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The cold starting control of engine using Large scale database-based Online Modelling

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Abstract: In order to solve the environmental pollution problem and the energy depletion problem in recent years, a control technology that improves the quality of engine in automobile is demanded. However, thanks to the developments of electrical and electronic mounting technology, advanced control of the power train has become possible. This paper presents an application of "Large scale database-based Online Modeling (LOM)" for the cold starting control of SI engine. LOM is a local modeling technique based on the database to predict and control a large-scale process. The intake air mass flow in cylinder is predicted in order to reach the desired engine speed in cold starting by using LOM, and adequate fuel injection quantity is derived from the intake air mass flow and the fuel injection model.

1. INTRODUCTION

In order to cope with global environmental protection and energy depletion problem in recent years, a control technology that improves the quality of the engine is demanded. However, developments of electrical and electronic mounting technology allow advanced control of the power train.

On the other hand, with the development of the computing machine and the database system, accumulating and retrieving a large amount of data at high speed have become possible. Local modelling techniques of a new idea called "Just-In-Time (JIT) modelling", see (Stenman, A., *et al.*, 1996; Ushida, S., *et al.*, 2005), or "Lazy Learning", see (Bontempi, G., *et al.*, 2001), have gotten attention.

The method accumulates the data measured in the wide operating range to a database. Whenever there is a need for prediction in system, the data which have a high relevance the "demand point (Query)" of the input are retrieved from the database as neighbouring data. And an output of retrieved data is interpolated to obtain an output of "the demand point" by compositing the local model. The method the ability features to deal with changes easily by discarding an existing local model and recomposing a new local model, whenever further accumulation of observed data occurs.

Moreover, to apply "JIT modelling" to a large amount of database online, "Large-scale database-based Online Modelling (LOM)", see (Ito, M., *et al.*, 2004a; Ito, M., *et al.*, 2004b; Ito, M., *et al.*, 2005; Uchida, K., *et al.*, 2005), has been proposed.

The purpose of this research is an application of "Large scale database-based Online Modelling (LOM)" for the cold starting control of SI engine. LOM is a local modelling technique based on the database to predict and control a large-scale process. An intake air mass flow in the cylinder is predicted in order to reach the desired engine speed in cold starting by using LOM, and adequate fuel injection quantity is derived from the calculated intake air mass flow and the fuel injection model.

This paper is structured as follows. Section 2 explains the control object and problem establishment in SI engine control. Section 3 introduces the JIT modelling and LOM. Section 4 discusses a prediction method of an intake air mass flow in cylinder by LOM and prediction results. Section 5 introduces the cold starting control method of engine by LOM.

2. CONTROL OBJECT AND PROBLEM ESTABLISHMENT

2.1 Control object

A control object is a SI engine with 6 cylinders. It is shown as the following equation (1), (2).

$$\frac{d}{dt}x(t) = f(x(t),u(t)), \quad x(0) = x_0 \qquad (1)$$

$$y(t) = g(x(t),u(t)) \qquad (2)$$

Here, $x(t) \in R^n$ is the system state, $u(t) \in R^{13}$ is system input, and $y(t) \in R^2$ is system output. The input includes the throttle angle, the fuel injection quantity of each cylinder port and the ignition timing of each cylinder. The number of input is 13. The output includes the engine speed and the air mass flow in throttle. The number of output is 2.

2.2 Problem establishment

It is demanded that following main control specification is satisfied.

1) Reach an engine speed of 650 ± 50 [rpm] within 1.5 seconds from engine starting.

2) Reduce overshoot of the engine speed.

3) Minimize integrated value of the fuel injection quantity.

3. LARGE-SCALE DATABASE-BASED ONLINE MODELLING (LOM)

This section explains the JIT modelling as basic conception of "Large-scale database-based Online Modelling (LOM)".

