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Combustion Process Analysis in Engines Using Vibration Signals

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Abstract: *This work analysis the scope of non-intrusive measurements by engine vibration monitoring. These signals complex in nature due to contributions of various sources like valve operations, fuel pump operation, combustion events and piston motion. The vibration signals obtained from tests has been analysed into various components. Tests were done to select an optimum location for placement of accelerometer to measure engine block vibrations, which are sensitive to combustion contribution due to rapid rise in cylinder pressure. A suitable range of frequency has been identified in which there is high correlation between engine block vibrations and the cylinder pressure using time frequency analysis methods.*

Keywords: *Automotive; Noise; Acoustic*

1. Introduction

There are generally three phases of injection process used in diesel engines, namely pre-injection period, main-injection period & post injection period. There is a delay period between instant at which fuel is injected inside the combustion chamber and actual start of ignition process. Greater this delay period, more is the temperature achieved during course of combustion and hence better conditions exist for NOx formation. In order to shorten this delay period, a small amount of fuel is pre-injected before main injection occurs during the phase of pre-mixed combustion. Torque and power produced in engine mainly depends on the duration of main injection period. It is advantageous to vary the injected fuel mass with time in order to reduce the specific consumption of fuel. This is achieved by rate shaping as seen in figure no 1. Rate shaping curve may be rectangular, step or boot type in shape. Post-injection of fuel is done in order to reduce the soot emissions and in some cases may be useful for exhaust gas recirculation treatment [1-12].

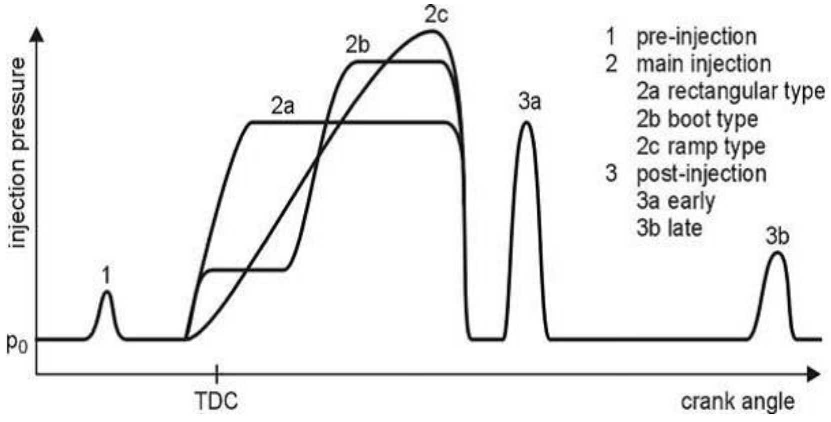

Fig. 1. Multiple injection methods adopted for modern diesel engines [1]

The amount of fuel injection during pre-injection period is denoted by Q_{pre}(mm^{3}per stroke), whereas the amount of fuel injected during main-injection period is denoted by Q_{main}(mm^{3}per stroke).
Various methodologies used to diagnose working of combustion engines are as follows:

A. Vibrations- location of transducer to monitor vibrations is a major issue as there are chances of due contamination of signals due to environmental issues. Frequency analysis, peak and RMS values are effective to monitor imbalances, bearing damage or shaft misalignments [1-11].
B. Noise emissions- Noise levels are perceived by the humans as air pressure oscillations reaching ears which lead to motion of the ear drums. It provides information about injection faults, wear, and improper valve operation.
C. In cylinder pressure- it is effective to monitor injector faults, wear, valve operational problems, incorrect injection timings and hence overall combustion efficiency of engines. However, higher temperatures conditions make various pressure sensors expensive with short life span time [12].
C. Noise emissions - Various sound features can be analyzed by means of sound pressure levels (SPL). In order to obtain the levels that bear a closer relationship to loudness judgment, three different networks of frequency weighting (A, B, and C) filters have been incorporated into various sound level meters with the A weighting most closely matching the hearing capacity of human ears [13].
Various signal processing methods that may be used for effective condition monitoring of engines includes:
A. Power spectral density function (PSD)- This function (Ψ^2) provides the frequency composition of data in terms of its mean square values [14]. The average square values approach mean square values as $T\rightarrow\infty$.

$$\text{i.e. } \Psi^2 (\omega, \Delta\omega) = \text{Lim}\ \Delta x\rightarrow\infty \int x^2 (t)\, dt / T \tag{1}$$

B. Time frequency analysis -The Fourier transformation of a function f(t) in frequency domain can be represented as:

$$f(\omega)= \int x(t)e^{-i\omega t}\, dt \tag{2}$$

This analysis is useful as long as frequency content of signals do not vary with time.
Hence time frequency analysis or wavelet analysis are more suitable for analysis of transient signals [15]. The short time-frequency analysis (STFT) of signal may be represented as:

$$\text{STFT } (\tau,f)= \int x(t)\, h^*(t-\tau)\, e^{-i\omega t}\, dt \tag{3}$$

Where $x(t)$ is input signal & $h(t-\tau)$ is window

The presented work aims at study of engine block vibrations for combustion process monitoring using time and frequency domain processing techniques.

