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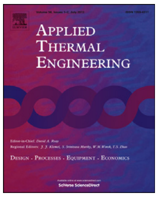

Real-time combustion parameter estimation algorithm for light-duty diesel engines using in-cylinder pressure measurement

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HIGHLIGHTS

- We develop a real-time estimation algorithm of combustion parameters for MFB50 and IMEP.
- Proposed estimation algorithm reduces 49% of the execution time compared to the conventional method.
- The estimation results were validated with engine experiments.

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ABSTRACT

This paper proposes a real-time estimation algorithm of combustion parameters for the location of 50% of mass fraction burnt (MFB50), and indicated mean effective pressure (IMEP). The proposed estimation algorithm uses the difference pressure only instead of the in-cylinder pressure for calculation of the combustion parameters. Since the difference pressure is the pressure that is generated only by the combustion, it occurs between the start of combustion (SOC) and the end of combustion (EOC); this allows the proposed algorithm to estimate the combustion parameters with fewer cylinder pressure data samples and low computational load compared with the conventional method. The proposed algorithm estimates the IMEP with a result acquired during the MFB50 calculation and that can significantly reduce the computational load required to calculate the combustion parameters. Consequently, the proposed estimation algorithm requires only 51% of the execution time to calculate the combustion parameters compared to the conventional method. The proposed estimation algorithm is validated with an engine experiment under 131 operating conditions that showed high linear correlation with the original combustion parameters. In-cylinder pressure based combustion control using the estimated combustion parameters is introduced as a case study and the proposed estimation algorithm validated its significant potential for real-time applications.

1. Introduction

In-cylinder pressure considers as a valuable information source for design and research of the internal combustion engines [1]. It provides quantitative information such as peak pressure, indicated mean effective pressure (IMEP) and pumping work for the mechanical design and engine calibration [2,3]. In addition, in-cylinder pressure analysis can be used for complex applications: knock detection [4], misfire detection [5], air mass flow estimation [6], noise estimation [7], PM estimation [8], and NO_x estimation [9].

Among these applications, heat release analysis is a commonly used in-cylinder pressure based applications which is used from the early stage of the in-cylinder pressure sensor. This approach provides direct information on the instantaneous mass of fuel burned by applying the first law of thermodynamics for the energy balance in the cylinder. This can be realized as an apparent heat release law, which is a good approximation of the heat release law [1]:

$$\frac{\mathrm{d}Q}{\mathrm{d}\theta} = \frac{\gamma}{\gamma-1}P\frac{\mathrm{d}V}{\mathrm{d}\theta} + \frac{1}{\gamma-1}V\frac{\mathrm{d}P}{\mathrm{d}\theta} \tag{1}$$

where γ is the adiabatic coefficient, P is the in-cylinder pressure, V is the instantaneous volume and θ is the crank angle. The apparent heat release analysis has been applied to researches including combustion detection [10,11], and estimation of emissions [12].

Nonetheless, one factor that used to cause the in-cylinder pressure analysis to be challenging for automotive applications is the expansive cost of the in-cylinder pressure sensor [6]. However, this issue has been resolved as there are several mass produced in-cylinder pressure sensors available for application and some

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automotive manufacturers already have implemented the in-cylinder pressure sensor in mass produced vehicles [13]. Moreover, the cost issue can be resolved through several previously mentioned applications that justify the cost of an in-cylinder pressure sensor [14].

Recent requirements for low emissions and higher fuel efficiency demands real-time feedback control strategies, such as an in-cylinder pressure based feedback control of the combustion. This can compensate for the effects of environmental factors such as coolant temperature, ambient conditions, aging, and fuel quality over the life-time of the vehicle; in addition, it enhances real-world engine performance that can satisfy the future requirements for On-Board Diagnostics (OBD) and In-Use Compliance (IUC) [13].

The extraction of meaningful combustion parameters from the in-cylinder pressure is crucial to apply an in-cylinder pressure based feedback control of the combustion. The location of 50% of mass fraction burnt (MFB50) and indicated mean effective pressure (IMEP) are the representative combustion parameters that represent the combustion phase and engine torque, respectively.

The MFB50 is a combustion parameter which represents the combustion phase [15]. This parameter represents the location of 50% of the total apparent heat release that provides the angular location of the center of combustion. The MFB50 is a useful combustion parameter, which is widely used in in-cylinder pressure based combustion control due to its close relationship with emissions and fuel economy [10,16–18]. IMEP represents the relative torque generated per cycle by the cylinder volume and provides quantitative information for the determination of the injection quantity to generate the torque demanded by the driver [2].