3.1 JIT Modelling

An objects process is a nonlinear dynamic system, and characteristics of the system are given by a regression model expressed in the following equation (3).

$$y(t+p) = f\{y(t), y(t-1), \cdots, y(t-n_y), u(t-d), u(t-d-1), \cdots, u(t-d-n_u)\} \quad (3)$$

Where,

$u(t)$ is the control input vector of system at time t,

$y(t)$ is the observational output vector of system at time t,

n_u is the order of control input vector,

n_y is the order of observational output vector,

p is the estimated time (or the predicted time)

d is the time delay,

f is the unknown nonlinear function

Furthermore, the system input vector x^k and the system output vector y^k are redefined as the following equation (4) and (5).

$$y^k = y(k+p) \quad (4)$$

$$x^k = \{y(k), y(k-1), \cdots, y(k-n_y), u(k-d), u(k-d-1), \cdots, u(k-d-n_u)\} \quad (5)$$

As time passes, a large number of data, composed of the system input vector x^k, the system output vector y^k, for example (x^1, y^1), (x^2, y^2), $\cdots$, are stored in the system as a data sets $\{(x^k, y^k)\}, (k = 1,2,\cdots,)$, Where k is the discrete time. Then, JIT modelling is to find out the nonlinear function f from the stored data sets $\{(x^k, y^k)\}$ whenever they are required to be estimated (or predicted, controlled).

For example, when it becomes necessary to estimate a system state at time t, the present system state $\{(x^{k_q}, y^{k_q})\}$ is defined as the demand point. Neighbouring data $\{(x^{k_i}, y^{k_i})\}$ $(k_i < k_q)$ similar to the demand point as past observed process data in the database are selected. When a number of data sets are obtained, a local model to interpolate output of the dataset will be constructed. By using the local model, the system output vector y^{k_i} is estimated. Then, the local model is discarded and neighbouring data sets in measured data sets updated database are selected in the next estimation. The schematic diagram of Just-In-Time modelling is shown in Fig.1.

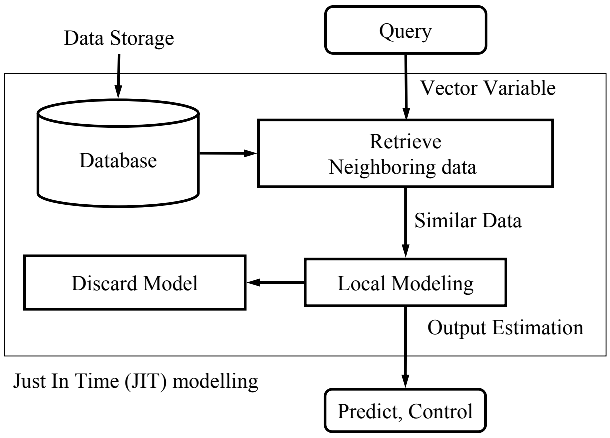


Fig. 1. Schematic diagram of Just-in-Time modelling

3.2 LOM

The LOM makes the retrieval of neighbouring data more efficient by using "stepwise method" and quantization. The stepwise method decreases the dimension of multi-dimensional space of actual process. In addition to that, the multi-dimensional space is quantized. Schematic diagram of the LOM is shown in Fig.2. Stepwise method is a technique that adds and deletes input variables by a statistical test to decrease input variables within the bound enough for practical use in the regression model.

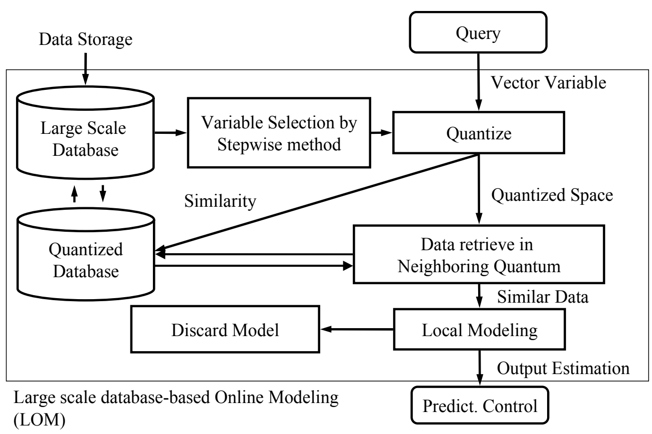


Fig. 2. Schematic diagram of LOM

3.3 *Quantization of topological space and searching the "neighbour"*

At first, by defining quantized space X^k as follows, a vector input variable x^k is classified.

