Power spectral estimation of engine block vibrations to classify and predict the occurrence of knock

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Abstract. The study focuses on developing a sophisticated technology for determining the occurrence of knocking in SI engines. Fast Fourier Transform is performed on the engine block vibration signal to obtain the power spectral estimation. Window size of the signal is varied to extract the signals produced during the combustion inside each cylinder alone. The results obtained show that there is a clear demarcation between the power spectrum obtained during the occurrence of knock and normal combustion. Also, knock can be classified based on the intensity as strong, moderate or weak by analysing the vibration signals alone. This technique makes it suitable to be used in SI engine to investigate the combustion process in all the cylinders individually using an accelerometer mounted on the engine block.

1. Introduction

Knocking acts as a major hindrance for enhancing the performance of SI engines, leading to major research works ranging from the knock suppression to knock detection and control. During the combustion process, the flame propagation gets accelerated with the increase in in-cylinder temperature, resulting in the development of cool flames in the end gas. This end gas heating and compression caused by the propagating flames results in the auto-ignition of unburned mass, leading to the occurrence of knocking [1]. The studies also show that, all the auto-ignition process does not lead to knock [2]. The auto-ignitions occurring before nearly 80% of the total fuel is burnt results in knock, else, it will only accelerate the combustion process in the end gas mixture, without leading into any sharp pressure fluctuations [2]. Therefore, all the knock suppression methods focus on reducing the end gas temperature or to reduce the duration of combustion. This includes the use of Cooled EGR [3], increase the turbulence, reduce the compression ratio, improve the fuel octane number etc. [4]. While the knock detection techniques comprise of the methods based on in-cylinder pressure, engine block vibrations, exhaust gas temperature, end-gas analysis, heat release analysis etc. [4-10]. Among these, exhaust gas temperature, end gas analysis, and heat release analysis could not be used effectively for the real-time detection and control of knocking. This is due to the time lag in obtaining the required data and its processing as compared to that of the in-cylinder pressure and engine block vibration signals.

Even though the above two methods could be used to detect the knock in real-time, the control measures could only be taken in the next cycle. This had led to the generation of knock models that focuses on the probability of the knock occurrence rather than determining the angle of knock onset [11]. However, probabilistic approach could not perform well as compared to the realistic approach and could not lead to the performance enhancement in SI engine by improving its compression ratio. Hence, in-cylinder pressure signals and engine block vibration signals are still treated as the most...
relevant signatures of knock. In-cylinder pressure could only be obtained by using pressure transducers mounted in each cylinder. This increases the cost of the system as well as the computational cost, since the signals from all the sensors need to be analysed parallel. As against this, a single accelerometer mounted on the engine block could be used to extract the vibrations produced during the combustion in all the cylinders. This makes the engine block vibration signals most acceptable for determining the occurrence of knocking.

Non-intrusive vibration sensors have excellent durability and low cost. This makes it widely acceptable and more practical in SI engines for determining the occurrence of knock. There are numerous works done for determining the occurrence of knock by analysing the engine block vibration signals. Rather than just identifying the occurrence of knock from the results, the process should be automated for the efficient implementation of the system. One such method was proposed by Ettefaghi et al. [12]. They had modelled engine block vibration signals using the Auto Regressive Moving Average (ARMA) parametric model [12]. The tachometer signal in parallel to the accelerometer signal is used to calculate the Knock Sensitive Window (KSW) [12]. They had shown that the fourth moving average parameter could be used as an indicator of the knocking [12]. However, due to the non-stationarity of the signal, knock intensity could not be determined. This affects the effectiveness of the control measures adopted. The estimation of KSW, which is a small portion of the vibration signal captured during the compression process, starting from the onset of knock and extends till the end of vibrations produced during the knock, increases the computational power. In the present work, the window length is taken as the function of engine speed in such a way that, window completely encloses the vibrations produced during the single combustion process alone. This reduces the computational time required for the estimation of KSW. At the same time, enabling us to evaluate each combustion process individually i.e., we could estimate the power spectrum of the vibrations produced during the combustion process in each cylinder. This method also could locate the cylinder at which the knock occurs without further calculations. The study focuses on determining the occurrence of knocking, with much lower complexity, less computational power, and higher accuracy. Further details about the model developed are discussed in the following sections.

