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CORRELATION BETWEEN CYLINDER PRESSURE AND NOISE EMISSIONS FROM DIESEL ENGINES

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Abstract

The aim of this paper is to study the results obtained from a common rail dual cylinder diesel engine. Modern methodology involves the use of non-intrusive techniques of cylinder pressure measurements using sensors installed in the engine test rig. This work analysis the experiments carried out on a dual cylinder diesel engine .The results obtained are analysed to develop the relationship between the cylinder pressure levels and noise emitted from engine. Multiple injection process in diesel engines; engine test rig setup; cylinder pressure levels, noise levels; PSD plots for cylinder pressure signals, PSD plots for cylinder noise signal, PSD plots for cylinder pressure derivative signals for 1600, 2000 RPM; in cylinder pressure spectrogram at 1600 RPM, 100% load; motored cylinder pressure spectrogram at 1600 RPM; cylinder pressure and noise emission spectrograms; piston slap noise emissions, valve noise emissions and valve noise emissions spectrograms; and correlation between cylinder pressure and radiated noise levels are presented in the paper.

Keywords*: diesel engine noise, acoustics, vibrations*

1. Introduction

Demands for improvements in engine efficiency have been aimed at reduction of fuel consumption as well as emissions. Control of injection parameters is a key strategy of Noise control based on the information provided by speed, torque, vibrations and acoustics measurements [1-6]. Analysis of combustion has been carried out using vibration measurement techniques as discussed in [7]. A six Cylinder engine has been tested in order to sense combustion faults in [8]. The noise emitted from engines is dependent on type of combustion process as well as structure of engine. There are several sources that contribute towards the engine noise e.g. piston slap, oil pump noise, valve noise, flow noise etc. [9]. In diesel engines, combustion noise is due to sudden pressure rise in the combustion chamber due to fuel injection.

In [10] a method using Spectro-filters has been presented to separate the combustion noise from mechanical noise. The acoustic emissions recorded from engine are dependent on the position of transducer. Hence, location of transducer is a key issue for recording acoustic data. Knock features of engine are determined by auto ignition of portion of gas during combustion. This sudden combustion gives rise to shock wave causing resonance of combustion chamber. Knocking occurs when the energy content in resonance frequency band exceeds threshold value [11]. A more effective method to utilize the acoustic data obtained is by use of time-frequency analysis, which uses simple Fourier transformations as depicted in [12].

In diesel engines, the study of combustion chamber structure can also reveal in sight about injection process. In [13] effects of different injection profiles have been discussed on engine oscillations. Scholl et al have used Finite element analysis to study shapes of acoustic modes of two spark ignition engines [14]. Ren et al have showed that the frequency ranges of noise radiated from engine can be divided into three zones[15].This work investigates the effects of load and various injection parameters on engine condition monitoring conditions e.g. in cylinder pressure and noise distribution form engines.

2. Background

Due to high efficiency, diesel engines have been a favourite choice for heavy-duty applications including trucks .However they suffer from drawbacks of high noise, weight and vibrations. These engines are of two types:

1. Direct Injection (D.I.) Engines,
2. In direct injection engines.

In the D.I. engines, the fuel is directly injected inside combustion chamber and due to lesser time for mixing, a heterogamous mixture consisting of both rich and lean parts is formed in the chamber.

Modern diesel injection systems use multiple injection process to control emissions like soot and Nitrous oxide (NOx) formation. These generally use three phases of injection namely pre-injection Period, Main –Injection Period & Post injection period as seen from Fig. 1.

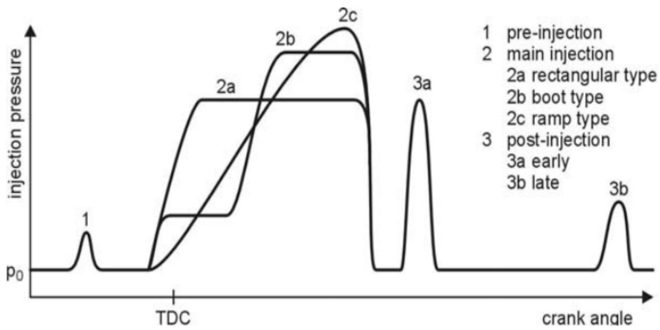

Fig. 1. Multiple Injection Process in Diesel Engines

There is delay period between the start of ignition process and fuel injected inside diesel engine. More this ignition delay more is the temperature during combustion and hence better condition for NOx formation. To shorten the delay period, small amount of fuel is pre-Injection before main injection during the phase pre-Mixed combustion phase. The torque and power produced in engine depends upon main injection period. It is advantageous to vary injected fuel mass with time to reduce the specific fuel consumption. This method is known as rate shaping as depicted in Fig. 1. Rate shaping may be rectangular, step or boot in shape. Post-injection of fuel is done to reduce soot emissions and in some cases may be useful for Exhaust gas recirculation treatment of gases [16]. It has been reported that post injection reduces soot by about 70% without increasing the fuel consumption [17].