$$X^k = Z\left(x^{k_i}\right), (i = 1,2,...,n) \tag{6}$$

Where, $Z(\cdot)$ is the quantizing operator, n is the number of the data that belongs to the same quantized space X^k. Second, It is shown as follows to define a similarity $S(k_i, k_j)$ between the quantized space X^{k_i} and X^{k_j}.

$$S(k_i, k_j) = \left\| X^{k_i} - X^{k_j} \right\|_\infty \tag{7}$$

Where, $\|\cdot\|_\infty$ is an infinite norm. Then, it is assigned that quantized space X^{k_q} includes demand vector x^{k_q}. A neighbouring space Ω_q of the vector x^{k_q} is defined as follows.

$$\Omega_q = \left\{ X^{k_p} \middle| S\left(k_q, k_p\right) = \min_{X^{kp} \in T} S\left(k_q, k_p\right) \right\} \tag{8}$$

Where, T is a set of topological space. By applying the quantization, similarity $S(k_i, k_j)$ is defined as a discrete value. The neighbouring data are retrieved simply and effectively by quantizing their distances with the demand point, at first within the shortest distance zone, then within farther and farther distance zones.

The several ways of determining the quantum's width are proposed. In this paper, a uniform equalized way, or the simplest way, is adopted.

3.4 *Local Model*

In representative local model of JIT modelling, Locally Weighted Averaging (LWA), Locally Weighted Regression (LWR) and etc. have been proposed. In this paper, the simplest averaging way is adopted. In other words, the estimated system output vector $\hat{y}^{k_q}$ is calculated as follows.

$$\hat{y}^{k_q} = F(X^{k_q}) = \frac{1}{M} \sum_{y^k;(x^k, y^k) \in \Omega_q} y^k \tag{9}$$

Where, M is the number of the system output vector y^k that belongs to the neighbouring space Ω_q.

4. PREDICTION OF INTAKE AIR MASS FLOW BY LOM

4.1 *Configuration and selected variables*

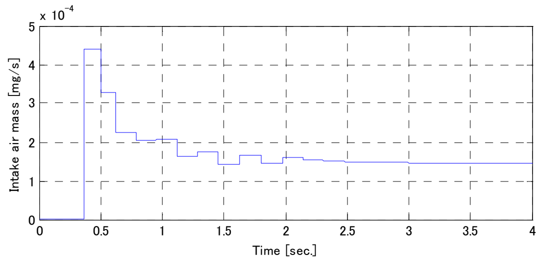
The prediction of the intake air mass flow in cylinder based on LOM is described. There are 4 data items of a high contribution ratio for the intake air mass flow rate by stepwise method. The sampling time is 0.05 seconds. The selected variables are shown in Table 1. For example, the current air mass flow in throttle, the current ignition timing, the engine revolution before 0.1 seconds, and crank angle before 0.3 seconds are selected.

Table 1 Variables selected by stepwise method

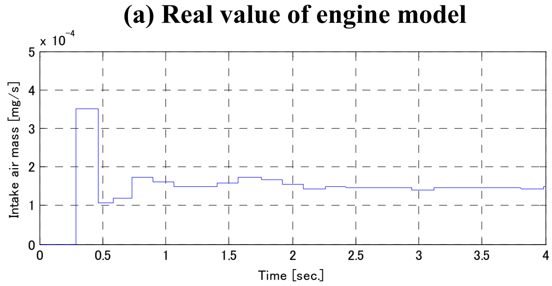
No.	variable	delay time
1	Air mass flow in throttle	current
2	Ignition timing	current
3	Engine revolutions	before 0.1 sec.
4	Crank angle	before 0.3 sec.

4.2 *Prediction examples of intake air mass flow*

The intake air mass flow rate in the cylinder that decides the intake fuel injection quantity is a key. When the intake air mass flow rate in the cylinder is estimated by the integrated value of the air mass flow rate in throttle, errors between real value and estimated value are observed for 1.0 second after cold starting as shown in Fig.1 (a) and (b). Therefore, LOM is applied to improve the estimation accuracy of the intake air mass flow rate in the cylinder.