2. Vibration signal processing and estimation

In this work, the experimental data’s required for the analysis is obtained from the works done by Fengrong et al. [13, 14] and Li et al. [15]. The engine block vibration signals during the normal combustion and during the occurrence of knocking are obtained from 4 cylinder 4 stroke, in-line SI engine. Knock is produced by advancing the ignition timing. During the occurrence of knock, the frequency of the signals produced varies from 8 kHz to 22 kHz [16]. Therefore, an accelerometer, DYTRAN - 621B40 [13-15], which could capture the vibration signals with frequency up to 30 kHz is mounted on the engine block to capture the engine block vibrations. The sampling frequency is 52 kHz [13-15]. In-cylinder pressure signals are captured using the pressure sensor AVL - GH13Z-31(24) [13-15] for confirming the occurrence of knock. The pressure transducer used could capture the pressure waves up to 250 bar and has a natural frequency of 115 kHz. The high frequency pressure fluctuations are produced during the occurrence of knock and the corresponding engine block vibration signals are analysed to obtain the power spectral estimation for evaluating the features of knock as against the signals produced during the normal combustion.

The engine block vibration signal obtained is denoised using Symlet wavelet. In order to avoid any discontinuity in the denoised signal, soft thresholding is used [17]. Better symmetry of the Symlet wavelet, reduces the chance of phase distortion. The window length is then calculated and the denoised signal is analysed to obtain the power spectral estimation. Further details about the denoising, window length estimation and the spectral estimation of the vibration signal are explained in the following sections.
2.1. Denoising using Wavelets
Signals obtained from the accelerometer are filtered for eliminating the noise using wavelet filters. Initially, vibration signals are split into high-pass and low-pass component known as wavelet decomposition tree [18]. The vibration signals are then decomposed by wavelet packets at level 8 using sym4. After decomposition, it is de-noised by using wavelet packet.

2.2. Window length estimation
In this work, the relation for window length is formulated based on the assumption that the combustion process occurs between the crank angles 330°CA and 420°CA. Therefore, the window length will be 90°CA. But this needs to be calculated in-terms of time. Hence, it should be developed as a function of engine speed as:

\[ WL = \frac{60 \times 7.33}{2\pi N} - \frac{60 \times 5.76}{2\pi N} \]

Where N is the engine speed. The vibration signals are analysed at regular intervals of \( \frac{30}{N} \) for an estimated window length to evaluate the combustion process in each cylinder.

2.3. Spectral Estimation
The denoised signals are then analysed further to obtain its frequency-domain representations at regular intervals of the estimated window length. This could give a better understanding about the signal which was missing in the time domain. Real-time spectral analysis of the signals obtained from the accelerometer could be analysed using the spectrum analyser available in MATLAB or spectrum analyser block available in Simulink. Welch method and filter bank methods are used for the spectral analysis. In this work, spectrum analysis of the signal is done using the filter bank method; a Fast Fourier Transform (FFT) based spectral estimation method. In this method, the input signal is split into multiple narrow frequency bands and the spectrum analyser computes the power in each narrow band. The main advantage of this method is that, it does not make any assumption about the input signal and could be used with any type of signals. In addition to this, the filter bank approach could be used for the signals with small lengths to produce the spectral estimates with higher resolution, and peaks more precise than Welch method, with low or no spectral leakage.

3. Results and Discussion
The in-cylinder pressure and engine block vibrations are obtained from a four cylinder 4 stroke SI engine. The signals corresponding to the occurrence of knock (Fig. 1) is obtained at an engine speed of 4000 rpm, 178 Nm torque and spark at 150 BTDC [13, 14]. While the signals obtained at an engine speed of 4000 rpm, 97 Nm torque [15] is taken as a benchmark for normal combustion (Fig. 2). In the figure 1, we can observe pressure fluctuations at the peak, this is due to the occurrence of knock. Correspondingly, the amplitude of the engine block vibrations are higher during the occurrence of knock, when compared to that of the vibrations produced during the normal combustion as shown in the figure 2. The amplitude of the vibrations produced during the occurrence of knock is of the order 100g, while that produced during the normal combustion does not go beyond 20g.

