Combustion Event Detection in a Single Cylinder Diesel Engine by Analysis of Sound Signal Recorded by Android Mobile

Sankar Kumar Roy

Abstract Combustion event detection is an important issue in internal combustion engine. The combustion is mostly detected by measurement of pressure by a pressure sensor which is mounted in cylinder head. However, the cost of pressure sensor is very high. Therefore, an effort has been made to detect the combustion event in a diesel engine by analysis of sound signal recorded by android mobile. The sound signal carries various frequencies. Therefore, an algorithm based on wavelet packet transform (WPT) has been developed to detect the combustion event in a single cylinder diesel engine.

Keywords Diesel engine · Sound signal · Android mobile phone

1 Introduction

Combustion and combustion-related parameters detection in an internal combustion (IC) engine is always an important concern as the power output relies on it [1]. Detection of combustion is mainly done by measuring the in-cylinder pressure by a pressure sensor [2, 3]. However, the cost of pressure sensor is very high and its installation on the cylinder head is a complicated exercise. Therefore, researchers are using alternate signals such as vibration signal [4–6], speed signal [7–15], acoustic signal [16–18] for detecting the combustion event. Based on these signals, standard monitoring systems have already been developed for detection and analysis of combustion event. These signals are mainly measured by standard sensors like accelerometer, optical encoder, hall effect sensor, microphone, etc. However, all of these sensors requires special mounting system for monitoring the in-cylinder combustion or pressure. Researchers have tried to reconstruct in-cylinder pressure by applying different techniques such as cepstral de-convolution technique [3], time domain smoothing technique [4], cyclostationary approach [5], inverse filtering tech-

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nique [6] on the vibration signal. Apart from vibration signal, researchers have also used speed fluctuations [7–9] to estimate the in-cylinder pressure. Besides pressure reconstruction, vibration signal and speed signal are also used for monitoring the in-cylinder combustion [3, 10–18]. Author [15] has earlier used instantaneous angular speed for combustion detection in four-stroke single cylinder gasoline engine. Recently, acoustic signal analysis has got tremendous application in monitoring purposes. The idea of acoustic signal analysis is that any change in the system will directly reflect on the intensity of sound signal. Researchers have used acoustic signal to find out combustion in IC engine [16–18]. Kaminsky et al. [16] have predicted the in-cylinder pressure variation through the analysis of sound signal by nonlinear multidimensional method. Recently, Delvecchio et al. [18] have detailed various ways of condition monitoring using acoustic signal. In their paper, they have mentioned that the sound signal captured from the IC engine is a combination of combustion, mechanical, and aerodynamic noise signals. Hence, acoustic signal needs rigorous signal processing technique to detect the combustion.

Recently, due to technological development, Android mobile phone becomes less costly and is used for multiple applications. Nowadays, it is also carried by most of the people and it can record the sound with sampling frequency 44.1 kHz. This sampling frequency allows to retain combustion frequency, rotational frequency, and its harmonics of an IC engine in the recorded sound signal. Recently, few researchers have found potentiality of the sound signal recorded by the Android mobile and used to detect fault in rolling element bearing [19, 20]. Siegel et al. [21] have used mobile-recorded sound signal to detect misfire in four-cylinder engine by applying machine learning technique. Hence, this sound signal has a lot of scope for monitoring various machineries. Therefore, the objective of the paper is to detect each combustion event in a four-stroke single cylinder diesel engine by analysis of sound signal recorded by an Android mobile. In the paper, the hypothesis is that the sound intensity will be higher during combustion rather than suction, compression, and exhaust strokes. Therefore, successive sound ratios of recorded sound signal has been measured and analyzed to execute the objective effectively.