2. Literature review

Combustion process plays an important role in emissions, NVH and engine power output. Hence, new methods of diagnosis have been developed to monitor this process and to relate the injection methods using non-intrusive sensors. Chamber oscillation are caused due to rapid rise in pressure gradient due to ignition of air-fuel mixture. Use of microphones is one of most important non-intrusive methods are and concerns of contact with high temperature surfaces is avoided. However, there may be signal contamination due to other sources superimposed [12-14]. Accelerometer signals have been analyzed to define the frequencies of cylinder pressure and vibration signals [15]. Cylinder pressure was reconstructed using vibration measurements are presented [16-20]. In [19] the various events have been analyzed using surface vibrations in engines.

The depletion of fossil fuels in modern times has pressed for need to find methods to save consumption of fuel [20]. Nadija et al. [13] presented an overview of automotive NVH engineering, classifying power train-related NVH, road- and tire-related NVH and wind related NVH. They also discussed brake and chassis, squeak and rattle noise. Automotive industries are concerned to minimize noise and vibration level for marketing [37]. Dynamic features of vibrations and instability of the front-end accessory drive belt system was investigated. Various challenges in NVH testing of engines that constitute complexities to the development were explored.

3. Materials and methods

Tests were done on a single cylinder HARTZ engine having specifications as presented in Table no 1. A fully opened electronic control unit connected to computer was used to manage the injection system with aim to control operational parameters. The engine was coupled with a synchronous motor of SIEMENS 1PH7 make thus allowing to control speed and load. The in cylinder pressure was monitored by an AVL transducer having specifications shown in Table 2. Block vibrations were measured by means of a Endveco7240C type Mono axial accelerometer having features accelerometer are presented in Table no 3. Engine testing speed of 2000 RPM,3000 RPM and load values of 80%, 100% was chosen with an aim to cover complete engine operational conditions. Main operational parameters are listed in Table no 4.

Table 1: The features values of engine

Type	Diesel Engine
Make	HARTZ
No of cylinders	1
Stroke	65mm
Displacement	0.243 liter
Compression	22:1
Maximum Power	3.5kW@4400RPM
Bore	69mm
Maximum Torque	10N-m @2000RPM

Table 2: Pressure Transducer Specifications

Range	0-250Bar
Sensitivity	20pC/Bar
Resonance Frequency	160kHz

Table 3: Accelerometer Transducer Specifications

Range	1000g
Sensitivity	3pC/g
Resonance Frequency	90kHz

Table 4: Fuel injection Specifications

Case	Injection pressure	Q_{pre}	Q_{main}	SOI_{pre}	SOI_{main}	Load	Speed
1	700	1	15.4	19.3°	6.02°	80%	2000RPM
2	700	1	16.7	20°	6°	100%	2000RPM
3	700	1	17.8	22.4°	9°	80%	3000RPM
4	700	1	14.6	18.2°	9.5°	100%	3000RPM
5	--	--	--	--	--	--	3000RPM

4. Results and discussions

Low frequency components in cylinder pressure curve are related to compression curve, whereas higher order harmonics are related to sudden rise in cylinder pressure. The motored condition can be used a baseline for combustion comparison as it contains contribution only due to motion of engine parts (figure 2−11).

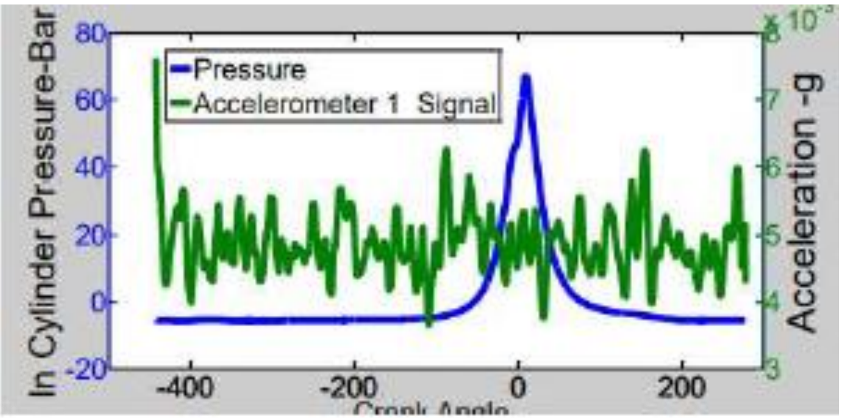

Fig. 2. Comparison of signals (Case 1)