The spectral estimation of the vibration signals shown in Fig. 1 and 2 are obtained as shown in the figure 3 and 4. While comparing the spectral estimations, we can see that, during the occurrence of knocking (Fig. 4), there are higher energies in the frequency ranges between 7-22 kHz. This is supposed to be the frequency range of signals produced during the occurrence of knocking [16]. During the normal combustion (Fig. 3), maximum energy in the vibration signal is 33.78 dB corresponding to 7.631 kHz. At higher frequencies above 20 kHz, the energy obtained is 15.33 dB. While, during the occurrence of knocking (Fig. 4), the maximum energy is observed to be 42.23 dB corresponding to 7.595 kHz. Also, at higher frequencies above 20 kHz, the energy of the signal falls up to 25.99 dB. From this, we can infer that, energy of the vibration signals produced during the occurrence of knock falls in the higher frequency region, while it is very less during the normal combustion process.
Figure 1. In-cylinder pressure (top) and engine block vibrations (bottom) produced during the occurrence of knock at an engine speed of 4000 rpm [13, 14].

Figure 2. In-cylinder pressure (top) and engine block vibrations (bottom) produced during the normal combustion at an engine speed of 4000 rpm [15].

Figure 3. Power spectral estimation of the engine block vibration signal captured during the normal combustion process at 4000 rpm.

Figure 4. Power spectral estimation of the engine block vibration signal captured during the occurrence of knock at 4000 rpm.

Figure 5 shows the in-cylinder pressure and the engine block vibrations produced during the combustion process in each cylinder. The signals were captured while the engine was running at 2800 rpm and spark at 28° BDC [15]. From the figure 5 we could see that, there are fluctuations in the in-cylinder pressure obtained during the combustion process occurring in the cylinder 1 and 3. This is due to the occurrence of knocking. Among these, peak pressure is higher in the cylinder 1 than in the cylinder 3. Correspondingly is the behaviour of vibrations signals also. Engine block vibrates with larger amplitude during the combustion process occurring inside the cylinder 1 and comparatively lower amplitude vibrations are produced during the combustion process inside the cylinder 3. In
addition to these two, another higher amplitude vibrations are observed corresponding to the combustion process inside the cylinder 2. However, the in-cylinder pressure obtained from the cylinder 2 is having the lowest peak pressure among the others and the pressure fluctuations are also not observed in it. Therefore, any higher amplitude fluctuations in the vibration signals observed in the time domain could not be considered as due to the occurrence of knock. Hence, in order to determine the occurrence of knocking using vibration signals alone, it needs to be processed further. Power spectral analysis of these signals are done by capturing the vibration signals produced during the combustion process in each cylinder separately using window length estimation. Figures 7-10 show the power spectral estimation of the engine block vibration signals obtained, corresponding to the cylinder 1, 3, 4 and 2 respectively.
Alike the signals shown in the figure 5, in-cylinder pressure signal and the corresponding engine block vibration signals obtained at an engine speed of 4000 rpm and spark at 20° BTDC is shown in the figure 6 [15]. Pressure fluctuations are observed in the cylinder 3 and 2. But the amplitude of vibrations produced corresponding to the combustion inside the cylinder 3 fails to give a clear demarcation from that produced during the normal combustion process. While, higher amplitude vibrations are produced corresponding to the combustion process inside the cylinder 2. Further analysis is done on these vibration signals to obtain the power spectrum. Figures 11-14 show the power spectral estimation of the engine block vibration signals obtained corresponding to the cylinder 1, 3, 4 and 2 respectively.