Hardware specifications to calculate the combustion parameters require a large memory to save the calculated data. The calculation load of the combustion parameters is enormous and is a significant problem for real-time applications [19]; subsequently, the apparent heat release analysis is traditionally applied only for off-line analysis where a long processing time is acceptable [1,20]. In order to solve these problems, Lim et al. [10] suggested a MFB50 estimation algorithm based on Normalized Difference Pressure (NDP), and Oh et al. [21] presented an IMEP estimation algorithm based on the Difference Pressure Integration (DPI). These two estimation algorithms calculate real-time combustion parameters by reducing the required cylinder pressure samples and computational load. These estimation methods can estimate the combustion parameters in real-time; however, the implementation of MFB50 and IMEP estimation methods into a single application is complex due to memory and computation power requirements.

This paper proposes a real-time estimation algorithm of the combustion parameters (the MFB50 and IMEP) based on the difference pressure apparent heat release analysis. The proposed algorithm uses the difference pressure instead of the in-cylinder pressure for apparent heat release analysis. Since the difference pressure is the pressure that is generated by combustion, it only exists between the start of combustion (SOC) and the end of combustion (EOC). Furthermore, the proposed estimation algorithm estimates IMEP based on a result acquired through the calculation of MFB50. These can dramatically reduce the required cylinder pressure data samples and computation load; subsequently, it is more suitable for real-time applications than the conventional apparent heat release analysis.

2. Experimental environment

Fig. 1 shows a schema of the engine experiment environment with the instruments. The experiments were conducted with a 4 cylinder, 16 valve, 2.2 L common-rail high-speed direct injection diesel engine. Table 1 lists the representative engine characteristics. The engine is installed on an engine test bench of Eddy Current (EC) dynamometer. The intake air, engine coolant, and intercooler temperature are controlled to constant values using the closed-loop control method.

The in-cylinder pressure is measured in 4 cylinders with BERU glow-plug type piezo-resistive sensors with a range between 0 and 200 bar. The off-line analysis of the in-cylinder pressure data is acquired by AVL IndiModul at 0.5 deg crank angle (CA) resolution. The off-line analysis used an average of 100 cycle's in-cylinder pressure data. For real-time analysis, Cylinder Pressure Analysis System (CyPAS) was developed using the dSPACE MicroAutoBox. The CyPAS acquires the in-cylinder pressure data at 0.5 deg CA resolution and calculates the real-time combustion parameters.

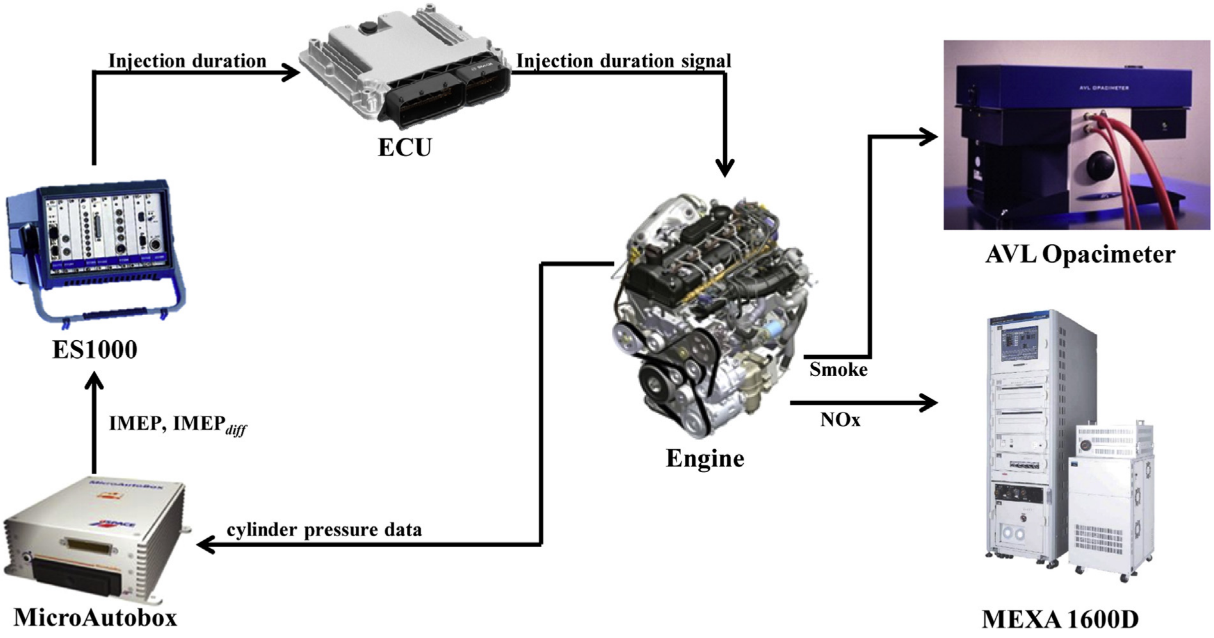

Fig. 1. Schema of the engine experimental environment.