Applied Acoustics 116 (2017) 205–215

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Technical note

Combustion parameters identification and correction in diesel engine via vibration acceleration signal

Xiuliang Zhao, Yong Cheng *, Shaobo Ji

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

ARTICLE INFO

Article history:
Received 25 May 2016
Received in revised form 24 August 2016
Accepted 26 September 2016

Keywords:
Internal combustion engine
Vibration acceleration signal
Combustion parameters
EMD
Angle deviation

ABSTRACT

Using closed loop control of the internal combustion engine is beneficial to reducing emission and fuel consumption. Accurate combustion parameters are the foundation of effective closed loop control. Some combustion parameters, including the start of combustion, the location of maximum pressure rise rate and the location of peak pressure can be identified from the vibration signals. Empirical Mode Decomposition (EMD) method is introduced to reconstruct the vibration acceleration signal, from which the combustion parameters are identified. However, there are angle deviations between the combustion parameters extracted from the reconstructed vibration acceleration signal and those from the cylinder pressure. Algorithms to correct the angle deviations are introduced. A system deviation value is used to correct the extracted start of combustion with an error bound being within 0.6 °CA. Two algorithms are proposed to correct the deviation between the predicted location of maximum pressure rise rate and that from the cylinder pressure. Test results show that the two algorithms are able to correct the deviation within 0.3 °CA error bound. The location of peak pressure can be predicted with the knee point following the peak value in the reconstructed vibration acceleration signal. The predicted result is then corrected using a linear regression of the location of peak pressure versus the knee point within 0.5 °CA error bound. A real-time monitoring framework is utilized for calculating the combustion parameter prediction.

1. Introduction

The monitor and control of internal combustion engine combustion process is of great importance with increasingly stringent emission regulations and fuel economy requirements. The combustion parameters such as start of combustion, the crank angle of maximum pressure rise rate, and the location of peak pressure can provide useful information when implementing engine close loop control. These parameters are generally obtained from the cylinder pressure curve [1–3]. Unfortunately, the pressure measurement method is an intrusive method. Moreover, cylinder pressure transducers are usually expensive and not feasible for all situations, especially for on-line applications. Some indirect measurement techniques such as knock sensors [4], acceleration sensors [5–8], acoustic emissions [9], engine speed [10], or ionization current measurements [11,12] are also strategies to provide combustion parameters for engine control. In the literature, surface vibration signal of the engine block attracts extensive attention since it contains a wealth of combustion-related information, and vibration sensors are inexpensive and easy to install.

Various signal analysis techniques have been applied to determine combustion parameters from the engine surface vibration signals. To this end, some predecessors proposed Complex Cepstrum method [13], radial basis function networks [14] to reconstruct cylinder pressure signal, from which the combustion parameters were identified. These methods, based on the neural network algorithm, a large amount of sample data is needed to reconstruct cylinder pressure and the model has to be re-trained when the engine type changed, which reduced identification efficiency. Arnone et al. [5] indicated that regardless of the engine's load conditions, vibration signals in the vertical direction in the frequency band of approximately 500–1100 Hz were highly related to the cylinder pressure. Such a behavior makes it possible to achieve the combustion information using vibration sensors. The method requires analyzing the frequency band highly related to the combustion, and the frequency band would be different with different engines. Tang [15] analyzed the amplitude-frequency characteristics of a single diesel vibration system with multi-dimensional model, and proposed that the combustion parameters could be directly identified from the feature points of the vibration

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

http://dx.doi.org/10.1016/j.apacoust.2016.09.030
0003-682X/

Nomenclature

ICE	internal combustion engine
EMD	Empirical Mode Decomposition
IMF	intrinsic mode function
SNR	signal to noise ratio
STCP	start of combustion identified based on the cylinder curve
LMPP	location of maximum pressure rise rate identified based on the cylinder curve
LPP	location of peak pressure identified based on the cylinder curve
STCC	start of combustion identified based on the composite signal
LMPC	location of maximum pressure rise rate identified based on the composite signal
LPC	location of peak pressure identified based on the composite signal
φ_i	angle deviation
β	damping ratio
q_i	frequency ratio
m	weight of the vibration system
k	stiffness of the system
c	system damping
E_i	energy of half cycle in vibration signal
$\delta\varphi$	interval between the start of combustion and the location of maximum pressure rise rate
S_{IMF}	area in the composite signal between point A′ and point B′
$\frac{S_{IMF}}{\delta\varphi}$	Intensity of combustion process

velocity signal. 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 generated by the reciprocating inertia force [16]. The low-frequency interference superposed in the vibration velocity signal affected the resolution of the combustion parameters.

