Measurement 94 (2016) 19–25

Contents lists available at ScienceDirect

Measurement

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

Estimation of optimum number of cycles for combustion analysis using measured in-cylinder pressure signal in conventional CI engine

Rakesh Kumar Maurya

School of Mechanical, Materials and Energy Engineering, Indian Institute of Technology Ropar, Rupnagar 140001, India

ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form 7 July 2016
Accepted 21 July 2016
Available online 22 July 2016

Keywords:
Diesel engine
Compression ignition
Filtering
Cyclic variations
Cylinder pressure

ABSTRACT

Analysis of measured in-cylinder pressure data provides various parameters that characterize engine combustion process. Advanced engine control technologies use cylinder pressure based combustion parameters for closed loop control. Four step signal processing (i) absolute pressure correction, (ii) crank angle position referencing, (iii) cycle averaging and (iv) filtering is typically applied to get sufficiently accurate cylinder pressure data for an engine cycle. This paper focuses on cycle averaging and filtering of in-cylinder pressure signal from a conventional compression ignition (CI) engine. Experiments are conducted at different engine load and compression ratios at 1500 rpm. The in-cylinder pressure trace of 2500 consecutive engine cycles is recorded and analyzed. Effect of in-cylinder pressure signal noise and cyclic variation on combustion analysis is investigated. A method based on standard deviation of pressure and pressure rise rate is used to find sufficient minimum number of engine cycles to be recorded for averaging to get reasonably accurate pressure data independent of cyclic variability.

1. Introduction

In-cylinder pressure measurement and analysis is an essential tool for automotive engine research and diagnosis due to its direct relationship with combustion process. In-cylinder pressure signal analysis can provide large amount of informations such as peak pressure, pressure rise rate, heat release rate [1], air-fuel ratio [1], gas temperature [2], wall temperature [3], and wall heat transfer [4] that are used for further development, optimization and tuning of engines. Study conducted by Maurya et al. provides comprehensive summary of parameters derived by cylinder pressure signal analysis [5]. Advanced engine technologies need closed loop control of combustion process. Feedback signal for closed loop control of engine is derived from measured cylinder pressure data [6]. Normally piezoelectric pressure transducers are used for measuring in-cylinder pressure from engine combustion chamber. For getting a sufficiently accurate data, signal processing of pressure signal is required because experimentally measured signal is subject to cyclic variations, noise and offset issues. Noise in the measured signal gets amplified in signal derivative. For heat release calculation, derivative of pressure is multiplied with combustion chamber volume; therefore noisy pressure signal can give erroneous result in heat release. In-cylinder based heat release analysis of engine combustion cycle typically used to (i) validate mathematical models used for simulation, (ii) analysis of alternative fuel on engine combustion (iii) developing new combustion modes and (iv) investigating different fuel injection strategies and EGR [7]. Higher accuracy of the in-cylinder pressure data is required for study in above research areas with high reliability.

Piezoelectric sensors are widely used in engine research due to their small size and high sensitivity along with larger measurement range in amplitude and frequency [8]. Pressure transducer must be flush-mounted on engine combustion chamber for accurate measurement [9]. Significant unwanted noise appears in pressure signal due to non -flush mounting of the pressure transducer [7]. In-cylinder pressure signal processing is usually a four-step process consisting absolute pressure correction (pegging), correct crank angle referencing, cycle averaging and filtering. Piezoelectric pressure sensors are dynamic type sensors and measures relative pressure. Absolute pressure is calculated by pegging or referencing. There exist several methods presented in literature for online and offline for absolute pressure correction [10,11]. Correct crank angle referencing is very important as it introduces significantly large errors in some of the calculated parameters [12]. Crank angle referencing is done either by physically using TDC sensors or various tuning methods [12]. Cycle averaging and filtering are in the scope of present investigation.

Random noise in measured pressure signal can be removed by cycle averaging but systematic errors cannot be removed by averaging. Cyclic variability in combustion leads to averaging of con-

E-mail address: rakesh.maurya@iitrpr.ac.in

http://dx.doi.org/10.1016/j.measurement.2016.07.065
0263-2241/

secutive engine cycles for calculation of average indicated engine performance characteristics and heat release. Usually averaged values of engine speed, mass of fuel and air are used for calculation of performance and combustion parameters; therefore averaged in-cylinder pressure of desired accuracy is required. The averaged in-cylinder pressure is also required to be independent of cyclic variations. In published literature, various researchers have used different number of cycles for averaging in-cylinder pressure data such as 25 cycles [13], 30 cycles [14], 46 cycles [15], 50 cycles [16], 64 cycles [17], 80 cycles [18], 100 cycles [19], 150 cycles [20], 200 cycles [21], and 1000 cycles [22] in their respective studies. Therefore it is important to find out a systematic method for determination of the optimal number of cycles required for the study. In this study, an adaptive method is used to determine sufficient minimum number of cycles that minimizes the effect of cyclic variations and noise at various engine operating conditions.