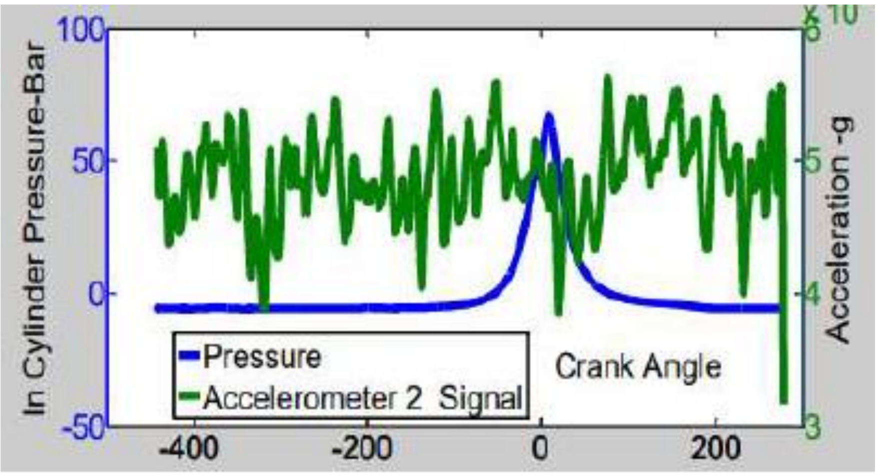

Fig. 3. Comparison of signals (Case 1)

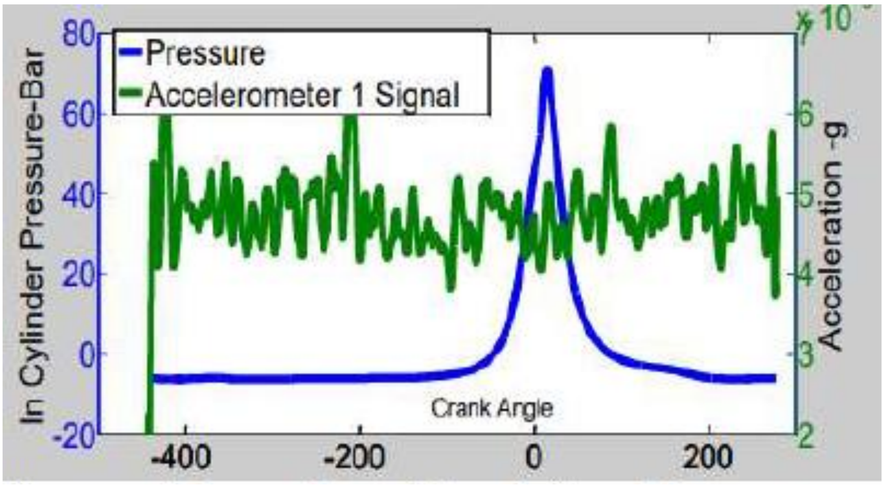

Fig. 4. Comparison of signals (Case 2)

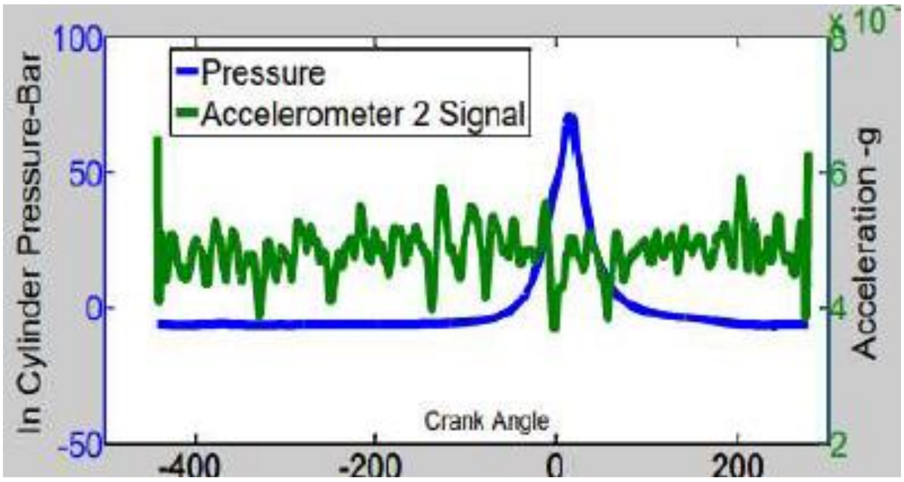

Fig. 5. Comparison of signals (Case 2)

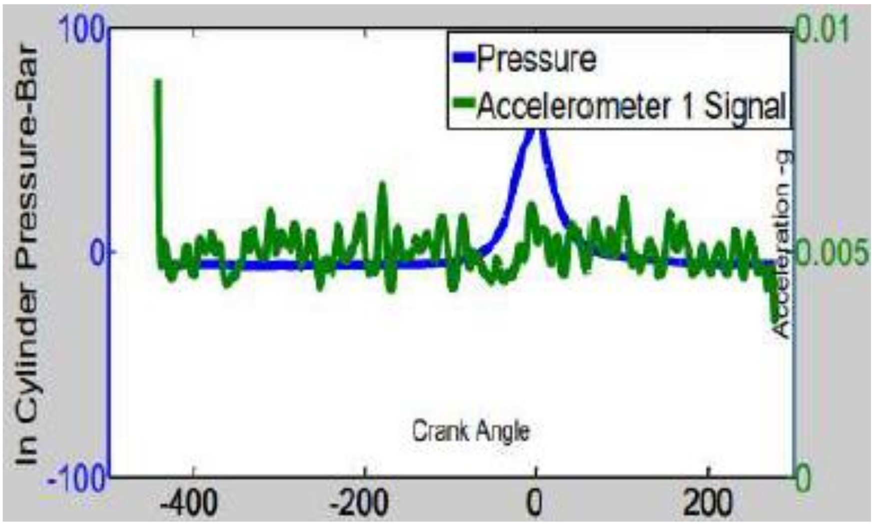

Fig. 6. Comparison of signals (Case 3)

