Palm Oil Board
MSE	Mean-Square-Error
NARX	Nonlinear Autoregressive eXogenous

NARMAX	Nonlinear Autoregressive Moving Average with eXogenous
NOE	Nonlinear Output Error
OLS	Orthogonal Least Squares
PID	Proportional-Integral-Derivative
PME	Palm Methyl Esters
PRBS	Pseudo Random Binary Sequence
RLS	Recursive Least Squares
RELS	Recursive Extended Least Squares
RMS	Root-Mean Square
RMSE	Root Mean Square Error
RPM	Revolution Per Minute
SISO	Single-Input-Single-Output
SOHC	Single Over Head Cam
SSE	Sum of Square Error
TDC	Top-Dead-Centre
WCCM	Within-Cycle, Crank-angle-based Model

LIST OF SYMBOLS

A	system denominator polynomial
B	system numerator polynomial
C	noise numerator polynomial
d	dead time
$e(t)$	discrete white noise.
$\hat{e}(t)$	modelling or fitting error
$f(.)$	polynomial function
$f^{l}(\cdot)$	nonlinear function
F	mutation factor with real number between 0 to 2
$G(s)$	Laplace transfer function
G_p	process s-domain transfer function
g_m	the corresponding estimated parameter
k	time delay (discrete)
$J(\theta)$	cost function for estimation
K_p	proportional gain (PID)
K_i	integral gain (PID)
K_d	derivative gain (PID)
M_p	Maximum percent overshoot
l	degree of nonlinearity
M	maximum number of terms in the polynomial model
N	numbers of consecutive data vectors
n_y	maximum lag of output
n_u	maximum lag of input
$\mathbf{P}(t)$	covariance matrix
Δt	clock period
P_i	polynomial expansion
T_s	sampling time
T_c,	time constant
T_m	desired closed loop time constant
$T(z^{-1})$	Tayloring polynomial
$u(t)$	discrete input signal

w_m	the auxiliary orthogonal regressor
$y(t)$	discrete output signal
$\hat{y}(t)$	model predicted output
Δt	discrete time interval
$\boldsymbol{\varepsilon}(t)$	output prediction error
θ	true parameter vector
$\hat{\boldsymbol{\theta}}$	vector of adjustable model parameters
λ	forgetting factor
$\eta(t)$	stationary random signal source
$\varphi(t)$	regression vector consist of measured input-output variables
α_{rm}	constant coefficient in the orthogonal polynomials
$x_{i,j,G}$	target parameter vector $i = 1, 2, \ldots\ldots, NP$ (number of members in a population) $j = 1, 2, \ldots\ldots, D$ (dimensional parameter vector) G (generation)
$v_{i,G+1}$	mutant vector
$u_{i,G+1}$	trial vector
C_d,	threshold value criterion to stop the regression
ζ	damping factor
ω_n	natural frequency
g_i	controller coefficients