The maximum energy of vibrations produced, corresponding to the pressure fluctuations in the cylinder 1 and 3 (during the occurrence of knock) shown in the figure 5 is estimated to be 38.45 dB at 7.241 kHz and 32.05 dB at 7.186 respectively (Figures 7 and 8). At higher frequency range around 20 kHz, the maximum power spectral estimation is 22.82 dB and 16.38 dB respectively. While the power spectral estimation of the vibrations produced during the normal combustion inside the cylinder 4 and 2 is 27.14 dB at 6.453 kHz and 31.35 dB at 7.35 kHz respectively, and in the higher frequency range, the values are 14.57 dB and 13.46 dB respectively (Figures 9 and 10). Similar to the above results, the vibration signals shown in the figure 6 were also analysed to obtain the power spectral estimations. The power spectral estimate of vibration signals produced during the occurrence of knock in the cylinder 3 and 2 are 35.62 dB at 7.375 kHz and 38.6 dB at 7.601 kHz respectively (Figures 12 and 14). Also, the maximum energy of vibrations in the higher frequency ranges is 16.74 dB and 25.25 dB respectively. While during the normal combustion process inside the cylinder 1 and 4, the maximum energy produced by the corresponding vibrations are found to be 31.01 dB at 7.192 kHz and 31.38 dB at 7.43 kHz respectively, and in the higher frequency range, the values are 16.22 dB and 18.55 dB respectively (Figures 11 and 13).

From these results, the common observation is that, during the occurrence of knock the maximum energy level of the vibrations produced is in the range of 35 dB or above. While the energy level at the frequency ranges above 20 kHz depends on the intensity of knock. For a strong knock, the values are greater than 20 dB and for weak knock, it’s below 20 dB. The intensity of knock increases/decreases as the energy level of the vibrations moves above or below 20 dB in the higher frequency region. While, during the normal combustion process also, the energy distribution falls between 16-18 dB in the higher frequency region. However, we could observe a dip in the energy of the vibration signals.
produced during the normal combustion, between the frequency range 7-20 kHz, which was absent during the occurrence of knock.

**Figure 11.** Power spectral estimation of the engine block vibration signal captured during the combustion process in the 1st cylinder at an engine speed of 4000 rpm.

**Figure 12.** Power spectral estimation of the engine block vibration signal captured during the combustion process in the 3rd cylinder at an engine speed of 4000 rpm.

**Figure 13.** Power spectral estimation of the engine block vibration signal captured during the combustion process in the 4th cylinder at an engine speed of 4000 rpm.

**Figure 14.** Power spectral estimation of the engine block vibration signal captured during the combustion process in the 2nd cylinder at an engine speed of 4000 rpm.

The higher pressure fluctuations shown in the figure 5 and 6 corresponding to the cylinder 1 (Fig. 5) and cylinder 2 (Fig. 6) indicates the strong knock. Comparatively lower pressure fluctuations in the figure 5 corresponding to the cylinder 3 indicates weak knock. This is because, the energy of vibration signal is below 20 dB in the higher frequency range. Also, it maintains a constant energy range in the higher frequency region 7-20 kHz, which is against the observations produced for the normal combustion condition. Hence, it could be treated as a weak knock, as it shows the characteristic of knock, even though the energy distribution in the high frequency region is low. In the figure 6, corresponding to the cylinder 3, we can see that, pressure is fluctuating throughout the combustion process. Here, the pressure energy released during the abnormal combustion lasts for longer duration but with lower intensity. This is also evident from the corresponding engine block vibration signal due to its lower amplitude. Also, from its power spectral estimate (Fig. 12), we can see that, even though the maximum energy around 7 kHz is above 35 dB, energy of the signal at higher frequency range
above 20 kHz is only 16.74 dB. We could also observe a dip in the energy distribution between 10-20 kHz, similar to that of the normal combustion case. Hence, this could be treated as much weaker knock, having more inclination towards normal combustion process.

4. Conclusion
Spectral estimation of the engine block vibrations produced during the combustion process in each cylinder is done individually by calculating the window length as a function of engine speed. This could considerably reduce the size of the signal that is to be analysed, resulting in lower computational time. This methodology also helps to identify the cylinder in which knock is occurring at the same instant. The results show that, the frequency of vibrations produced during the occurrence of knock falls in the range between 7-22 kHz. Based on the energy distribution in the higher frequency ranges, knock can be classified into strong, moderate or weak. Vibration signals corresponding to the occurrence of knock during the entire operating range are required to train and implement a knock detection algorithm. Genetic algorithm can be used to fix the window length as well as to analyse the power spectral estimation of the signals to determine the occurrence of knock.

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