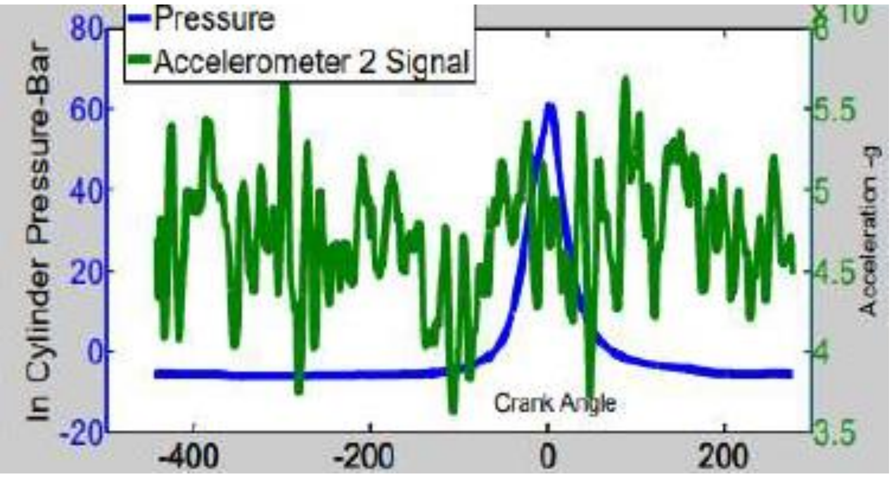

Fig. 7. Comparison of signals (Case 3)

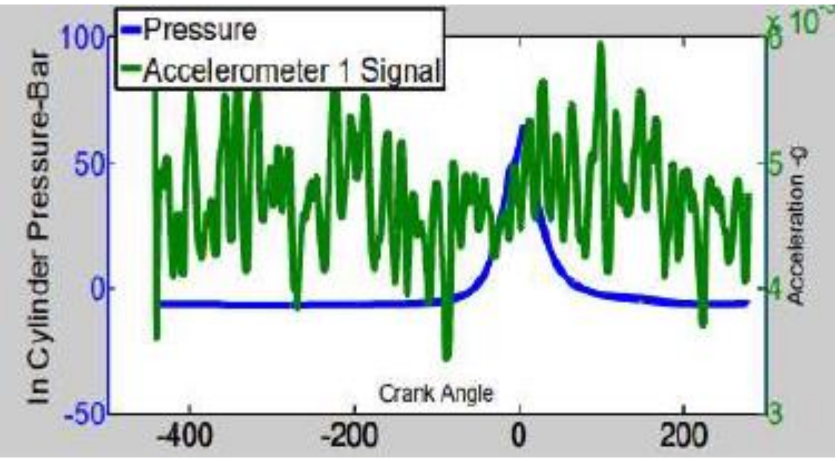

Fig. 8. Comparison of signals (Case 4)

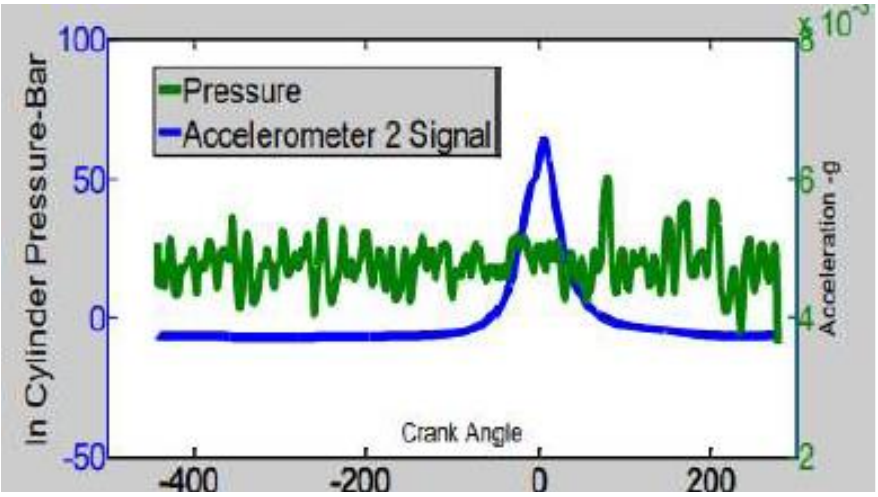

Fig. 9. Comparison of signals (Case 4)