PERMODELAN DINAMIK DAN KAWALAN SUAI PID ENJIN BIODIESEL MINYAK SAWIT

ABSTRAK

Penggunaan biodiesel sebagai bahan api alternatif bagi pengangkutan menjadi semakin popular bagi menggantikan bahan api petroleum yang tinggi harganya. Kejayaan pelaksanaan penggunaan biodiesel dalam pengangkutan memerlukan pemahaman yang baik terhadap dinamik enjin dan pengawal yang boleh diharap untuk menguruskan enjin. Justeru itu, kajian ini bertujuan untuk membangunkan model matematik dan pengawal suai bagi enjin automotif yang menggunakan bahan api minyak sawit "methyl ester" (minyak sawit biodiesel). Penyelidikan pemodelan proses bermula dengan model matematik dinamik lelurus satu-masukan-satu-keluaran mewakili hubung kait antara kelajuan enjin dengan pendikit enjin bagi satu unit uji enjin diesel. Kedua-dua jenis model berketentuan dan stokastik telah diterbitkan dan disahkan. Tiga teknik anggaran parameter iaitu kaedah Jadi Semula Kuasa Dua Terkecil, Jadi Semula Di Panjangkan Kuasa Dua Terkecil dan Evolusi Kebezaan digunakan untuk menganggar parameter enjin. Kemudian, model dinamik jenis tak lelurus pula telah dibangunkan dan disahkan. Teknik anggaran Ortogon Jadi Semula Kuasa Dua Terkecil bersama dengan tatacara Nisbah Pengurangan Ralat digunakan untuk memilih struktur model kikir dan menganggarkan parameter model tak lelurus tersebut. Ketepatan model dinamik lelurus dan tak lelurus telah dibanding dan dianalisa. Keputusan kajian menunjukkan semua model yang telah diterbitkan adalah stabil dan bagus dalam menganggarkan keluaran enjin. Seterusnya, pengawal suai kelajuan PID yang berpandu kepada kaedah tugasan kutub telah direkabentuk, dibangunkan, diuji dan disimulasi sebelum dilaksanakan dalam masa nyata pada unit uji enjin. Pengawal suai ini telah direkabentuk bagi tujuan menjejaki dan melaras kelajuan titik set disamping menolak gangguan yang diperkenalkan kepada sistem tersebut. Sepanjang penyelidikan ini, algoritma kawalan yang dibangunkan telah diuji pada kelajuan titik set yang pelbagai dan gangguan beban. Keputusan kajian menunjukkan algoritma yang digunakan menghasilkan sambutan keluaran dinamik yang amat baik oleh enjin minyak sawit biodiesel. Algoritma yang dibangunkan telah berjaya mencapai objektif kawalan bagi mengesan dan melaras kelajuan enjin. Tambahan pula, keputusan ujikaji telah membuktikan pengawal ini mempunyai kemampuan menolak gangguan. Prestasi pengawal suai ini dalam mengesan, melaras dan menolak ganguan dibandingkan dengan enjin yang menggunakan bahan api diesel petroluem. Dalam kedua-dua kes, pengawal yang dibina telah menunjukkan prestasi yang amat baik dan terbukti boleh diharap untuk penggunaan kedua-dua jenis bahan api. Kajian ini telah membuktikan dengan nyata bahawa pengawal suai kelajuan berkadaran-kamiran-terbitan yang dibangunkan berjaya menunjukkan prestasi yang berkesan dalam mengawal kelajuan enjin automotif tanpa pengubahsuaian yang menggunakan minyak sawit biodiesel dan petroleum diesel.

DYNAMIC MODELLING AND ADAPTIVE PID CONTROL OF PALM OIL BIODIESEL ENGINE

ABSTRACT

The use of biodiesel seems set to become a popular alternative fuel for transportation to replace the high price petroleum fuel. To successfully implement the usage of biodiesel in transportation requires good understanding of the engine dynamics and reliable controller to manage the engine. Hence, this study is aimed at the development of mathematical models and adaptive controller of automotive engine fuelled with palm oil methyl esters (palm oil biodiesel). The process modelling investigation started with linear discrete-time single-input-single-output (SISO) dynamic mathematical models representing the relationship between engine speed and engine throttle of a diesel engine test-unit. Both deterministic and stochastic model types are derived and validated. Three parameter estimation techniques of Recursive Least Squares (RLS), Recursive Extended Least Squares (RELS) and Differential Evolution (DE) are used to estimate the engine parameters. Then, the nonlinear dynamic model of the engine type is derived and validated. Orthogonal Least Squares (OLS) estimation technique together with Error Reduction Ratio (ERR) procedures are used in the selection of the parsimonious model structure and parameter estimation for nonlinear ARX (NARX) model. The accuracy of linear and nonlinear dynamic models are compared and analyzed. The results show that all models derived are stable and good in predicting the engine output. Next, adaptive PID speed controller based on pole assignment method was designed, developed, tested and simulated before implemented in real-time on the engine test-unit. The adaptive controller is designed to track and regulate set-point speed as well as reject the disturbance introduced to the system. Throughout the investigation the control algorithm developed is tested at various engine set-point speeds and load disturbances. The results show that the algorithms produce very good dynamic output responses of the palm oil biodiesel engine. The algorithms have successfully achieved the control objective of tracking and regulating the engine speed. Furthermore, the experimental results also proved the disturbance rejection capability of the controller. The performance of the adaptive controller is compared with tracking, regulating and rejecting disturbance of automotive engine fuelled with petroleum diesel. In both cases, the controllers performed very well and proved to be reliable for both types of fuel. This study has significantly proved that adaptive PID speed controller developed performed effectively in controlling automotive engine speed fuelled with palm oil biodiesel and petroleum diesel without engine modification.