3. Experimental setup

The Lombardini LDW442CRS common rail double direct injection engine system was used to conduct tests. This engine has specifications as given by Tab. 1.

Tab. 1. Engine Features

Type	Direct Injection
Number of Cylinders	2
Bore	68 mm
Stroke	60.6 mm
Displaced Volume	440 cm^3
Compression Ratio	20:1
Maximum Power	8.5Kw@4400 RPM
Maximum Torque	25 N-m @2000 RPM

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. A Bruel and Kjaer free field microphone of 4939 type with a 2670 type preamplifier was used to obtain noise signals. This engine test rig has a piezo electric type Kistler 6056A make pressure transducer for in cylinder pressure measurements and an optical crank angle encoder of AVL 364C make for detection of Top dead Centre (TDC) position as well as engine speed. The given system can do maximum of 2 injections per cycle. All signals were simultaneously acquired by NI boards of 6110 type (for analog type) & 6533 type (for optical encoder signals) using Lab VIEW 10 software. During the tests, the sampling rate was varied in order to guarantee a resolution of 0.25° Crank angle degree (CAD). The engine was operated at speeds of 1600 revolutions per minute (RPM) & 2000 Revolutions per minute (RPM)under both fired and motored conditions and the data acquired is represented in Tab. 2. Signals were found to be contaminated by surrounding environment. Hence a grid was built around the engine to allow microphone to be located at fixed positions from the engine.

Fig. 2. Engine Test Rig with Microphone

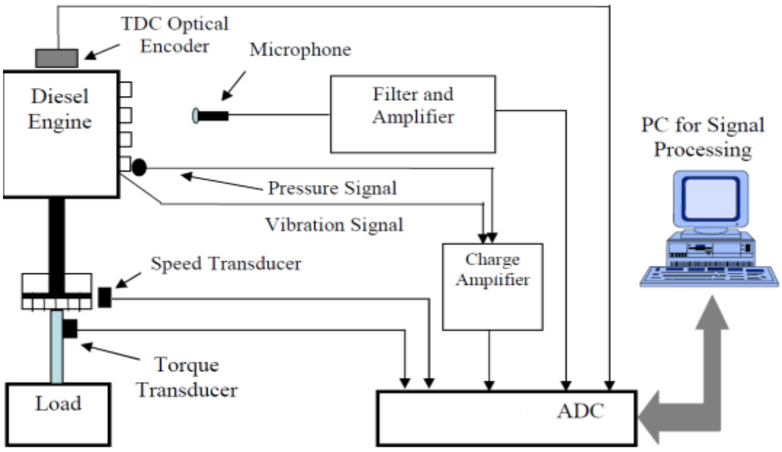

Fig. 3. Engine Test Rig Setup

4. Results

The injection strategy used for the tests is that of dual injection method having Pre and Main injection Periods before piston reaches Top dead centre position during the compression stroke. The amount of fuel injected during pre-injection period is denoted by Q_{pre} whereas amount injected during main injection is denoted by Q_{Main}. The instant at which these injections start are defined by positions of piston in terms of crank angle degrees before it reaches top dead centre position during compression stroke. For the given two injection periods, these are defined by SOI_{pre} & SOI_{main} Positions. The fuel is injected inside cylinders through a common rail system at a pressure of P_{rail} expressed in Bars. Tests were conducted at motored and full load conditions varying the crank angle positions of fuel injected.

Tab. 2. Testing Conditions

CASE	P_{Rail} (Bar)	Q_{pre} (mm^3/stroke)	Q_{main} (mm^3/stroke)	SOI_{pre} (Degree Before TDC)	SOI_{main} (Degree Before TDC)	RPM	Load
B1	714	1	13	14.6°	6.29°	1600	100%
B2	-	-	-	-	-	1600	0%
B3	710	1	13.8	16.5°	6.29°	2000	100%
B4	-	-	-	-	-	2000	0%