2 Theory

2.1 Hilbert Transform

Hilbert transform [22] is a mathematical technique where a signal *x(t)* is transformed as

$$H[x(t)] = x(t) * \frac{1}{\pi t} = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau \tag{1}$$

The technique is mainly a convolution of two signals *x(t)* and $1/\pi t$, respectively. As a result, the signal is shifted by a phase of 90°. Hence, the signal *x(t)* can be further analytically represented as

$$z(t) = x(t) + jH[x(t)] = A(t)e^{j\phi(t)} \tag{2}$$

where $A(t)$ and $\phi(t)$ are amplitude and phase modulated part, respectively. Further amplitude demodulation is done to find out amplitude modulated part $A(t)$

$$A(t) = \sqrt{\{x(t)\}^2 + \{H[x(t)]\}^2} \tag{3}$$

A(t) is also called envelope of the signal.

2.2 *Wavelet Packet Transform*

Wavelet packet transform (WPT) [23, 24] is an extension of discrete wavelet transform (DWT), where a signal is decomposed into sub-signals of different frequency band. In WPT, the wavelet function can be written as

$$W^n_{j,k}(t) = 2^{j/2}W^n(2^j t - k) \tag{4}$$

where j, k are two integers denoting scale and translation parameters. While, j and k are zero then scaling function $\phi(t)$ and mother wavelet $\psi(t)$ can be defined as

$$W^0_{0,0}(t) = \phi(t) \tag{5}$$

$$W^1_{0,0}(t) = \psi(t) \tag{6}$$

while, $n = 2, 3, \ldots$, the wavelet packet functions are defined as

$$W^{2n}(t) = \sqrt{2}\sum_{k=1}^{N} h(k)W^n_{1,k}(2t - k) \tag{7}$$

$$W^{2n+1}(t) = \sqrt{2}\sum_{k=1}^{N} g(k)W^n_{1,k}(2t - k) \tag{8}$$

k is varying by $\{k = 1, 2, \ldots\ldots 2^n, N = 2^n\}$ and N is the length of the signal, where *h(k)* and *g(k)* are high-pass and low-pass filter defined in terms of inner product as

$$h(k) = 1/\sqrt{2}\langle\phi(t), \phi(2t - k)\rangle \tag{9}$$

$$g(k) = 1/\sqrt{2}\langle\psi(t), \psi(2t-k)\rangle \tag{10}$$

where < :,: > are addressing the inner product. Further, *h(k)* and *g(k)* are orthogonal and expressed through this relationship as

$$g(k) = (-1)^k h(1-k) \tag{11}$$

The wavelet packet coefficients are achieved by the inner product of signal *x(t)* and wavelet packet function.

$$C_{i,j}^n = \langle x, W_{j,k}^n \rangle = \int_{-\infty}^{\infty} x(t) W_{i,j}^n(t) dt \tag{12}$$

Hence, at *j*th level, a signal *x(t)* will be decomposed into 2^j packets. The wavelet packet tree has been formed with the binary order $n = 1, 2, \ldots 2^j$. Hence, each level, the sampling frequency decreases by *2*. At *j*th level, *p*th packet coefficients will be of the frequency band from $(p-1)*Fs/2^{j+1}$ to $p*Fs/2^{j+1}$. Hence, a different passband signal can be reconstructed by making the coefficients of undesired nodes to zero. Thus, the WPT has been utilized for signal filtering [24, 25].

3 Experimental Setup

The sound signal is captured from a four-stroke, single cylinder, horizontal Diesel engine with rated power 10 HP at 500 RPM, which is located in internal combustion engine laboratory at NIT Patna. The engine is made by UNI-INSTAS. The engine is water cooled, where loading on the engine can be applied through rope brake dynamometer. An Android mobile with specification (Samsung J5, Android 5.1 with quad-core 12 GHz cortex-A53) is used to record the sound by its in-built sound recorder from 30 cm distance from the engine (Fig. 1).

4 Result and Discussion

Sound signal has been acquired by the Android mobile phone in Wma format. Further, this has been converted into WAV format and it has been analyzed in MatLab environment. Figure 2a shows the sound signal recorded by the Android mobile phone during no load and 500 RPM running speed. Therefore, the combustion frequency and running frequency of the diesel engine are 4.16 Hz and 8.32 Hz, respectively. Figure 2b shows frequency spectrum of the recorded sound signal. The frequency spectrum shows harmonics of rotational frequency and combustion frequency. However, amplitude of 1st combustion frequency and rotational frequency are very much

Fig. 1 Single cylinder diesel engine

low. Therefore, the signal needs alternative signal processing technique to extract combustion frequency rather than direct fast Fourier transform.

