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Real time identification of the internal combustion engine combustion parameters based on the vibration velocity signal

Xiuliang Zhao, Yong Cheng*, Limei Wang, Shaobo Ji

School of Energy & Power Engineering, Shandong University, Jinan 250061, China

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ABSTRACT

Accurate combustion parameters are the foundations of effective closed-loop control of engine combustion process. Some combustion parameters, including the start of combustion, the location of peak pressure, the maximum pressure rise rate and its location, can be identified from the engine block vibration signals. These signals often include non-combustion related contributions, which limit the prompt acquisition of the combustion parameters computationally. The main component in these non-combustion related contributions is considered to be caused by the reciprocating inertia force excitation (RIFE) of engine crank train. A mathematical model is established to describe the response of the RIFE. The parameters of the model are recognized with a pattern recognition algorithm, and the response of the RIFE is predicted and then the related contributions are removed from the measured vibration velocity signals. The combustion parameters are extracted from the feature points of the renovated vibration velocity signals. There are angle deviations between the feature points in the vibration velocity signals and those in the cylinder pressure signals. For the start of combustion, a system bias is adopted to correct the deviation and the error bound of the predicted parameters is within 1.1°. To predict the location of the maximum pressure rise rate and the location of the peak pressure, algorithms based on the proportion of high frequency components in the vibration velocity signals are introduced. Tests results show that the two parameters are able to be predicted within 0.7° and 0.8° error bound respectively. The increase from the knee point preceding the peak value point to the peak value in the vibration velocity signals is used to predict the value of the maximum pressure rise rate. Finally, a monitoring frame work is inferred to realize the combustion parameters prediction. Satisfactory prediction for combustion parameters in successive cycles is achieved, which validates the proposed methods.

1. Introduction

To meet the increasingly stricter regulations on pollutant emissions and fuel consumption, new cleaner combustion methodologies for internal combustion engines (ICE) are being progressively proposed. In these approaches, information associated with cylinder thermodynamic conditions helps achieve closed loop combustion engine control. Unfortunately, the cylinder pressure testing method, being an intrusive testing technique, is expensive and inconvenient. This method requires a special gas channel which might reduce the compression ratio, especially in the high compression ratio diesel engine.

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* Corresponding author.
E-mail address: cysgd@sdu.edu.cn (Y. Cheng).

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Nomenclature

ICE	internal combustion engine
SNR	signal to noise ratio
pir	pressure rise rate
RIFE	reciprocating inertia force excitation
STCP	start of combustion from cylinder pressure curve
LMPP	location of maximum pressure rise rate from cylinder curve
LPP	location of peak pressure from cylinder pressure curve
STCV	start of combustion from vibration velocity
LMPV	location of maximum pressure rise rate from vibration velocity
LPV	location of peak pressure from vibration velocity
c_1, c_{2i}	modulus variations
B_0, B_1, B_{2i}, B_{2i+1}	model parameters
$\delta\theta$	interval from LMPV to LPV
P_j	**RIFE**
m	reciprocating mass of the crank train
r	crank radius
ω	crank angular velocity
α	crank angle
λ	ratio of the connecting rod length to the crank radius
A_1	modulus of the 1st harmonic component of the RIFE
A_{2i}	modulus of the 2i-th order harmonic component of the RIFE
V_{P_j}	vibration velocity created by the RIFE
α_1, α_2	Phase differences
n	instantaneous speed at crank angle α
$\text{pir}_{A'B'}$	increase from the knee point preceding the peak value point to the peak value
n	engine speed

Techniques based on the analysis of the engine block vibrations are promising due to advances in the progress of digital signal processing algorithms [1,2]. Various signal processing techniques have been applied to analyze the ICE vibration signals, mainly focusing on the following four aspects: 1, recognizing the excitation source from the vibration signals with time domain and/or frequency domain analysis methods [3]; 2, extracting features from the vibration signals for fault diagnosis [4–8]; 3, exploring the relationship between the vibration signal and the cylinder pressure [9,10]; 4, identifying combustion parameters based on vibration signals [11–14]. The identification of combustion parameters based on vibration signals will contribute to closed loop control in an ICE. Previously published results demonstrated that there was a direct relationship between the cylinder pressure and the engine block vibration. This indicated that the vibration signals could be used for extracting useful information to characterize the combustion process [15–17].

Morello et al. [18] identified the frequency content of the block vibration acceleration to accurately and robustly estimate the combustion signature based on singular value decomposition. El-Ghamrya et al. [19] successfully reconstructed the engine cylinder pressure waveform by using cepstrum analysis of acoustic emission in the frequency domain. Johnsson [20] reconstructed the cylinder pressure and evaluated combustion related parameters based on the Fourier transforms of both engine structure vibration and crankshaft speed fluctuation with a complex radial basis function. This method, based on the neural network algorithm, needs a large amount of sample data to train the model, and the accuracy of the neural network algorithm depends on the selection of the input vectors, as well as the selection of training working condition. Liu et al. [21] attempted to separate the vibration sources by blind source separation techniques and the combination of the Blind Least Mean Square algorithm with a deflation method. Vulli et al. [3] used the short term Fourier transform method to identify different excitation events of ICE vibration. Such methodologies could be used to identify the main events including normal combustion, valve impacts and piston slaps, but it is unsuitable for separating closely overlapping or weak events. Tang [15] analyzed the amplitude-frequency characteristics of a diesel engine vibration system with multi-dimensional model, and proposed that the combustion parameters could be directly identified from the feature points of the vibration velocity signals. Despite the convenience, this method still faced the issue that the measured vibration velocity signals were usually overlapped with a low-frequency interference which was considered to be generated by the RIFE. And there are yet angle deviations between the feature points in the vibration velocity signals and those in the cylinder pressure signals. For the above issues, tests are performed on a single cylinder diesel engine to measure the block vibration velocity signals. A pattern recognition method is introduced to remove the RIFE related contributions from the measured vibration velocity signals and novel algorithms are presented to predict the combustion parameters.

The layout for the rest of the paper is arranged as follows: Section 2 describes the diesel engine facility and the tests process. Section 3 proposes a method to renovate the vibration velocity signals that are highly related to the combustion process. A mathematical model is established to describe the response of the RIFE. The parameters of the model are recognized with a pattern recognition algorithm, and the response of the RIFE is predicted and then the related contributions are removed from the measured vibration velocity signals. In Section 4, the combustion parameters are identified from the feature points of the renovated vibration signals. Algorithms are introduced to correct the identification parameters. An algorithm is also introduced to predict the value of maximum pressure rise rate. Section 5 describes the monitoring framework on identification of combustion parameters according to the vibration velocity signals. In Section 6, the proposed methods are validated by a successive cycle tests. Finally, the research is summarized in Section 7.

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