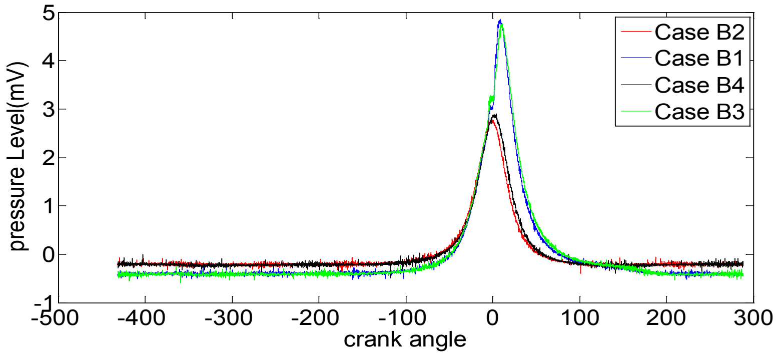

Fig. 4. Cylinder Pressure Levels

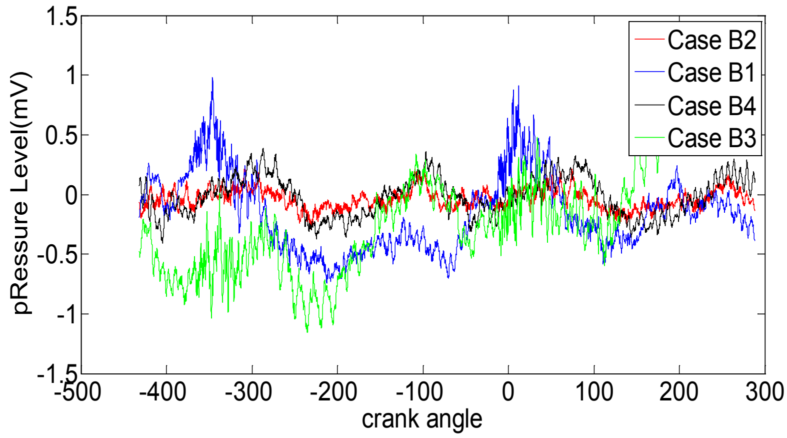

Fig. 5. Noise Levels

Figure 4 and 5 shows the data acquired at 1600RPM & 2000 RPM for both fired and motored conditions. The combustion events in the engine are 360° crank angle apart. The highest-pressure levels were found to be during test 3 due to largest amount of fuel injected.

The power spectral density (PSD) of a random process provides the frequency composition of the data in terms of the spectral density of its mean square value. The mean square value of a sample time-history record, in a frequency range ω and $\omega + \Delta\omega$, can be obtained by passing the sample record through a band pass filter with sharp cut-off features and computing the average of the squared output from the filter. The average square value will approach an exact mean square value as $T \rightarrow \infty$.

$$\Psi^2 = limit\ \Delta x \to \infty \frac{\int_0^T X^2(t,\omega,\Delta\omega)\,dt}{T}, \quad (1)$$

where $x(t, \omega, \Delta\omega)$ is the portion of $x(t)$ in the frequency range ω and $\omega + \Delta\omega$.

Power spectrum plots of in cylinder pressure signals acquired were plotted at full and motored conditions. In low frequency range, the spectrum of cylinder pressure PSD plots depends upon peak pressure and integral of pressure curve. In middle frequency, range depends upon pressure rise rate whereas during high frequency ranges peaks are due to rapid pressure rise. Peaks were found in spectra at frequencies, which were integral multiples of fundamental firing frequency. These plots high lite that main change due to firing of fuel inside cylinder occurs at 300 Hz Frequency. Hence, all the combustion events must be considered above this frequency.

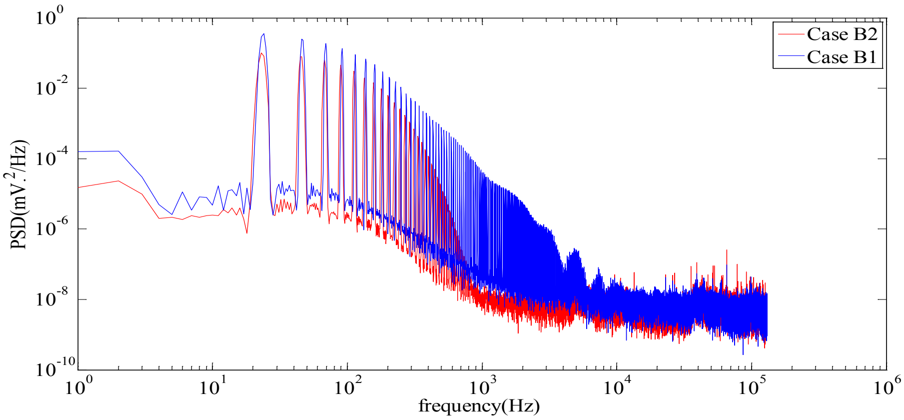

Fig. 6. PSD plots for Cylinder Pressure Signals (1600 RPM)