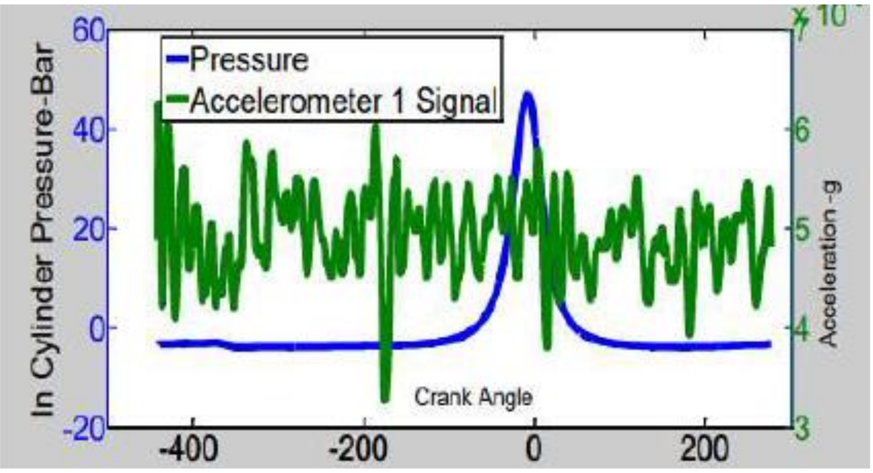

Fig. 10. Comparison of signals (Case 5)

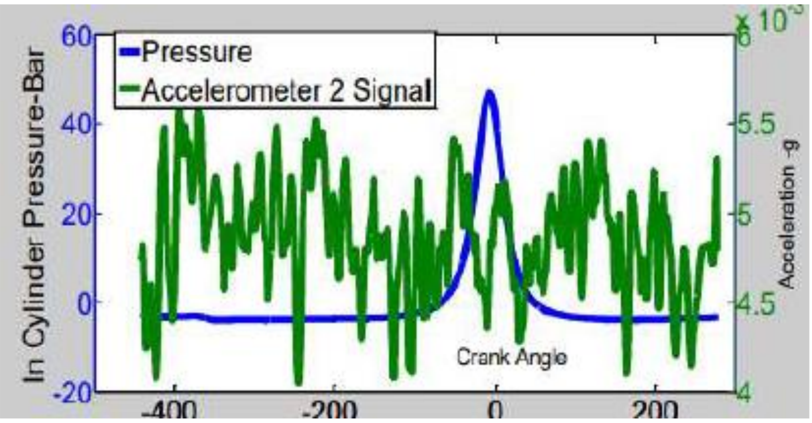

Fig. 11. Comparison of signals (Case 5)

Further frequency peaks can be observed in range 500Hz-1kHz regardless of operational conditions which can be considered as direct contribution due to combustion process. It has been proved that at low frequency ranges there is high structural attenuation upto1 kHz which decays and then again rises with frequency. This is responsible for low vibrations in engine block in spite of rapid rise in cylinder pressure. Also, all signals show same trends without concerning loading conditions (figure 12−16).

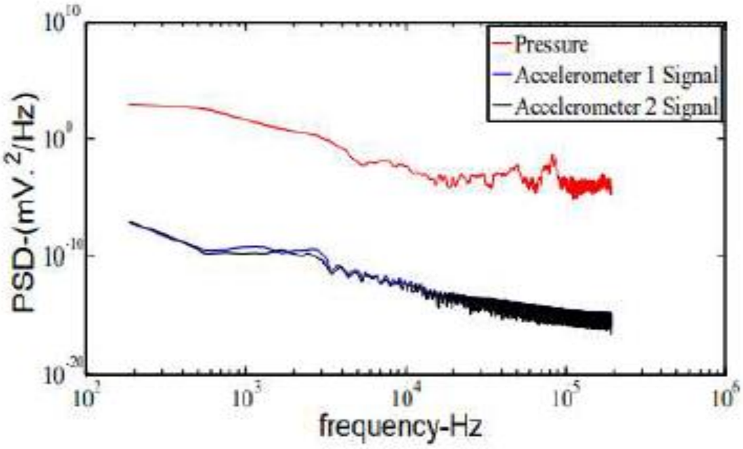

Fig. 12. Comparison of signals (Case 1)

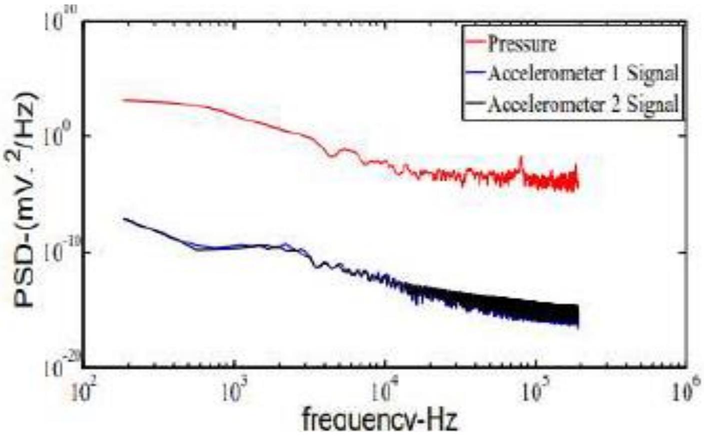

Fig. 13. Comparison of signals (Case 2)