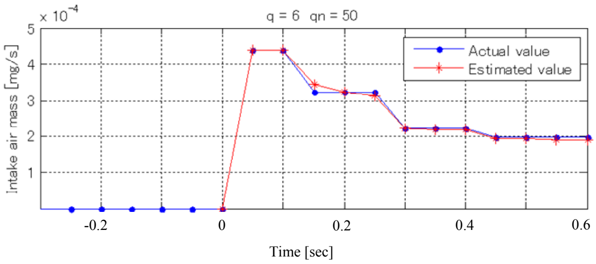
(a) Real value of engine model



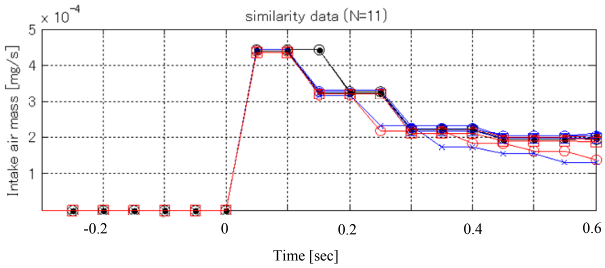
(b) Estimated value derived by sum of throttle air mass flow

Fig. 1 Comparison of estimated value and real value

For example, data set of No.1 demand point is selected. LOM predicts the intake air mass flow in cylinder after 0.6 second. The past similar data retrieved by LOM is shown in Fig.3 (b). The estimated value and actual value of intake air mass flow in cylinder based on the past similar data are shown in Fig.3 (a). The horizontal axis of the graph represents time from past 0.6 seconds to future 0.6 seconds and the position of zero is the time of demand point. The vertical axis is the intake air mass flow in cylinder. Past data similar to present operation data are obtained in 11 points. It is confirmed that the estimated value are similar to the actual value, as shown in Fig.3 (a).



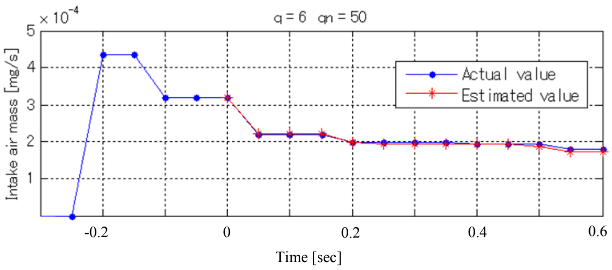
(a) Actual and estimated intake air mass flow in cylinder



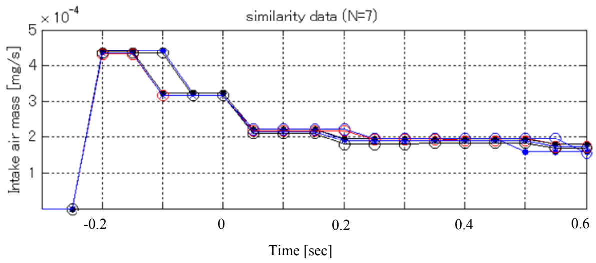
(b) Actual past similar data of intake air mass flow in cylinder

Fig. 3 Estimated results for intake air mass flow in cylinder (No.1 demand point)

Moreover, data set of No.2 demand point is selected. The past similar data retrieved by LOM is shown in Fig.4 (b). The estimated values and actual values of intake air mass flow in cylinder based on the past similar data are shown in Fig.4 (a). Past data similar to present operation data are obtained in 7 points. The decreasing intake air mass flow in cylinder after 0.6 seconds is understood from the estimated value, as shown in Fig.4 (a).



(a) Actual and estimated intake air mass flow in cylinder



(b)Actual intake air mass flow in cylinder of the past similar data

Fig. 4 Estimated results of intake air mass (No.2 demand point)

4.3 *Prediction accuracy*

The prediction accuracy of an intake air mass flow in cylinder is evaluated by the scatter diagram between the estimated value and the actual value of 200 randomly picked up demand points from all the 2013 data sets. The scatter diagram of actual intake air mass flow values and estimated intake air mass flow values after 0.05 seconds in cylinder by LOM is shown in Fig.5. The correlation coefficient is 0.9120 as shown in Fig.5. Therefore, it is confirmed that the LOM can predict the intake air mass flow with satisfactory accuracy from a practical standpoint.