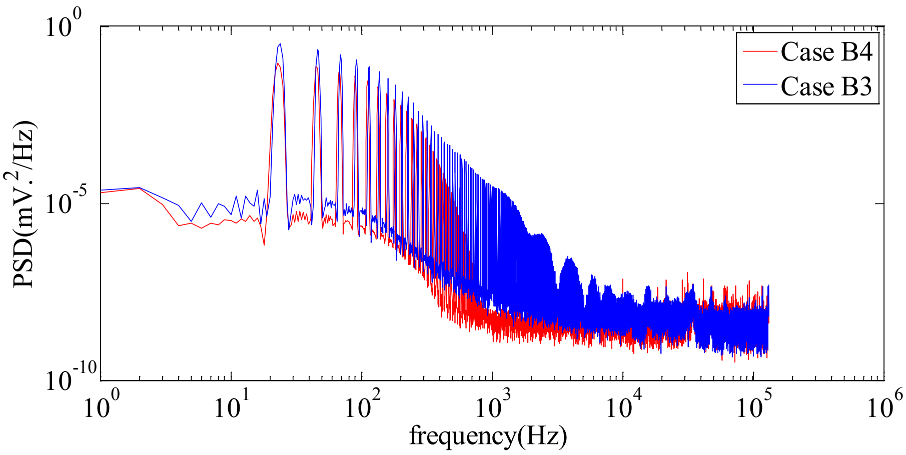

Fig. 7. PSD plots for Cylinder Pressure Signals (2000 RPM)

Once the excitation source for combustion noise has been characterized, the radiated noise was investigated to understand relation between signals. Fig. 8 and 9 show the PSD plots for Noise signals acquired both at motored as well as fired conditions. It can be seen that contribution of combustion process towards noise emissions occurs at wide frequency bands compared to cylinder pressure spectrum. This may be due to several non –linear paths of noise propagation through engine as depicted in [18].

Since the acoustic power radiated from engine depends upon block velocity, the velocity of in cylinder pressure evolution represents the combustion source. PSD plots of this parameter for given testing conditions were plotted as seen from Fig. 10 and 11. It is clear that the region 2 corresponding to medium range begins after 100 Hz for the given testing conditions.

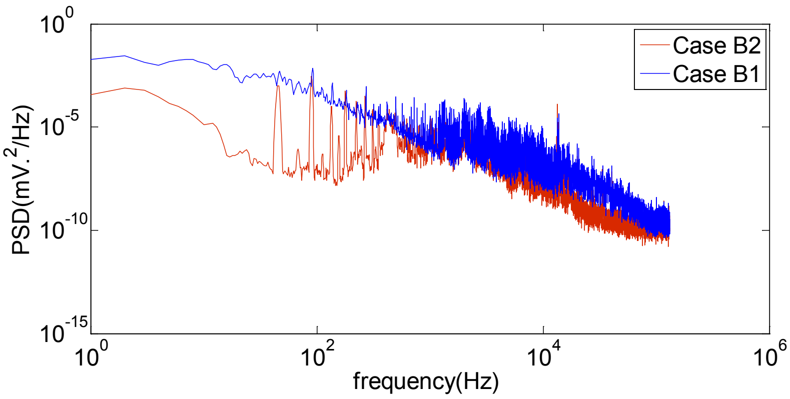

Fig. 8. PSD plots for Cylinder Noise Signals (1600 RPM)

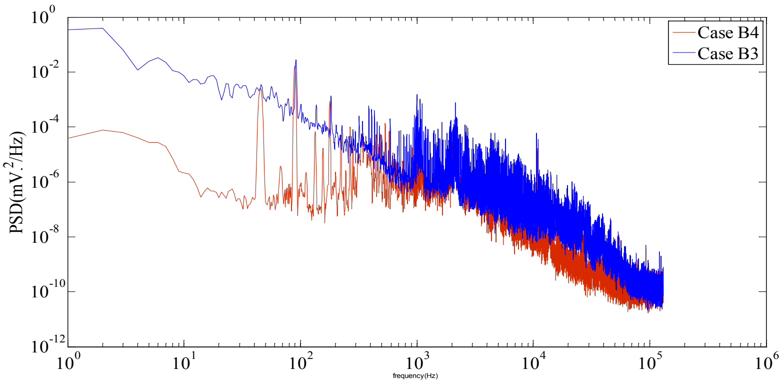

Fig. 9. PSD plots for Cylinder Noise Signals (2000 RPM)

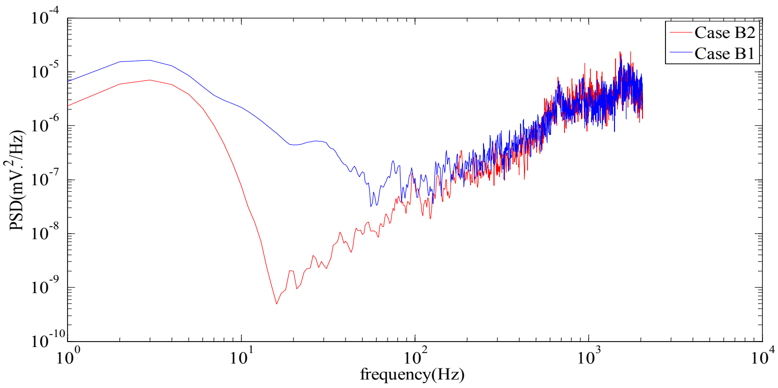

Fig. 10. PSD plots for Cylinder Pressure Derivative Signals (1600 RPM)

