AN APPLICATION OF THE PARAMETER – INFLUENCE TECHNIQUE FOR A REDUCED HEAT TRANSFER MODEL IDENTIFICATION

Chanyut Khajorntraidet[1], Kazuhisa Ito[2]

[1]Graduate School of Engineering and Science, Shibaura Institute of Technology

[2]College of System Engineering and Science, Shibaura Institute of Technology

nb13504@shibaura-it.ac.jp[1], kazu-ito@shibaura-it.ac.jp[2]

ABSTRACT

Heat transfer effects in the combustion processes of spark ignition (SI) engines have been considered for combustion processes analysis and control. There are many researches have proposed the convective heat transfer models for SI engines. However, the models for approximation of the heat transfer contain strong nonlinearities that are difficult to incorporate in the heat release model for control problem. Therefore, the reduced model is introduced in some works. There are two important objectives of this reduced model, to simplify the convective heat transfer model and retain the effects of heat transfer during combustion. On the other hand, the effective identification technique is necessary for obtaining the model parameters. In this work, we proposed the application of the parameter-influence (sensitivity) technique for the reduced heat transfer model identification. With this technique, the parameters of the reduced model are identified online during combustion and expansion period. The results show that the parameters obtained from the identification can be utilized to estimate the convective heat transfer of the SI engine compared with the original model.

1. INTRODUCTION

The heat transfer modeling in internal combustion engines has been a challenge task because of the difficult prediction of this phenomenon. Several papers have been researched on the effects of heat transfer in internal combustion engines (Soyhan *et al.,* 2009, Huber *et al.,* 1990, Woschni, 1967, Hohenberg, 1979, and Han *et al.*, 1997). This heat loss is mainly from the heat transfer by convection to the combustion chamber walls and affects the performance of the SI engine. Additionally, the knocking problem is strongly depending on the amount of heat transfer because it affects ignition timing, combustion duration, and rate of pressure rise, which are correlated to knock (Hou *et al.,* 2010 and Machrafi *et al.,* 2008). In the work of Woschni, 1967, an empirical law was proposed, where the heat transfer coefficient depends on the pressure, temperature and engine speed. The estimation of heat transfer during the compression and combustion strokes allows representing the system during the combustion. However, the model contains strong nonlinearities and difficult to implement in the heat release modeling (Rivas *et al.,* 2012). Hence, in the work of Rivas *et al.,* 2012, the reduced heat transfer model was proposed. In general, the heat transfer to the combustion chamber walls is quite difficult to estimate and be examined. Many studies pay attention on the heat transfer estimation but the challenged problem is the accuracy of the heat transfer model parameters. The system identification techniques both online and offline are proposed for this task. An adaptive model parameters estimation technique is interesting because it can be applied to minimize the objective online (Eykhoff, 1974). This technique has many advantages, for instance, low computational load compared with some offline techniques and good tracking performance. The results of the heat transfer model identification can be incorporated into cylinder pressure analysis by using heat release approach based on the first law of thermodynamics (Heywood, 1988). Moreover, the knocking effects caused from the convective heat transfer can be analyzed.

This research presents the adaptive identification algorithm based-on parameter-influence technique for the reduced heat transfer model identification. The results show that this proposed technique has effective performance for the heat transfer model identification. Additionally, it can be applied online to handle the model parameter's variation cycle by cycle. The results of reduced model identification can be incorporated in the heat release model for explanation of the heat losses to the cylinder walls during combustion.

2. HEAT TRANSFER MODEL

The heat transfer from the gases in the combustion chamber to the cylinder walls are given by Woschni's law as it was presented in Eq. (1) to (3). These are written for a single zone scheme:

$$\frac{dQ_{th}(t)}{dt} = h_c(t)A_w(t)\left(T(t) - T_w\right) \tag{1}$$

where T_w is the cylinder walls temperature (K) which is considered as a constant. The burn gas temperature (K) is $T(t)$ and the wall heat transfer area (m^2), $A_w(t)$, is defined as

$$A_w(t) = \frac{\pi d^2}{2} + \frac{4V(t)}{d} \tag{2}$$

where d is the constant cylinder bore (m). Next, the heat transfer coefficient can be computed from Woschni's equation

$$\begin{aligned} h_c(t) = \alpha_{th} d^{-0.2} p(t)^{0.8} T(t)^{-0.53} \Big(& C_1 S_p \\ & + C_2 \frac{V(t)T_1}{p_1 V_1}\left(p(t) - p_0(t)\right)\Big) \end{aligned} \tag{3}$$

where α_{th} is the scaling factor, p denotes the in-cylinder pressure (bar), S_p denotes the mean piston speed (m/s), V is the cylinder volume (m^3), C_1 and C_2 are calibration constants. p_1, V_1 and T_1 are the known states at intake valve close (IVC) and p_0 is the motoring pressure.