CHAPTER 1

INTRODUCTION

"The use of vegetable oils for engine fuels may seem insignificant today. But such oils may become in the course of time as important as the petroleum and coal tar products of the present time"

Rudolf Diesel, 1912

The importance of energy in our lives is very crucial that without energy life will be badly affected. The economic activities will cripple if the energy demand is not met. Development will stop without fuel supply. The industrial revolution came together with the dependency on energy. With the demand for energy to increase skyrocketing in this new century, searching for alternative energy is no longer an option but rather a must for the world to survive. In addition, awareness of environmental issues is becoming another factor that forces people to look for 'greener' alternatives to energy sources. One of the promising alternative energy available is biodiesel.

This chapter introduces the scenario of biodiesel in Malaysia, with a description of its history and its chronology of development. The implementation of advanced control engineering conducted for this research is presented. The thesis objectives and outline of this research are also discussed.

1.1 Introduction

Currently, there is extensive interest in using biofuel, especially biodiesel, in transportation (Kalam & Masjuki, 2008b; Demirbas, 2007a, b; Pichalai, 2005). In Malaysia, the effort to use renewable energy in transportation is highly supported by the government. However, to successfully implement the usage of biodiesel in transportation requires a thorough study in all related areas such as availability and reliability of the fuel and also the performance of the engine. Most of the studies carried out in Malaysia focuses on the engine performance and tribology (Adnan, Azre & Zulkifli, 2008; Masjuki, Abdulmuin & Sii, 1997; Masjuki et al., 2006; Fazal, Haseb & Masjuki, 2010) but very few focus on modelling and control. Among the studies involving in the modelling of biodiesel fuelled engine is a thermodynamic model developed by Ramadhas, Jayaraj and Muraleedharan, (2006) for analyzing the performance characteristics of the compression ignition engine fuelled by biodiesel and its blends. Using the model, the effect of relative air-fuel ratio and compression ratio on the engine performance of different fuels is analyzed. However, the model is based on a steady-state single zone thermodynamic model.

Thus far, no study on dynamic modelling of biodiesel engine, particularly using palm oil biodiesel, has been reported. Hence, there is a need to carry out such studies for engine controller design and development especially with the usage of palm oil biodiesel in public transportation. The findings from this study will provide researchers as well as engine control designers with a better understanding of the dynamic response of the existing automotive diesel engine fuelled with palm oil biodiesel.

The present study is to design and implement adaptive controllers in managing biodiesel engine. This research will focus on modelling and control for a palm oil biodiesel engine. In this work, dynamic mathematical models of palm oil biodiesel engine will be derived, validated and an adaptive control system for the engine will be developed. This study was motivated due to the unstable oil price situation in the world market, the fast depletion of fossil fuel and the environmental issues of public transportation. Research by Choo, Ma, Chan and Basiron, (2005) indicated that tests on palm oil biodiesel as diesel substitute from 1983 to 1994 have shown that palm oil biodiesel is suitable for diesel engine. In the studies they found that in general, palm oil biodiesel exhibits fuel properties comparable to those of petroleum diesel and can be used directly in unmodified diesel engines. Thus, this study will develop the first ever linear and nonlinear dynamic mathematical models for unmodified automotive diesel engine running on Malaysian palm oil biodiesel. In addition, an adaptive PID controller will be designed, developed and implemented in real-time for speed tracking and regulating as well as the disturbance rejection capability based on the model derived. The performance of the adaptive controller will be compared to engine fuelled with petroleum diesel.

1.2 Biodiesel in Malaysia

When Rudolf Diesel, the inventor of the diesel engine, first demonstrated his invention in the 1900s he used peanut oils as fuel to run the engine. For several years vegetable oils continue to fuel diesel engines before petroleum diesel derive from fossil fuel emerged and replaced its usage. Petroleum diesel was cheaper and easier to get at that time. Because of its low cost and easy availability, petroleum became the dominant energy source and petroleum diesel was then developed as the primary fuel for diesel engine (Pousa, Santos & Suarez, 2007).