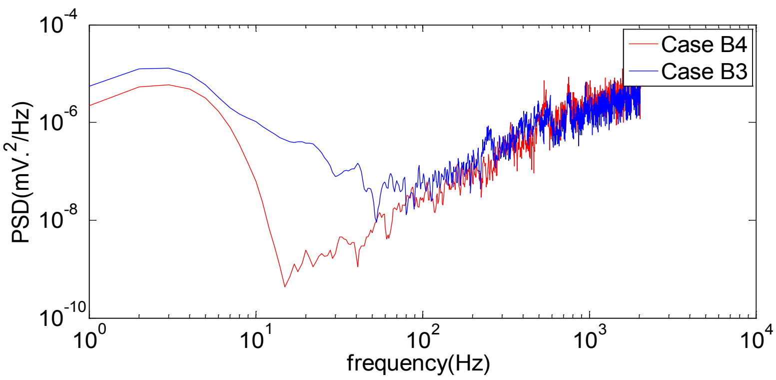

Fig. 11. PSD plots for Cylinder Pressure Derivative Signals (2000 RPM)

Fast Fourier transformations were introduced by coolie and Turkey which transform signals from time domain to frequency domain by breaking signals into sinusoidal waves. These can be represented in both continuous as well as discrete forms by following equations:

$$X(f) = \int_{-\infty}^{\infty} x(t)\, e^{-j\omega t} dt, \tag{2}$$

$$X(e^{j\omega}) = \sum_{n=-\infty}^{n=+\infty} x_n e^{-j\omega n}. \tag{3}$$

Transforming these back to time domain we have:

$$x(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} X(\omega) e^{j\omega n} d\omega, \tag{4}$$

$$x_n = \frac{1}{2\pi} \int_{-\infty}^{+\infty} X(\omega^{j\omega}) e^{j\omega n} d\omega. \tag{5}$$

However, information is lost in this transformation. Hence Short Fourier-Time Transformations are used which computes Fourier transformation of a signal within a window. This can be written in form of equations as:

$$y\,(t)=x(t)w(t), \tag{6}$$

$$y[n]=x[n])w[n]. \tag{7}$$

Taking inverse transformation into frequency domain, we have

$$X(\tau,\omega) = \int_{-\infty}^{+\infty} x(t)\, w(t-\tau)\, e^{-j\omega t} dt, \tag{8}$$

$$X(n,\lambda) = \sum_{n=-\infty}^{n=+\infty} x[n+m]\; w\,[m]\; e^{-j\lambda m}, \tag{9}$$

where w[n] is a windowed sequence and w(t) is wave form.

This method provides constant resolution in both time as well as frequency domains, however window size cannot be made small beyond certain limits.

In order to get information about time distribution of spectral energy, short time frequency Fourier transformation using spectrogram command was computed for both noise levels and in cylinder pressure at full load & motored conditions for the given test condition of . The results obtained can be seen in Fig. 12-19.

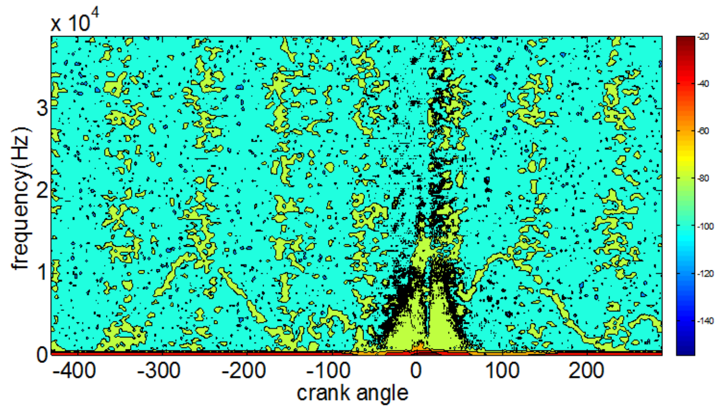

Fig. 12. In Cylinder Pressure spectrogram at 1600 RPM, 100% load

These plots reveal the contribution towards frequency domain of fuel injection and combustion process. Comparison of these noise spectrogram plots show broadening of frequency bands near Top dead centre position showing initiation of combustion events. In addition, the contribution of various sources towards overall noise levels is depicted in Fig. 20-22. It is evident from these contour plots that piston slap contributes higher towards noise frequency ranges compared to other motion based noise sources e.g. valve operation, injection events etc.

