Modeling a Diesel Engine

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INTRODUCTION

Modern internal combustion engines must satisfy increasing environmental concerns and legislative emission standards imposed by authorities. In addition, customers' demand on performance and efficiency must be delivered at low cost and high reliability. These stringent requirements coupled with the energy crisis have motivated the search to improve engine performance.

Internal combustion engines are becoming more sophisticated in order to meet pollution, fuel reduction and safety requirements. In order to realize an environmental friendly, safe and fuel efficient engine, a good understanding of the behavior of the engine is necessary. Thus, a mathematical model of the engine to represent the best approximation of the system is crucial to ensure a good and reliable result. Mathematical engine models allow perturbation studies, sensitivity and error analysis, and system response measurements, and the effect of such system modifications can be demonstrated easily. Generally there are physical models and empirical models developed for the purpose of controller synthesis.

Physical models are derived from fundamental thermodynamic, fluid mechanics and rigid body mechanics laws, the advantage of which can be used to evaluate controller performance for a range of different operating conditions and engine sizes. However, complexity is a major disadvantage. Empirical models, are based on functional relationship between input and output variables through either mapping techniques or statistical correlations, using measured engine data. The relative mathematical simplicity of empirical models compared to physical models is their main advantage.

A mathematical model of an automotive diesel engine is derived using a black-box modeling technique. A simple modeling structure intended for control purposes that will be implemented with Proportional Integral Derivative (PID) controller in the future work is presented.

SYSTEM UNDER CONSIDERATION

The system used is a 2000cc, Direct Injection, DOHC Mitsubishi Diesel Engine, (picture), mounted on a test bed with a Hydraulic dynamometer braking unit which is driven by the engine under test via a shaft. A 4 to 20mA input signal is transmitted through an auto throttle servo actuator providing automatic throttle control between 0 to100% of throttle opening. A linear sensor attached directly to the throttle assembly provides feedback with no backlash errors. Engine speed is transmitted by an optical encoder also with a signal range of 4 to 20mA.

DESIGN

System Identification estimates a model of a system based on observed input-output data, based on three basic ingredients:

1. The input-output data
2. The model structure
3. The identification method

The identification process repeatedly selects a model structure, computes the best model in the structure, and evaluates this model's properties to see if it is satisfactory, as shown in Figure 1.

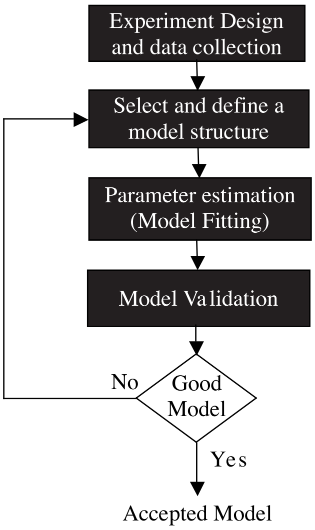

Figure 1: System identification flow chart

1. ***Experiment design and data collection*** – several sets of data describing system behaviour over its entire range of operating operation is collected. The idea is to vary the input and observe the response at the output.
2. ***Select and define a model structure*** – a set of candidate models from which the final mathematical model will be derived. It could be a linear or nonlinear model.
3. ***Parameter estimation*** – technique / strategy for parameter estimation implemented for model fitting.
4. ***Model validation*** – model estimate is evaluated to investigate whether or not it meets the necessary requirement.
5. Repeat the process until a good model is obtained.

Excitation Signal

A Pseudo Random Binary Sequence (PRBS) signal with Maximum Length Sequences (MLS) characteristics is selected as the input signal for identification purposes. The PRBS signal sequence period, T, can be varied according to:

$$T = P \, x \, N \qquad (1)$$

where P is the clock period and N is the sequence length. The sequence length is related to the number of registers through:

$$N+2^{n}-1 \qquad (2)$$

where n is the number of registers. As a rule of thumb in designing the PRBS signal, the clock period P is normally chosen to be approximately in the range of a fifth to a half of the output response time constant, i.e.

$$P+(0.2 \text{ to } 0.5)xT_c \qquad (3)$$

where T_c is the plant time constant. For a sequence of PRBS input to exhibit a complete transient behavior of the system, the sequence period T is chosen to be approximately equal to the settling time of the plant.

Mode Structure

In this initial stage, the simplest estimation discrete time mathematical model of the system that can be expressed with a single input and output Auto-Regressive with Exogenous (ARX) model is made. The system is assumed to have the special structure of:

$$y(t) = \frac{b_1 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}} u(t) \qquad (4)$$

Parameter Estimation

Recursive least squares technique allows significant saving in the computation. Instead of recalculating the least squares estimate in its entirety, requiring the storage of all previous data, it merely stores the 'old' estimate calculated at time t, denoted by $\hat{\text{è}}(t)$, and to obtain the 'new' estimate $\hat{\text{è}}(t+1)$ by an updating step involving the new data only. The aim is to select a value of $\hat{\text{è}}(t)$ so that the modeling error is minimized according to the sum of squares of errors:

$$J = \sum_{t=1}^{N} \hat{e}_i^{\,2}(t) = \hat{e}_i^{\,T} e_i \qquad (5)$$

The algorithm for updating $\hat{\text{è}}(t)$ is as follows:

At time step $t+1$:

(i) Form $x(t+1)$ using the new data

(ii) Form å$(t+1)$ using $\text{å}(t+1) = y(t+1) - \mathbf{x}^T(t+1)\hat{\text{è}}(t)$