The wall heat transfer rate dQ_{th}/dt is first modeled using Eq. (1). However, this approximation contains strong nonlinearities that are difficult to handle from the observation point of view. From this reason, a reduced model of the wall losses has been created by Rivas, *et al*, 2012. The proposed approximation keeps the convection principle from Eq. (1) but replaces the convection coefficient, $h(t)$, with a simpler structure:

$$h_{c,re}(t) = \omega p(t) \tag{4}$$

where ω denotes the engine speed (rad/s) which is constant in this case. Similar to Woschni's principle, the convection heat transfer coefficient is proportional to the engine speed and in-cylinder pressure. In this model, the heat transfer to the walls is calculated by

$$\frac{dQ_{th,re}(t)}{dt} = A_w(t)\omega p(t)\left(k_1 T(s) - k_0 T_w\right) \tag{5}$$

where k_0 and k_1 are tuning model parameters that is obtained from identification experiments. The reduced model presented in Eq. (5) is quite simple compared with the original model. However, the method to obtain the model parameters is mainly important because the combustion processes have high variation. Therefore, the adaptive algorithm is introduced for this task. Next, the detail of the algorithm will be explained.

3. AN ADAPTIVE ALGORITHM FOR THE MODEL IDENTIFICATION

The objective of this adaptive algorithm is to minimize the error between the original model and the reduced model. First, consider the tracking error as follows:

$$e = Q_{th,re}(t) - Q_{th}(t) \tag{6}$$

Second, minimize the objective function

$$J\left(k_0, k_1\right) = \frac{1}{2}e^2 = \frac{1}{2}\left(Q_{th,re}(t) - Q_{th}(t)\right)^2 \tag{7}$$

Next, for minimization of the objective function, it is reasonable to search the parameters in the direction of negative gradient of the loss function, J.

$$\frac{dk_0}{dt} = -\gamma_0 e \frac{\partial e}{\partial k_0} = -\gamma_0 e \frac{\partial Q_{th,re}}{\partial k_0} \tag{8}$$

and

$$\frac{dk_1}{dt} = -\gamma_1 e \frac{\partial e}{\partial k_1} = -\gamma_1 e \frac{\partial Q_{th,re}}{\partial k_1} \tag{9}$$

where the constants γ_0 and γ_1 are adaptation gains. To derive sensitivity equation, we consider the derivative of Eq. (5) with respect to k_0 yields

$$\frac{\partial^2 Q_{th,re}}{\partial k_0 \partial t} + A_w(t)\omega p(t) T_w = 0 \tag{10}$$

or

$$\frac{\partial v}{\partial t} + A_w(t)\omega p(t) T_w = 0 \tag{11}$$

where $\nu = \partial Q_{th,re}/\partial k_0$
for the parameter k_1, similarly

$$\frac{\partial^2 Q_{th,re}}{\partial k_1 \partial t} - A_w(t)\omega p(t) T(t) = 0 \tag{12}$$

or

$$\frac{\partial w}{\partial t} - A_w(t)\omega p(t) T(t) = 0 \tag{13}$$

where $w = \partial Q_{th,re}/\partial k_1$
Finally, with the proposed adaptive algorithm, we can estimate the reduced model parameters. In the next section, the identification results will be presented.

4. IDENTIFICATION RESULTS

In this identification, the experiment was conducted on speed constant mode at 1000 rpm and 60 Nm of torque. The engine was controlled by the engine control unit (ECU). The dSPACE DS2004, an interrupt or trigger based device, was utilized for collecting the data. The resolution of the in-cylinder pressure is one data per one crank angle degree (CAD). In-cylinder pressure and crank angle position in steady state experiment were recorded and transferred at 0.25 ms sampling time. Also, the offset of these signals are compensated by calibration processes. These data have been used to analyze the heat transfer effects cycle by cycle by offline calculation. The in-cylinder pressure and CAD are presented in Fig.1.

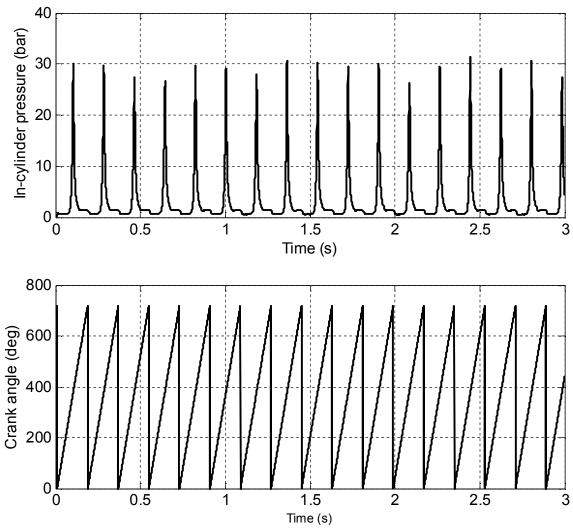

Fig.1. In-cylinder pressure and crank angle

The heat release from combustion is computed from in-cylinder pressure and crank angle data. The formula presented by Heywood, 1988 is applied for heat release calculation. For heat transfer during combustion, they are calculated by using some assumptions and Woschni's model.