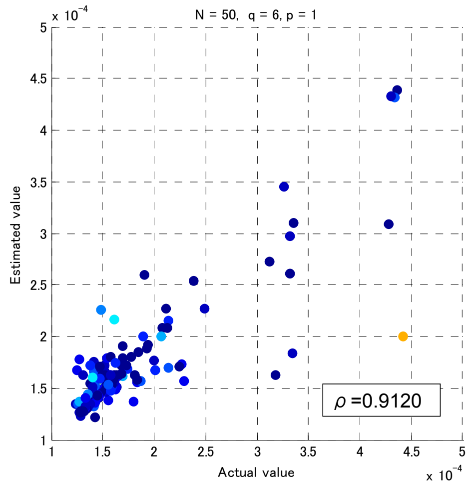


Fig. 5 Scatter diagram of actual intake air mass flow values and estimated intake air mass flow values after 0.05 seconds in cylinder by LOM

5. APPLICATION OF ENGINE CONTROL

The key is to control the engine speed by manipulating the fuel injection quantity, the throttle angle, and the ignition timing.

5.1 *Fuel injection quantity*

The intake air mass flow in cylinder is shown by equation (10); see (Society of Automotive Engineers of Japan, 1997).

$$f_{cr}(k) = (1-R)f_i(k) + (1-P)f_w(k) \tag{10}$$

Here,

f_{cr} is the intake fuel injection quantity in cylinder,

f_i is the fuel injection quantity,

f_w is the residual fuel quantity in intake port,

P is the residual factor of liquid membrane fuel,

R is the attachment rate of injection fuel,

k is the cycle number.

The inverse model equation (11) is derived from equation (10).

$$\hat{f}_i(k) = \frac{\hat{f}_{cr}(k) - (1-P) f_w(k)}{1-R} \qquad (11)$$

Here, the residual fuel quantity f_w in intake port is shown by equation (12).

$$f_w(k) = P f_w(k-1) + R f_i(k-1) \qquad (12)$$

Estimation of the intake fuel injection quantity in cylinder $\hat{f}_{cr}(k)$ is shown by equation (13).

$$\hat{f}_{cr}(k) = \frac{\hat{M}_{cf}}{\alpha_r} \qquad (13)$$

Where, α_r is the desired air-fuel ratio,

$\hat{M}_{cf}$ is the estimation for air mass flow in cylinder.

The air mass flow $\hat{M}_{cf}$ in cylinder is estimated by using LOM. Therefore, the fuel injection quantity is derived by using equation (11) and equation (13).

5.2 Ignition timing

The ignition timing is set from 10 degree to 50 degree based on the engine speed as shown in Fig.6. For example, if the engine speed is less than 600 rpm, the ignition timing is set to be 10 degree. If the engine speed is 650 rpm, the ignition timing is set to be 30 degree. If the engine speed is more than 700 rpm, the ignition timing is set to be 50 degree.

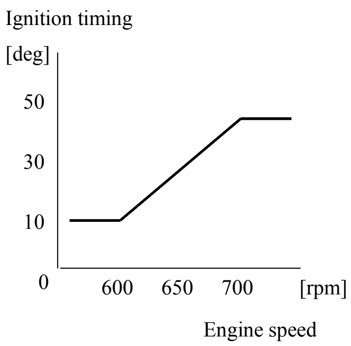


Fig. 6. Configuration of engine speed vs. ignition timing

5.3 Throttle angle

The engine speed is controlled by manipulating throttle angle based on PID controller using the present engine speed and the referenced value of engine speed as shown in Fig.7.

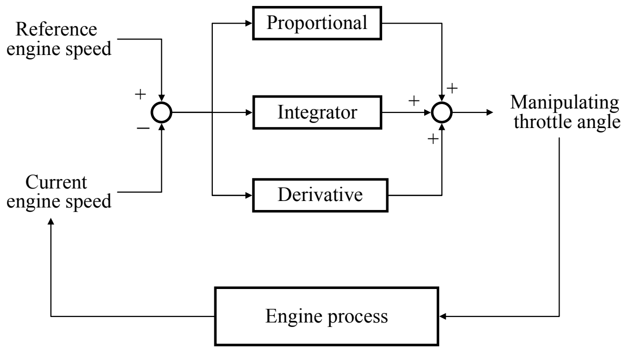
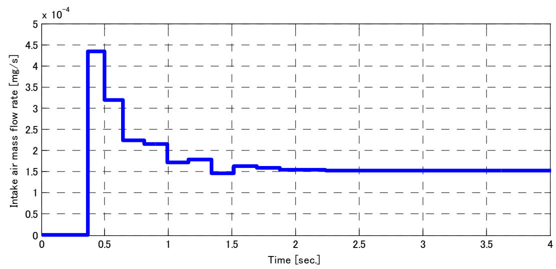