Hence, envelope of the sound signal has been extracted, which is shown in Fig. 3a. Further, frequency spectrum of envelope shows the combustion, rotational frequency, and its harmonics, which is shown in Fig. 3b.

Although the combustion frequency is detected, yet the detection of each combustion event is an important issue for online monitoring. Therefore, the envelope is low pass filtered using WPT. Daubechies10 wavelet has been used for the decomposition as it creates no redundancies [24]. The filtered envelope signal is shown in Fig. 4. However, the filtered signal was found not able to detect the occurrence of each combustion. As the envelope is unable to detect each combustion, the sound signal is analyzed by another methodology. Hypothesis utilized in the paper is that the amplitude variation of sound signal during combustion is generally higher as compared to other strokes like suction, expansion, and exhaust. Therefore, successive sound ratios will be higher during combustion stroke as compared to other strokes. Hence, the sound signal is already with zero mean. Therefore, an absolute value (slightly more than the minimum value of the signal) has been added with this signal to obtain

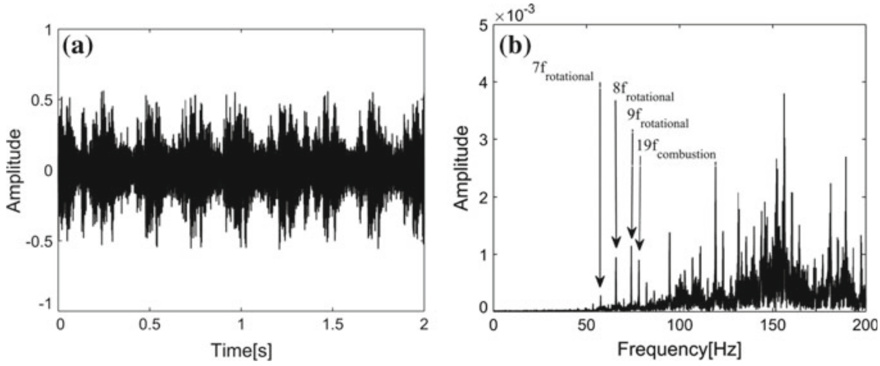

Fig. 2 **a** Recorded sound signal by Android mobile phone; **b** Frequency spectrum of the sound signal

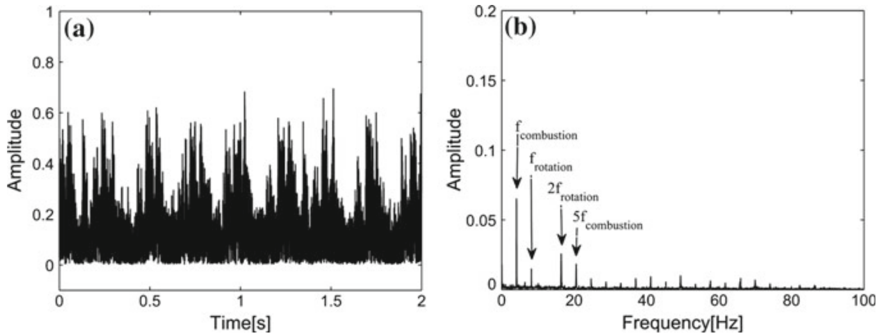

Fig. 3 **a** Envelope of the recorded sound signal; **b** Frequency spectrum of envelope signal

the sound signal with positive mean. Further, ratio of two successive points of the entire sound signal are calculated as successive sound ratios. The reason for making the sound signal with positive mean is that the calculated successive sound ratios become real. The *i*th successive sound ratio (SSR) for recorded sound signal (S) can be written as

$$SSR = \frac{S_{i+1}}{S_i} \tag{12}$$

The successive sound ratios measured from recorded sound signal are low pass filtered by WPT. The filtered successive sound ratios have been shown in Fig. 5. It shows that the peaks in the filtered successive sound ratios are appeared with around 0.243 s time gap. This time gap is an inverse of combustion frequency 4.16 Hz. Thus, the filtered successive sound ratios can detect the occurrence of each combustion effectively. Hence, WPT based low pass filtering of envelope and successive sound ratios have been performed through few steps. First, envelope and successive sound