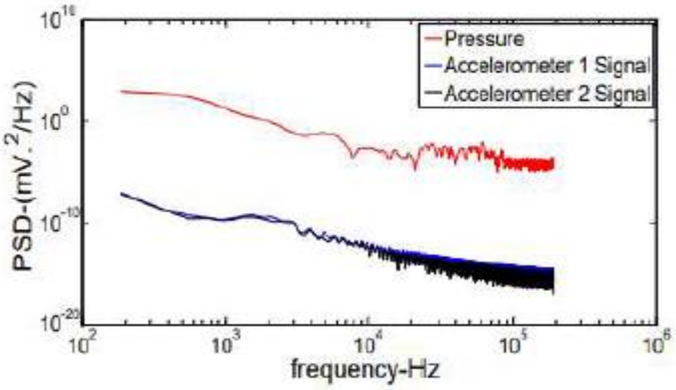

Fig. 14. Comparison of signals (Case 3)

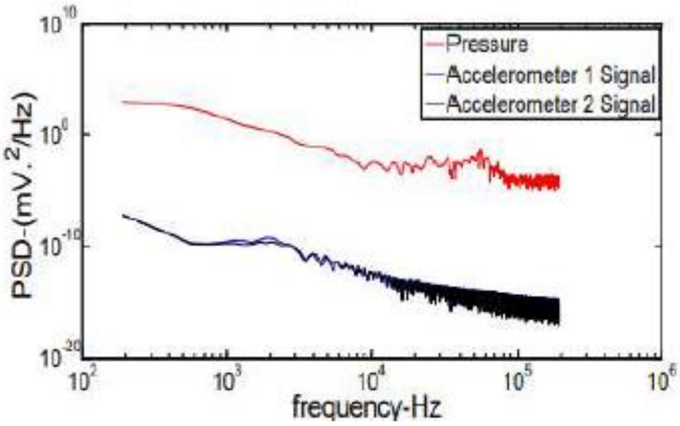

Fig. 15. Comparison of signals (Case 4)

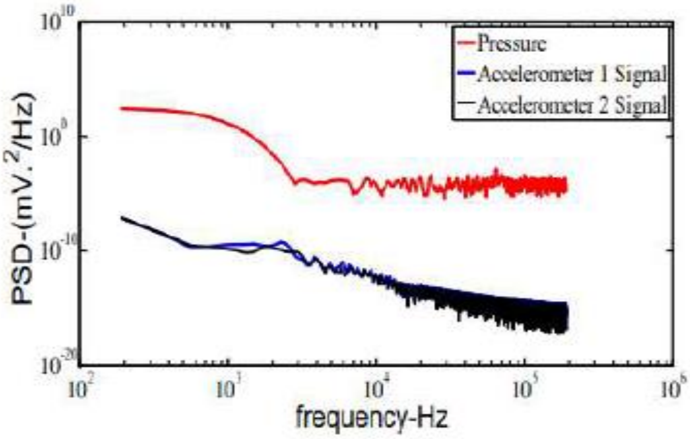

Fig. 16. Comparison of signals (Case 5)

Hence, coherence plots were drawn between cylinder pressure and accelerometer signals. Coherence function can be defined as ratio of product of cross spectral density of input signal (cylinder pressure) and output signals (accelerometer) to product of spectral densities of each signals. The range of this function varies from 0 to 1. Figures 17-21 show plots of squared magnitude of coherence functions between in cylinder pressure and both accelerometer positions for the given testing conditions.

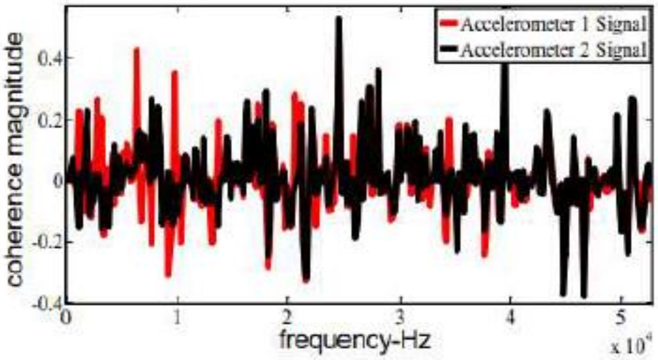

Fig. 17. Coherence signals (Case 1)

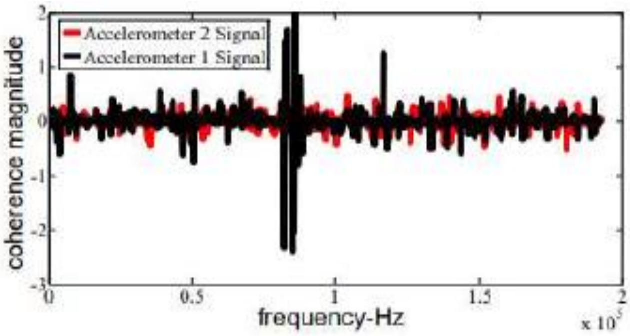

Fig. 18. Coherence signals (Case 2)