Fig. 7. PID controller for the throttle angle

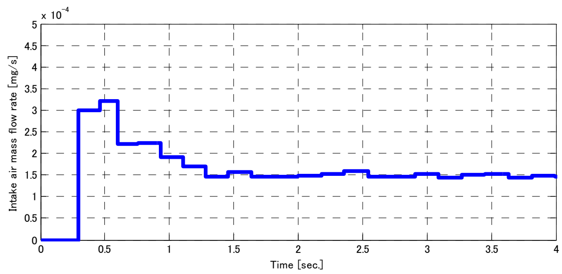
5.4 Prediction of intake air mass in control simulation

The actual intake air mass flow in cylinder in control simulation using engine model is shown in Fig.8 (a). The estimated value of the intake air mass flow in cylinder based on LOM is shown in Fig.8 (b). The estimated result locally-fluctuates because of sequential prediction. However, it is confirmed that the estimated value curve is similar to the actual value curve.

Furthermore, a result of control simulation is shown in Fig.9 (a) (b). It shows that the engine speed reached 650±50 [rpm]. Therefore, it understood the realization controller using LOM. However, it is necessary to improve the air-fuel ratio and overshoot of the engine speed.

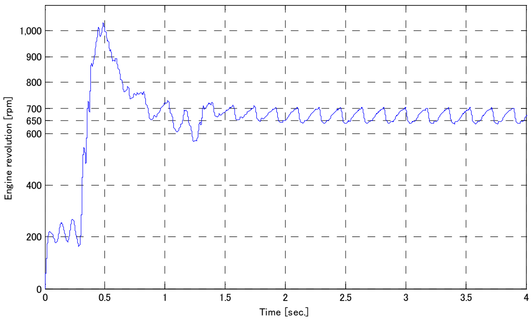


(a) The actual intake air mass flow in cylinder in simulation

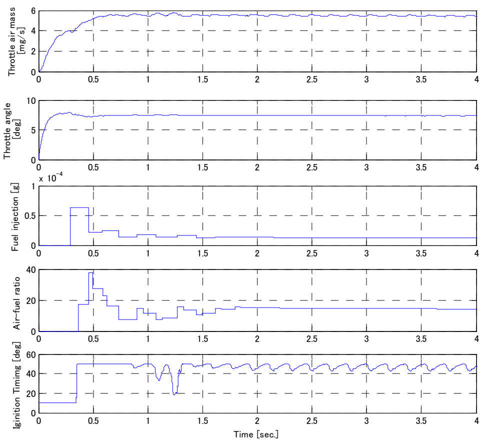


(b) The estimated intake air mass flow in cylinder by LOM

Fig.8 Comparison of estimated value and actual value



(a) Engine revolution



(b) Throttle air mass, throttle angle, fuel injection, air-fuel ratio and ignition timing

Fig. 9 Results of engine control simulation

6. CONCLUSIONS

In this paper, LOM of a prediction technique based on database has applied to the cold starting control in a SI engine. LOM has predicted the intake air mass flow in cylinder to derive the fuel injection quantity of a manipulating variable in order to satisfy the problem establishment. It has confirmed that the LOM can predict the intake air mass flow in cylinder with satisfactory accuracy from a practical standpoint.

LOM system has been implemented into engine controller in engine simulator to calculate the fuel injection quantity. Furthermore, the control method using LOM system for cold starting control in the SI engine has been proposed. It has confirmed that LOM is useful for the engine control by the control simulation.

In this paper, as the first step of the application for cold starting control in the SI engine, LOM has been used to decide the fuel injection quantity. As the next step, it is necessary to improve the air-fuel ratio and overshoot of the engine speed by using LOM.

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