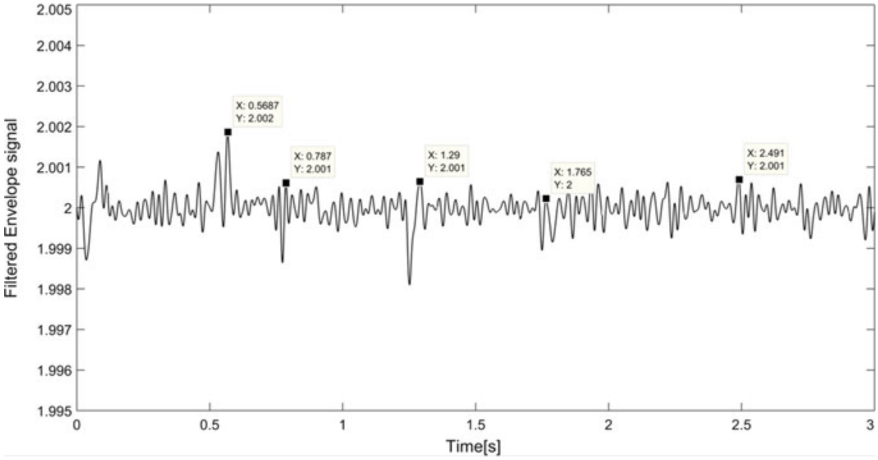

Fig. 4 Filtered envelope of sound signal

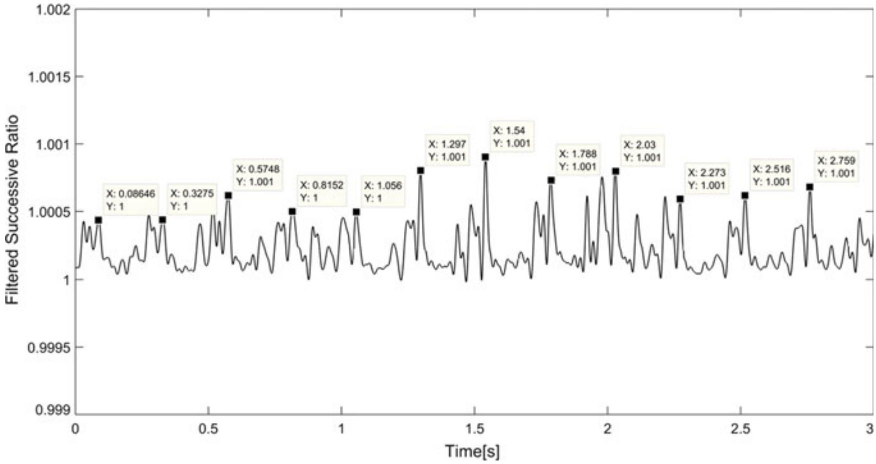

Fig. 5 Filtered successive ratio of sound signal

ratios are decomposed up to nineth level using WPT. Thus, *p*th node at nineth level of WPT tree contains the frequency band from $(p - 1) * 44100/2^{9+1}$ Hz to $p * 44100/29+1$ Hz. Hence, the frequency content of the first node is 0–43 Hz. As the first node contains less harmonics. Both the signals (envelope and successive sound ratios) have been reconstructed by setting the node's coefficients to zero except first node. Thus, the frequency content of filtered signals (envelope and successive sound ratios) become 0–43 Hz.

5 Conclusion

This paper has detected the combustion event in a single cylinder diesel engine by analysis of sound signal recorded by Android mobile. Hence, the sound signal has been utilized to detect the combustion quantitatively. WPT-based filtering of sound signal's envelope is unable to detect each combustion event. Therefore, successive sound ratios have been combined with WPT to detect each combustion event efficiently.

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