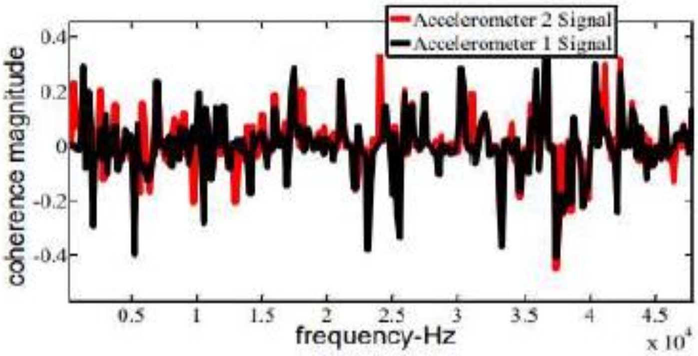

Fig. 19. Coherence signals (Case 3)

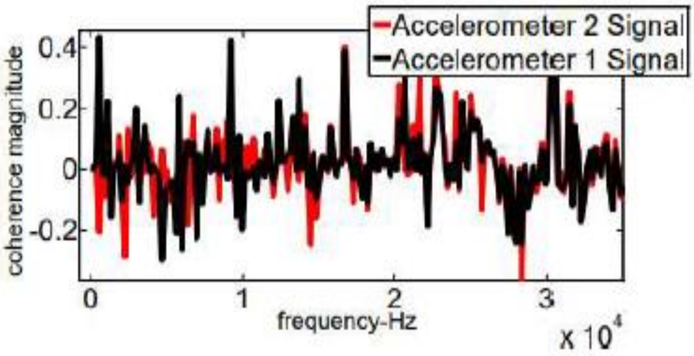

Fig. 20. Coherence signals (Case 4)

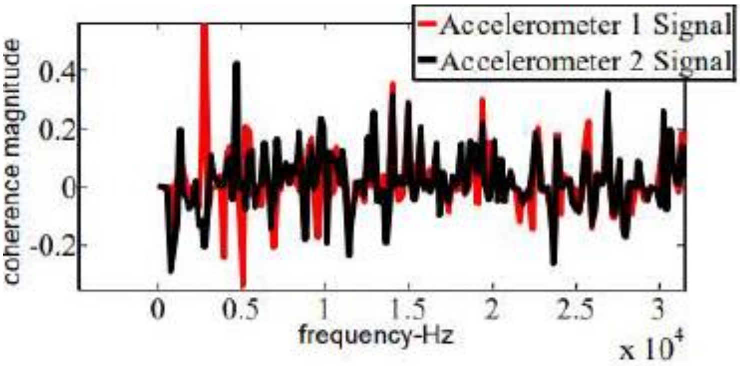

Fig. 21. Coherence signals (Case 5)

From these plots, it is clear that accelerometer signals along horizontal direction exhibit low coherence with cylinder pressure signals due to contamination of signals by other noise sources like piston slap. In addition, high values of coherence function between cylinder pressure and vertical accelerometer signals were exhibited in frequency range 500Hz-1100Hz. Table 5 shows maximum squared values of coherence functions for test cases in this frequency range.

Table 5: Coherence Specifications

Case	Value
1	0.84
2	0.85
3	0.86
4	0.81
5	0.83

In order to further analyzed signals, time-frequency analysis of pressure signals was done for the given testing conditions with focus in the frequency band defined earlier. The results obtained in figures 22-26 highlight higher frequency amplitudes near Top dead canter position, which denotes combustion events.

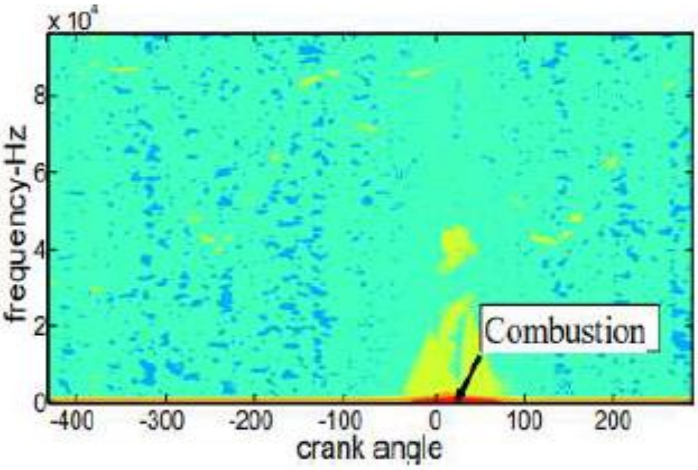

Fig. 22. Coherence signals (Case 1)