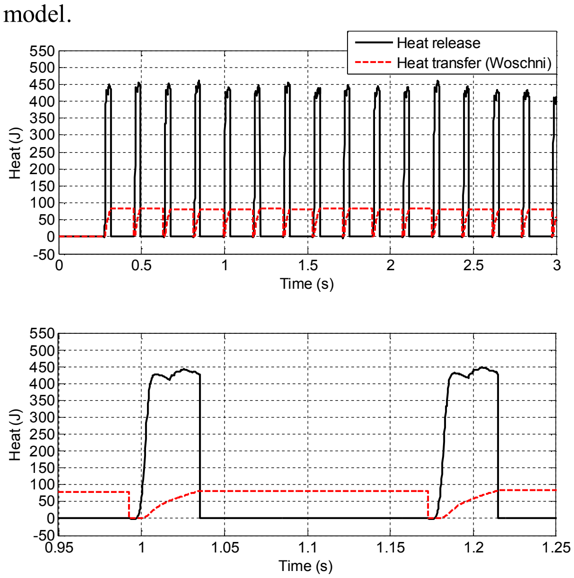

Fig.2. Heat release and heat transfer from combustion

Heat release and heat transfer calculation results are shown in Fig.2. The heat transfer is about 17% compared with the maximum value of the heat release in one working cycle (the first peak of the black line). The trigger signal and reset signal are designed for the convective heat transfer computation. Then the calculation is performed only during combustion period (330 to 500 CAD) of every cycle. Because of the limitation of data transfer between DS2004 and computer, we have to omit some cycle data if the unread data will be overwrite.

From previous results, the value of heat release has increased again after reach the maximum point. This was because the calculation processes used constant value of specific heat ratio. We utilized information computed from in-cylinder pressure for identification of heat transfer model that was mainly from convection through the cylinder wall. We have chosen the value of adaptation gains which make the system stable and satisfied tracking speed responses. The results of identification are exhibited in Fig.3. In this figure, the comparison of heat transfer using Woschni's model and reduced model, the tracking error between two models, and the model parameters tracking are presented, respectively.

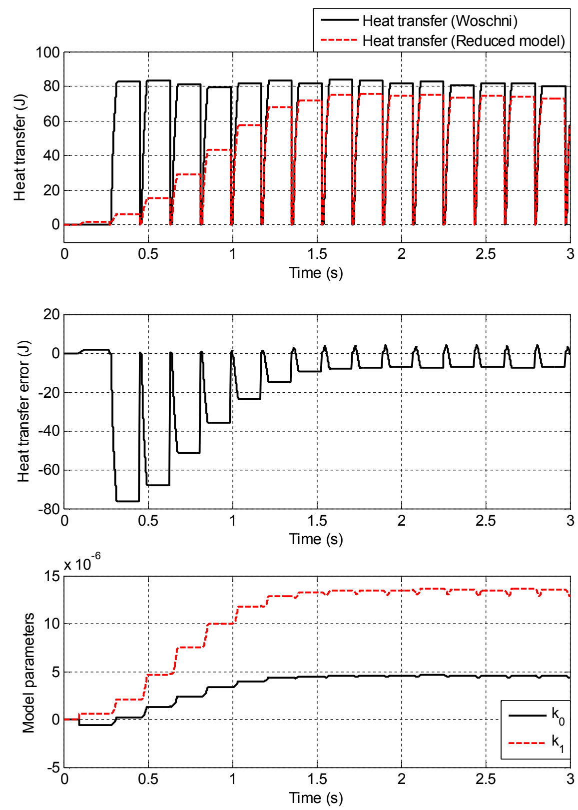

Fig.3. Heat transfer comparison, heat transfer error and model parameters

The proposed adaptive algorithm can estimate the reduced heat transfer model parameters and minimized the tracking error between Woschni's model and the reduced model. On the other hand, the response of the algorithm requires about eight working cycles to track the minimized error value. This response depends highly on the tuning adaptation gains. The higher adaptation gains, the faster responses. However, the stability of the algorithm must be considered first. The error between two models is not driven to zero. These effects are mainly from the short active period of the algorithm and the limitation of the reduced model.

5. CONCLUSION

From the experimental results, the proposed adaptive algorithm can estimate the reduced heat transfer model parameters during the combustion period. However, because the combustion is not continuous process and the reduced heat transfer model has a very simple structure compared with the original model. Therefore, there remains small error between two model outputs. With the reduced model structure, the constant parameters may not be suitable for making the responses of the proposed model close to the original one. Additionally, the stability of the proposed algorithm must be considered during identification.

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Chanyut Khajorntraidet received his B.E. (2005), M.E. (2008) degrees in mechanical engineering from Suranaree University of Technology, Thailand, and M.Sc. (2012) in Systems Engineering and Science from Shibaura Institute of Technology, Japan. He is currently a Ph.D. candidate at the Shibaura Institute of Technology. His main interests include the SI engine control, system modeling and adaptive control.

Kazuhisa Ito received his B.E. (1993), M.E. (1995), and D.E. (2001) degrees in mechanical engineering from Sophia University. He is a full professor at the Department of Machinery and Control Systems, Shibaura Institute of Technology. His current research interests include controller design for nonlinear systems and its application to the mechanical system and agricultural engineering.