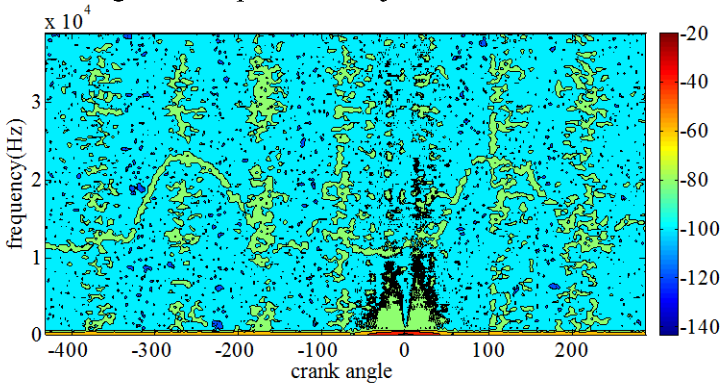

Fig. 13. Motored Cylinder Pressure spectrogram at 1600 RPM

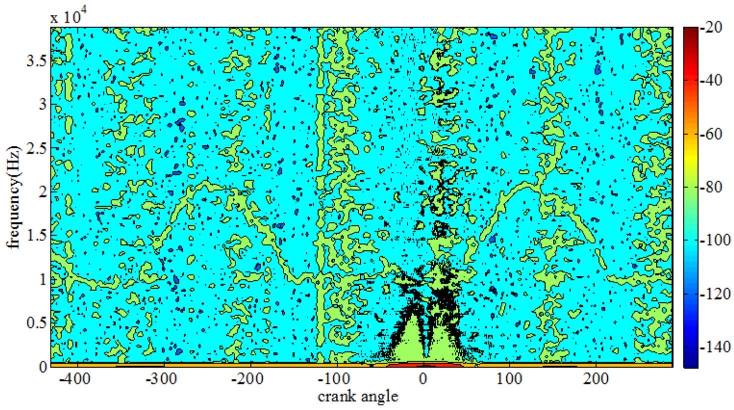

Fig. 14. Cylinder Pressure Spectrogram at 2000 RPM, Motored

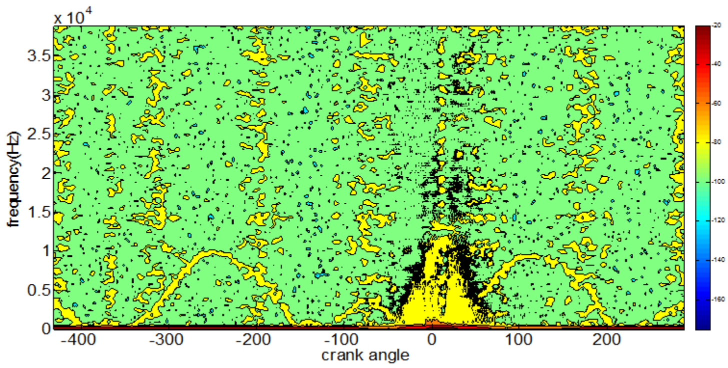

Fig. 15. Cylinder Pressure Spectrogram at 2000 RPM, 100% load

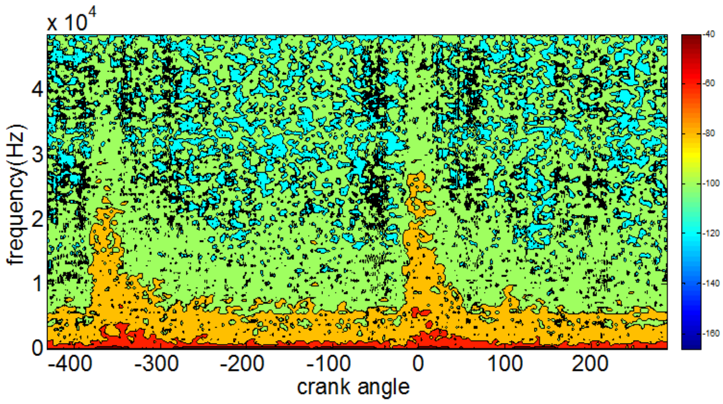

Fig. 16. Noise Emissions Spectrogram at 1600 RPM, 100% load

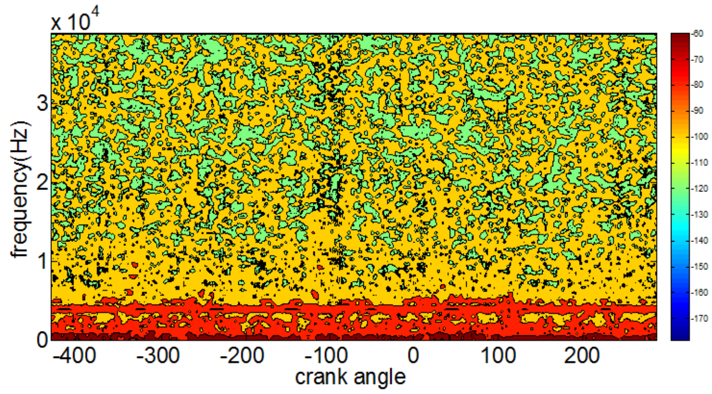

Fig. 17. Motored Noise Emissions Spectrogram at 1600 RPM

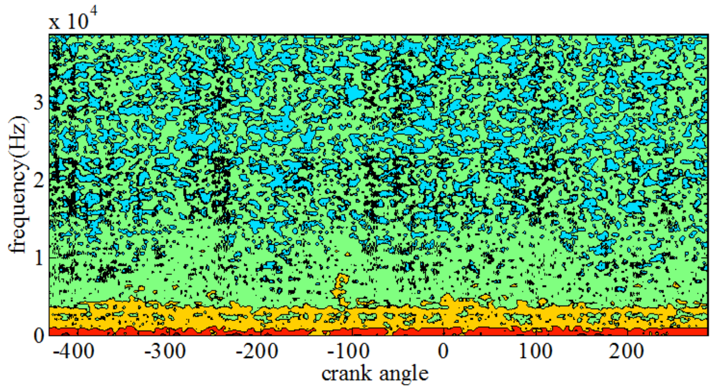

Fig. 18. Noise Emissions Spectrogram at 2000 RPM, Motored

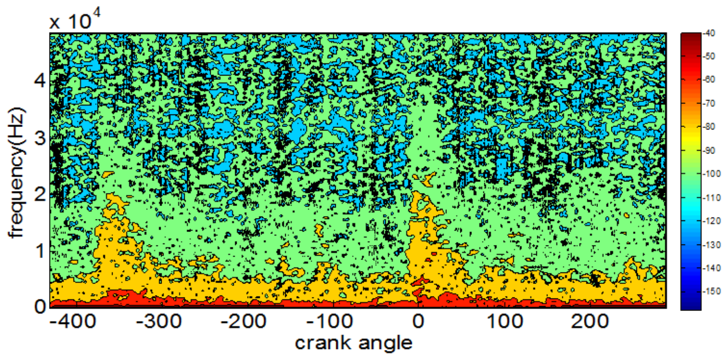

Fig. 19. Noise Emissions Spectrogram at 2000 RPM, 100% load