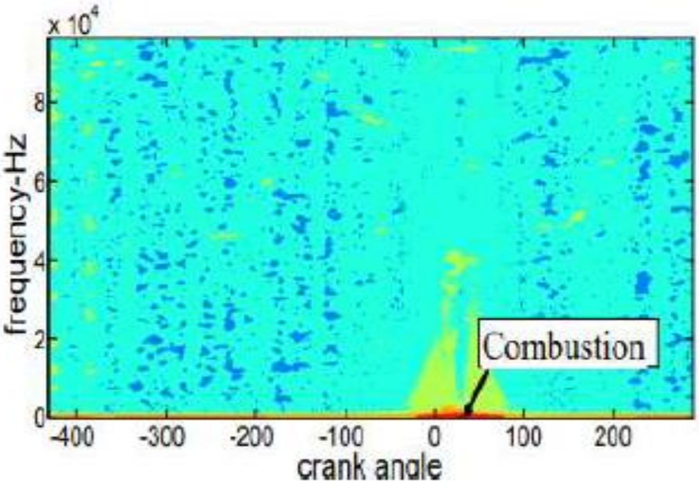

Fig. 23. Coherence signals (Case 2)

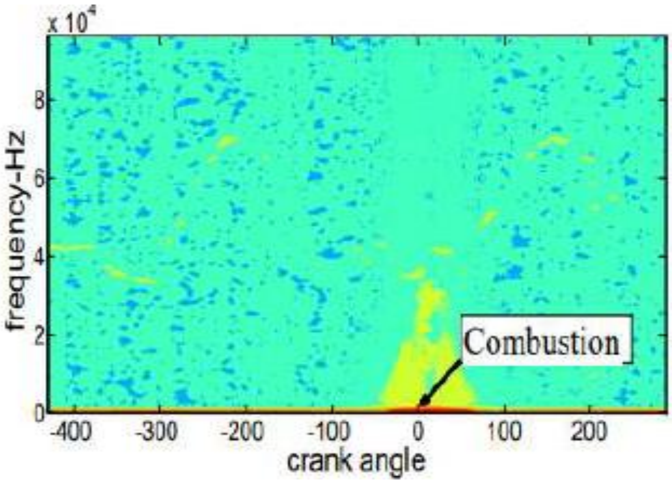

Fig. 24. Coherence signals (Case 3)

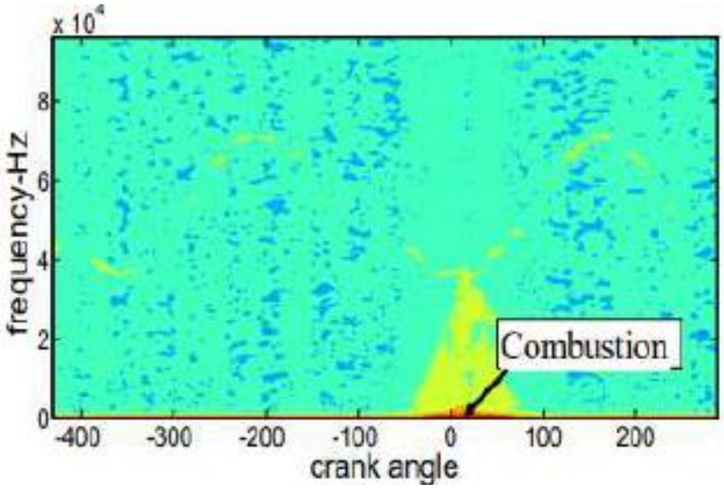

Fig. 25. Coherence signals (Case 4)

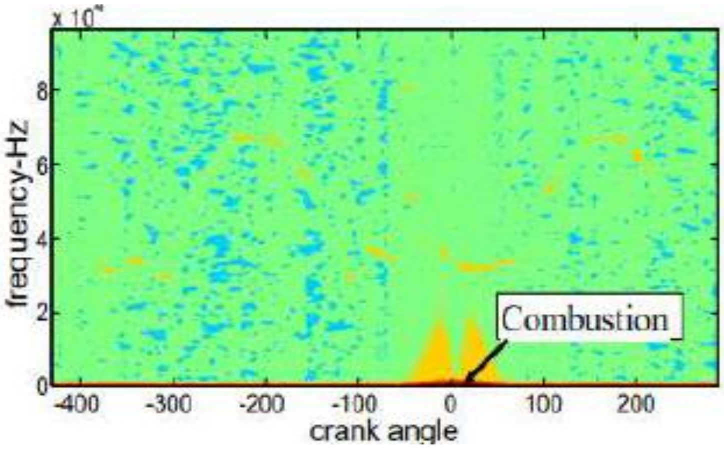

Fig. 26. Coherence signals (Case 5)

5. Conclusions

The work in this paper investigates the scope of use of block vibration signals as a means of condition monitoring of combustion process. Power spectral density plots showed the distribution of energy of various signals. Coherence analysis was used to define a frequency range in which cylinder pressure signals have strong relationship with engine block vibrations. The results have shown that accelerometer signals along vertical direction are most sensitive towards combustion process. The results showed minimum variations with change in the engine operational conditions, which demonstrate the suitability of engine block vibration for condition monitoring of engines.

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