However, the situation for energy supply and demand has changed drastically lately. Since the late 1970s the world has been facing critical fossil fuel supply. As a result, the fuel prices have been rocketing since then and supply is unstable. While the world fuel demand increases by each year unfortunately the world oil reserves are getting lesser and lesser. Fossil fuel has been used for years for all kinds of human activities. Economic activities especially are strongly related to the high usage of energy in infrastructure development and transportations of a country. The continuously high demand for energy has reached the point where looking for alternative energy to fulfil the demand is a must rather than an option for the world to survive. Fortunately, there are a lot of natural resources available to be explored and benefited as alternative energy. Renewable energy from natural resources like wind, sunlight, rain, tides, and geothermal heat are commonly used to replace fossil fuel. Until recently biodiesel, vegetable oil or animal fat based diesel fuel, has regained peoples' attention to be used as engines fuel.

The history of biodiesel sector in Malaysia could be dated back in 1980s. Being the world's largest producer and exporter of palm oil, Malaysian government had realized the importance of developing biodiesel as an alternative energy in the long term. Research and development of biodiesel in a laboratory scale started at the Palm Oil Research Institute of Malaysia (now known as the Malaysian Palm Oil Board, MPOB). Since then, palm oil biodiesel development systematically evolved to become an important alternative fuel for transportation. Table 1.1 summarized the chronology of biodiesel development in Malaysia.

Table 1.1: Chronology of Biodiesel Development in Malaysia

Year	Milestone
1982	Laboratory research on palm methyl esters (PME) biodiesel began
1983	Palm Diesel Steering Committee formed by the Minister of Primary Industries
1984	Construction of a PME biodiesel pilot plant (3000 tonnes a year capacity) began
1984-1985	Preliminary field trials in taxis conducted
1985	PME biodiesel pilot plant launched
1986-1989	Field trials phase I began—31 commercial vehicles and stationary engines
1990	Field trial phase II began—bench test by Mercedes Benz in Germany
1990-1994	Field trials phase III began—commercial buses
1995	Transfer of PME production technology to industry to produce oleochemicals, carotenes (pro-Vitamin A) and Vitamin E
2001	Use of a CPO and fuel oil blend for power generation initiated Research on low-pour-point palm oil biodiesel initiated
2002	Field trials using processed liquid palm oil and petroleum diesel blends (B2, B5, B10) in MPOB vehicles began (i.e. a straight vegetable oil [SVO] biofuel blend)
2004	Trials of refined, bleached and deodorized (RBD) palm oil and petroleum diesel blends (B5) using MPOB vehicles (i.e. an SVO biofuel blend) began
2005	Transfer of technology from the MPOB to Lipochem (M) Sdn Bhd and Carotino Sdn Bhd to build PME biodiesel plants. Design of commercial low-pour-point PME biodiesel plant. National Biofuel Policy drafted.
2006	National Biofuel Policy launched. First commercial-scale biodiesel plant began operations. Envo Diesel launched. 92 biodiesel licences approved.

2007	Increase in CPO price caused many biodiesel projects to be either suspended or cancelled
2008	Malaysian Biofuel Industry Act 2007 came into force Usage of Envo Diesel was scrapped and replaced with B5
2009	Government vehicles from selected agencies began use of B5 blend
2010	Government announcement that the B5 mandate for commercial use will be deferred to June 2011
2011	The palm oil-based B5 biodiesel program began on June 1 at Putrajaya
2012	B5 biodiesel program has been extended from June 2011 to Malacca, Negeri Sembilan, Kuala Lumpur and Selangor. Malaysia is ready to have nationwide implementation of the B5 biodiesel by year-end said Tan Sri Bernard Dompok-Plantation, Industries and Commodities Minister.

Sources: (Chin, 2011; Shen & Yeap, 2012)

Biodiesel is made through a chemical process called transesterification. In this process, the glycerin is separated from the fat or vegetable oil and leaves behind methyl esters and glycerin. In case of converting the feedstock crude palm oil (CPO) into fuel grade biodiesel, the CPO first undergoes pre-treatment processes to convert it into Bleach Palm Oil (BPO). Then, the BPO will undergo refining and separating processes to convert it into biodiesel. Figure 1.1 shows the block flow diagram of biodiesel production (Lim & Teong, 2010).