(iii) Form $\mathbf{P}(t+1)$ using $\mathbf{P}(t+1) = \mathbf{P}(t)\left[I_m - \frac{\mathbf{x}(t+1)\mathbf{x}^T(t+1)\mathbf{P}(t)}{1+\mathbf{x}^T(t+1)\mathbf{P}(t)\mathbf{x}(t+1)}\right]$

(iv) Update $\hat{\text{è}}(t)$ $\hat{\text{è}}(t+1) = \text{è}(t) + \mathbf{P}(t+1)\mathbf{x}(t+1)\text{å}(t+1)$

This algorithm is used to estimate the plant parameters a_1, a_2 and b_1

EXPERIMENTAL SET UP

A computer is interfaced to the throttle and the speed sensor via an Agilent U2351A Multifunction DAQ. A Matlab program then generates the PRBS signal that excites the actuator, as in Figure 2.

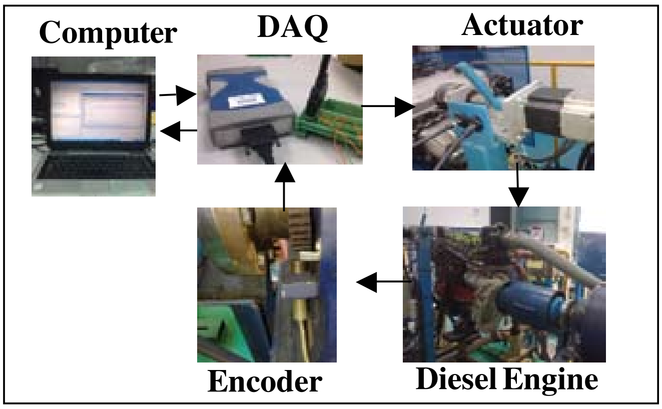

Figure 2: Block diagram of the data acquisition activities

In this experiment, a PRBS signal with a maximum length sequence of 31, period of 0.76 s, and sampling time of 0.16 s is used during data collection for high speed modeling at 3200 to 3400 rpm. 480 datas per set of 2 of real-time data are collected. The first set is for identification, while the other is for model validation.

RESULTS

The algorithm used enabled fast calculation of the required values in less than thirty iterations. Figure 3 shows the identification process of the diesel engine.

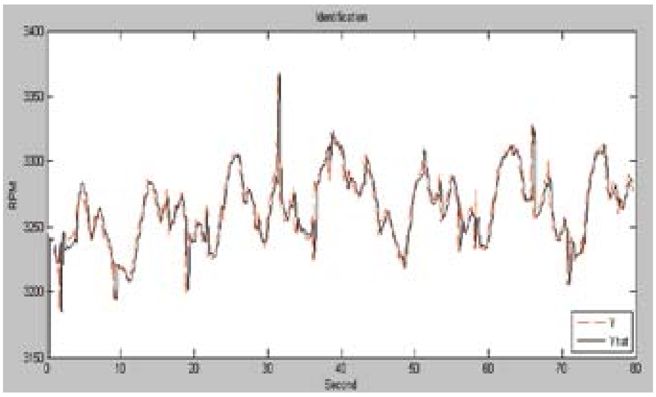

Figure 3: Identification

Figure 4 shows the final values of a_1, a_2 and b_1 identified by the recursive least squares program. All the parameters converge in less than 5 seconds.

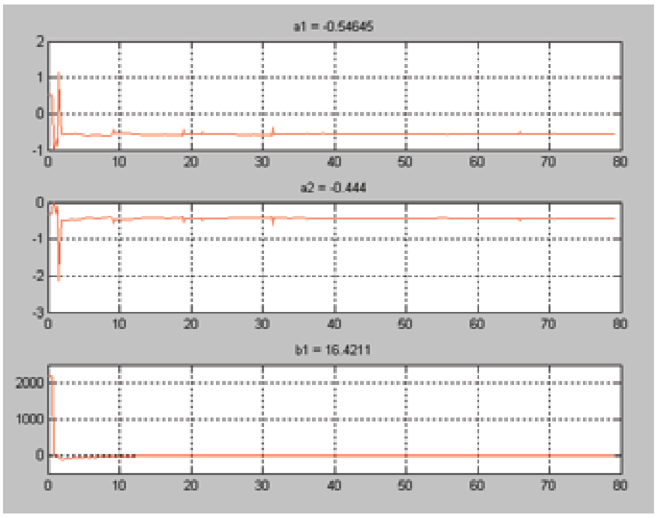

Figure 4 : The values of a_1, a_2 and b_1

Validation of the estimated values of the model output compared to the observed values of the engine speed shows very good agreement, with a fitting accuracy of 99.82%. The maximum error of the predicted model output compared to the measured data is 2.6%. Thus, the ARX model of the automobile diesel engine derived is acceptable.

CONCLUSION

In this work, the development of basic linear model of the automotive diesel engine has been presented. The model is successfully derived using a black-box modeling technique. The mathematical model developed presents analysis and simulation tools of the engine dynamics that forms the foundation for a systematic approach to the analysis, simulation and synthesis of automotive diesel engine control systems.

This manuscript is modified version of the original which will be presented in 'The 2nd International Conference on Engineering and ICT' February 2010 UTeM, Melaka as 'Modeling and Validation of Automotive Diesel Engine'.