This paper examines the methods that use the vibration acceleration signal to determine combustion parameters in a diesel engine. The measured vibration acceleration signal shows that there also exists low-frequency interference in the vibration acceleration signal whereas it is not as obvious as that in the vibration velocity. As a solution to this issue, Empirical Mode Decomposition (EMD) [17] is introduced to remove the low-frequency interference. EMD is an adaptive signal processing method, and it is very suitable for dealing nonlinear, non-stationary signals. This algorithm is widely used in fault diagnosis [18–22], the vibration excitation source identification [23] and so on.

The vibration acceleration signal is decomposed based on EMD to acquire intrinsic mode function (IMF). IMFs highly related to the combustion information are selected to reconstruct the vibration signal, called composite signal. The composite signal is used to identify combustion parameters. However, there are angle deviations between the combustion parameters extracted from the vibration acceleration signal and those from the cylinder pressure. The deviations are investigated based on the phase-frequency characteristic of the diesel engine system. Algorithms to correct the angle deviations are proposed. To demonstrate the adaptability of the proposed algorithms, the algorithms are applied to deal with successive cycle data. The monitoring framework then infers the combustion parameter prediction.

2. Test system and test results

2.1. Test system introduction

The tests are performed on a single cylinder 0.815 L diesel engine to record engine block vibration acceleration signals. To determine the best mounting position of the vibration accelerometer, four accelerometers were arranged on the cylinder head as shown in Fig. 1. The vibration acceleration sensors affixed to the surface of the cylinder head with super magnets. The first accelerometer was placed on the cylinder head cover. The second accelerometer was placed on the cylinder head with Z orientation, namely in the direction of the piston movement; the third one has been mounted with X orientation; the fourth one has been mounted with Y orientation. Fig. 2 shows the raw vibration accelerations acquired from four different points at 1200 r min^{-1}, 30 N m. Among these signals, the amplitude of the vibration signal at point 2 is the largest. Therefore, the point 2 is deemed as the most sensitive position of the vibration acceleration signals.

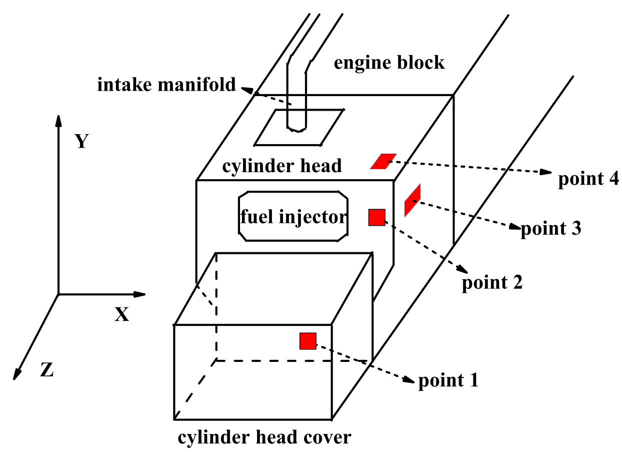

Fig. 1. Locations and directions of vibrations measurements.

The engine is connected to an eddy current dynamometer. The schematic illustration of the sensor position is shown in Fig. 3. Cylinder pressure has been measured with a piezoelectric transducer AVL 12QP250. The detailed engine and the sensors specifications are shown in Tables 1 and 2. The vibrations are monitored with an accelerometer, manufactured by Sinocera Piezotronics Corporation. The cylinder pressure, cylinder head surface vibration accelerations, crank angles and phase signals are collected synchronously by using MP426 at different engine speeds and engine loads (800–1400 r min^{-1}, 0–50 N m). MP426 component is a data acquisition card produced by WWLAB Co. Ltd. The acquisition rate of 100 kHz per channel provides an adequate acquisition rate. In the tests, the sampling rate is 50 kHz per channel.

2.2. Test results analysis

Fig. 4(a) shows the raw vibration acceleration and the cylinder pressure signal at 1200 r min^{-1}, 10 N m. Fig. 4(b) shows one cycle of vibration acceleration signal and the second derivative curve of cylinder pressure extracted from Fig. 4(a). The vibration