During the study of engine transients or cycle to cycle variation analysis, averaging of engine cycles is not possible. Therefore for such conditions, only filtering of pressure data can be done to remove signal noise. Signal noise in the measured pressure signal can be due to various reasons such as conversion of pressure to electrical signal in the sensor, analog to digital conversion, and signal transmission [5,23]. Researchers have used different filtering techniques such as adaptive low-pass finite impulse response (FIR) filter [24], Savitzky–Golay filter [21], center-weighted moving average filter [25], Butterworth low pass filter [5,7,26] for filtering signal noise from cylinder pressure data before heat release computations. It was found that a moving average filter might not remove duct resonances appropriately whereas sharp pressure fluctuations due to premixed phase combustion can be also deformed in diesel engines [25]. Moving average filter capability relies on the sampling interval. An optimal Weiner filter is also proposed with an assumption that 90% of the Fourier spectrum constitutes of noise with constant intensity [27]. A study concluded that low-pass filter can attenuate the noise components in measured pressure signal because most of the noise and resonant frequency components are mainly in the high frequency zone [7]. In this study low pass Butterworth filters with zero-phase shift is used to remove the signal noise in measured pressure data. After filtering the pressure signal, cycle averaging is done for steady state test condition analysis due to cyclic variability. It is interesting to select a limited number of cycles to be measured because acquiring more cycles than the optimal, do not provide extra accuracy in the averaged cycle. An adaptive method to choose the optimal number of cycles is demonstrated and discussed in this study.

2. Experimental setup

A four stroke single cylinder, naturally aspirated conventional diesel engine was used in this study. Engine was water cooled and fuel is directly injected in engine cylinder. Engine had variable compression ratio (range 12–18) capability. Experiments are conducted at various compression ratios. Engine displacement volume is 661 cc and rate power is 3 kW (BMEP 4.24 bar) at 1500 rpm with compression ratio 17.5. Fuel injection timing was 23° BTDC in this study. Fig. 1 shows schematic diagram of experimental setup used for present investigation.

Optical shaft encoder with resolution of 1 crank angle degree (CAD) is used for measuring angular position of crankshaft of engine. The in-cylinder pressure is measured using piezoelectric transducer having measuring range 0–350 bars. Pressure data acquisition and analysis is done using LabVIEW based program developed at IIT Ropar. In-cylinder pressure trace was logged for 2500 consecutive engine cycles for each operating condition.

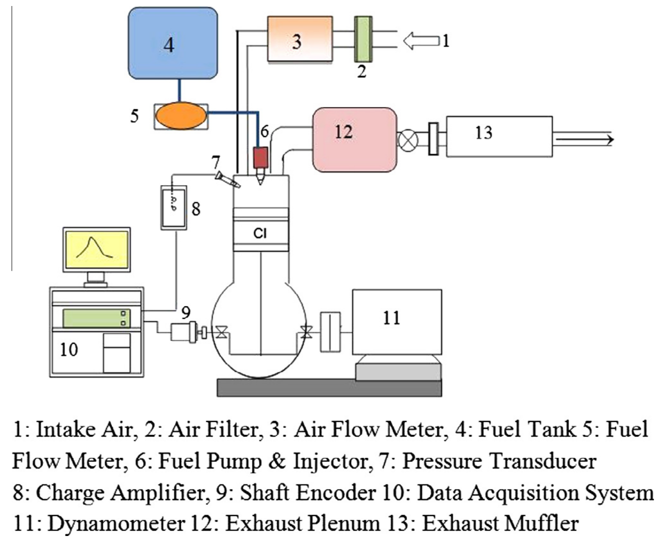

Fig. 1. Schematic diagram of the experimental setup.

Details of the equations used for the calculation of different combustion parameter in this study are given as follows.

Indicated mean effective pressure (IMEP) is ratio of indicated work (W_{ind}) and displacement volume (V_d) as

$$\text{IMEP} = \frac{W_{\text{ind}}}{V_d} \tag{1}$$

$$W_{\text{ind}} = \frac{2\pi}{360}\int_{-180}^{180}\left(P(\theta)\frac{dV}{d\theta}\right)d\theta \tag{2}$$

where P is pressure and V is volume as function of crank angle position (θ).

Coefficient of variation (COV) of IMEP was calculated using following equations

$$\text{COV}(x) = \frac{\sigma}{\bar{x}} \times 100\% \tag{3}$$

where $\bar{x} = \sum_{i=1}^{n} x_i/n$ and standard deviation (σ) $\sigma = \sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2/(n-1)}$

3. Results and discussion

In this section, effect of signal noise and cyclic variations in measured pressure data on combustion analysis are analyzed. Factors such as signal noise due to signal conversion and transmission, analog to digital conversion, and variations in engine input parameters affect the quality of measured pressure data. Cylinder gas pressure oscillations originate from different sources (combustion and resonance excitations) at different frequencies depending on cylinder geometry and engine operating conditions [23]. Pressure sensor gathers these pressure oscillations also. Signal noise from all sources appeared in pressure sensor can be observed in Fig. 2a. Fig. 2 shows the variation of measured in-cylinder pressure and calculated pressure rise rate (PRR) for 2500 consecutive engine cycles. It can be observed from Fig. 2a that variation in cylinder pressure is higher close to top dead center (TDC) position during combustion and significant variation in peak pressure. Variation in pressure data during combustion stroke is mainly due to signal noise other than the combustion oscillations. The effect of signal noise and cyclic variation is clearly observed in PRR curve (Fig. 2b), when derivative of measured in-cylinder pressure curve is calculated. This noise in pressure derivative will manifest significantly in heat release analysis and lead to erroneous results. Fig. 2 clearly