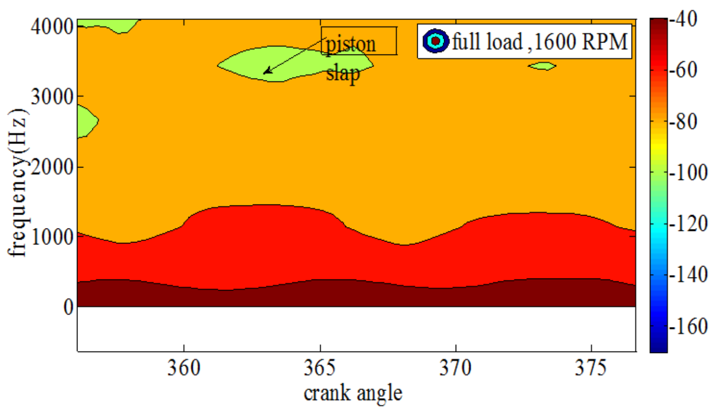

Fig. 20. Piston Slap Noise Emissions Spectrogram at 1600 RPM, 100% load

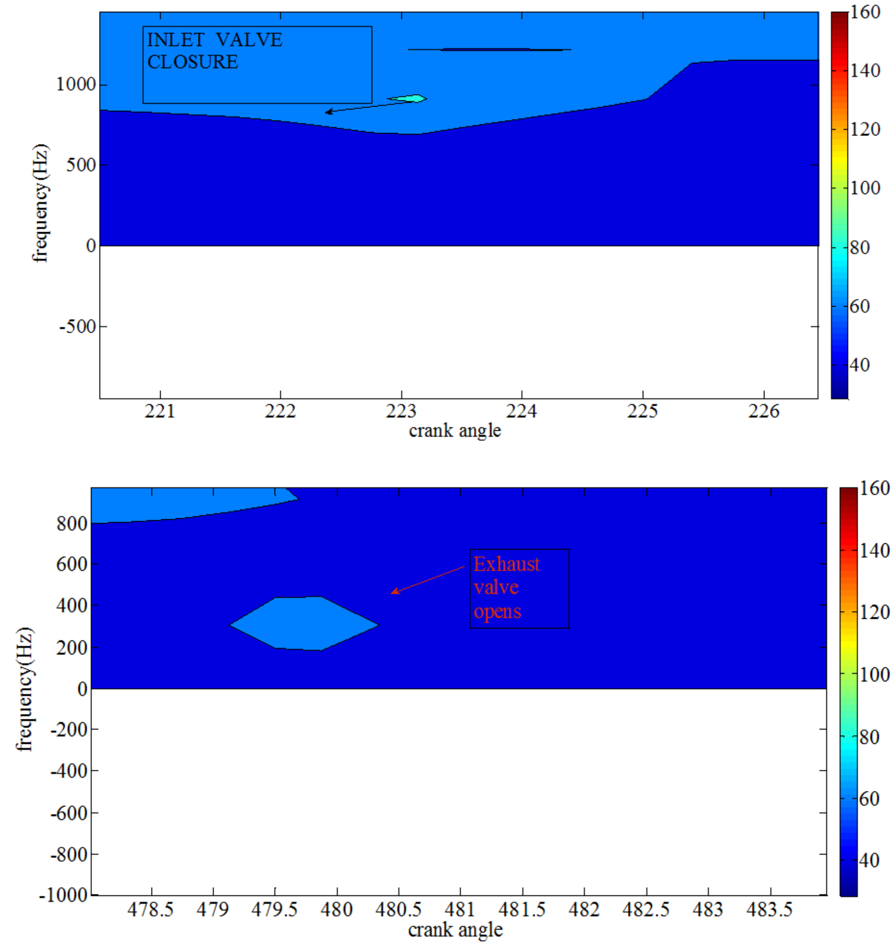

Fig. 21. Valve Noise Emissions Spectrogram at 1600 RPM, 100% load

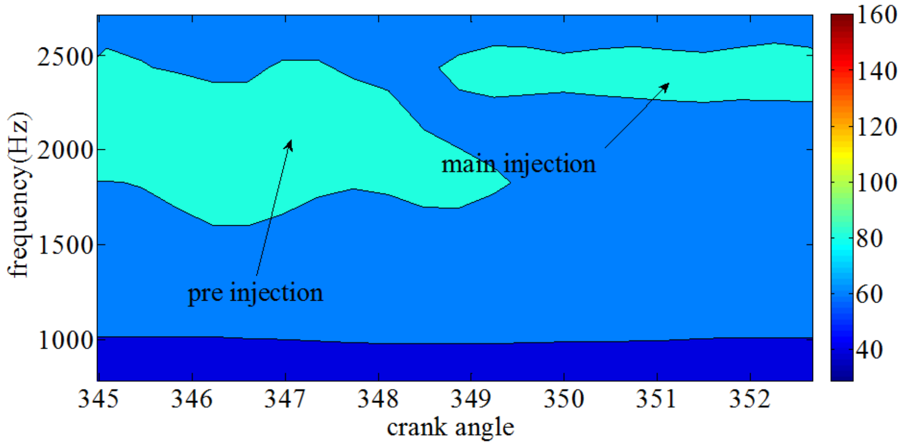

Fig.22. Injection Noise Emissions Spectrogram at 1600 RPM, 100% load

5. Conclusion

This work investigated the effect of changing injection parameters on noise emissions and combustion pressure. Noise emitted from engine depends on the quantity of fuel injected inside cylinder. Various ranges of noise signals sources were identified. Time-Frequency analysis showed the onset of combustion events. Based on the identification of various frequency bands it is possible to filter the noise to extract more information about combustion and motion based noise events for detailed analysis. Based such band observed from spectrogram plots of noise emissions are above 300 Hz in which combustion events is concentrated. Based on high pass filtering technique the noise and cylinder pressure signals for testing condition B1 were filtered in this band and a strong correlation was found between the two signals as depicted in Fig. 23.

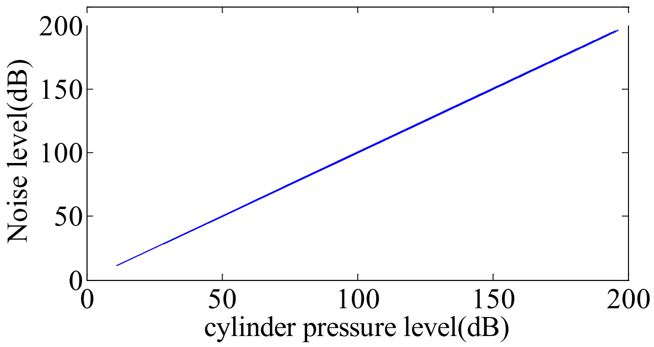

Fig. 23. Correlation between cylinder pressure and radiated noise levels

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