Knock Recognition System in a PCCI Engine Powered by Diesel

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Abstract. The measurement of engine vibrations components is used to identify combustion phases in a single-cylinder PCCI diesel engine in this work. A single channel Knock transducer was used to measure engine vibration caused by combustion pressure forces and knocking tendency. The transducer is used to obtain the engine's frequency spectrum in the temporal domain. Categorization discrete wavelet analysis is used to isolate the observed vibration data. Spectral analysis and filtration of fragmented sections of the source signal are used in this approach. Fast Fourier transforms (FFT) and short-time Fourier transform (STFT) are used to investigating the discrete parts of the observed signals (STFT). In order to study engine events, time is given in milliseconds in the time-frequency domain. The engine knocking is determined from the observed signal using time-frequency analysis. The outcomes reveal that the engine events derived from vibration signals are closely connected to the premixing fuel ratio, as expected.

Keywords: Fast Fourier Transforms (FFT); PCCI Knocking Tendency; Cylinder Vibration-time Signal.

1. Introduction

Direct injection (DI) Internal combustion engines have been the predominant common power option in public transportation in Africa in recent years. Diesel engines, on the other hand, are not immune to some issues, such as significant nitrogen oxide (NOX) and soot emissions, excessive noise, and the use of enormous amounts of fossil fuels. In terms of this latter point, the use of new technologies looks to be a viable option for reducing reliance on traditional engines [1]. Compression ignites low-temperature combustion (LTC) of the premixed charge of oxidizer and fuel by elevating the engine piston throughout the compression stage [2]. LTC approaches have the capacity to reduce NOx and soot emissions while also improving brake thermal efficiency (BTE) [3]. Premixed charge compression ignition (PCCI) or homogeneous charge compression ignition (HCCI) is a strategy of attaining general lean combustion in which the premixed charge is supplied ahead of the initiation of combustion. HCCI, on the other hand, has distinct flaws such as limited operational ranges, difficulties controlling combustion phase, cycle to cycle instability, and cold start, heavy load operating causing the knocking phenomenon, and significant CO and UHC emissions [4].

Several issues, such as mixture preparation and combustion phases management, as well as knock, can harm the engine and cause intense vibration [2]. These features make the use of this sort of combustion more difficult. The employment of a precise control system for port injection has sparked a great deal of interest in advanced diesel combustion in recent years as a way to minimize combustion knocking [5, 6].

In the PCCI ignition concept, the fast pressure rise caused by quick heat release in the homogeneous mixture leads the combustion chamber pressure to ring at particular specific frequencies. The ring frequency is determined by the combustion chamber shape as well as the sound velocity in the burning products. The cooling of the consumed gases gives a distinctive signature with decreasing frequency as the piston travels in the expansion stroke. The most frequent approach to evaluating the strength of a knock occurrence is to detect acoustical or structural vibrations at the knock frequency. Although in-cylinder pressure transducers are efficient knock detectors, their usage in commercial engines is typically limited due to expense and reliability problems. Interestingly, the knock waves in-cylinder pressure cause cylinder block vibrations. This permits an accelerometer calibrated physically or autonomously to the knock frequency band from the exterior of the engine block to measure knock.

The major focus of this research is to conduct an investigation of the combustion features, and functionality of a diesel engine using the PCCI combustion and premixed chamber injection system in an experimental setting. A conventional diesel engine was converted to function under the PCCI combustion approach for this goal, keeping in view the operational circumstances where this approach is more effective for decreasing NO_x and CO_2. To measure quantitative and qualitative features of combustion noise, a unique approach based on the fragmentation of the cylinder vibration signal was applied. The experimental setup and diagnostic equipment utilised are explained in the next section. The methods employed to conduct the research is then outlined in Section 3. The outcomes for combustion vibration are addressed in Section 4.1, and for spectral investigations, FFT is used to analyses the engine's vibrational characteristics. Sections 4.2 and 4.3 provide and analyse pollution levels and performances, respectively. In section 4.4, the ringing strength and combustion noise are investigated at multiple premixing percentages. The last section focuses on using the spectrum analyser as a diagnostic technique to offer detailed insights into the identification procedure of the knock recognition system. Finally, Section 5 summarises the key findings of our research.

2. Experimental Setup

2.1 Engine and Laboratory Equipment

In all of the experimental test findings, a single-cylinder diesel engine "DEUTZ FL 511/W" with a high-pressure direct fuel injection system was employed. It had a 100 mm diameter, a 105 mm stroke, and a 17:1 compression ratio. The essential engine information is listed in table 1, and the experimental arrangement is shown in figure 1.

Table 1. Engine specifications

Engine type	Single-cylinder, 4-stroke, CI diesel engine
Cylinder diameter (mm)	100
Stroke (mm)	105
Displacement (cm^3)	825
Compression Ratio (CR)	17:1
Rated power	6.8 kW @1500 rpm

A port injector (PI) installed in the premixing chamber injects the diesel. An attached injector was fitted on the test cylinder head with an independent fuel delivery system. The two injection systems were controlled by two distinct electronic control units (ECUs). As a consequence, two test fuels' injection timing, fuel split ratio, and fuel splitting amount may all be precisely regulated. The experiments allow for instant measurement of cylinder vibration, and regular and irregular gaseous emissions. The cylinder vibration observations were carried out with the help of an FAE cylinder knock detector and a piezoelectric ring for conveying vibrations from the cylinder block. An electromagnet dynamometer is used to monitor engine torque and speed. The cylinder vibration was recorded for each operational status while the cylinder vibrations were collected for 1000 successive cycles. The instantaneous fuel consumption indicator monitored the fuel mass flow out of each injector independently. A Coriolis-Effect flow rate metre is also used to determine the mass of incoming air. The premixing chamber is kept at a temperature of roughly 115°C.

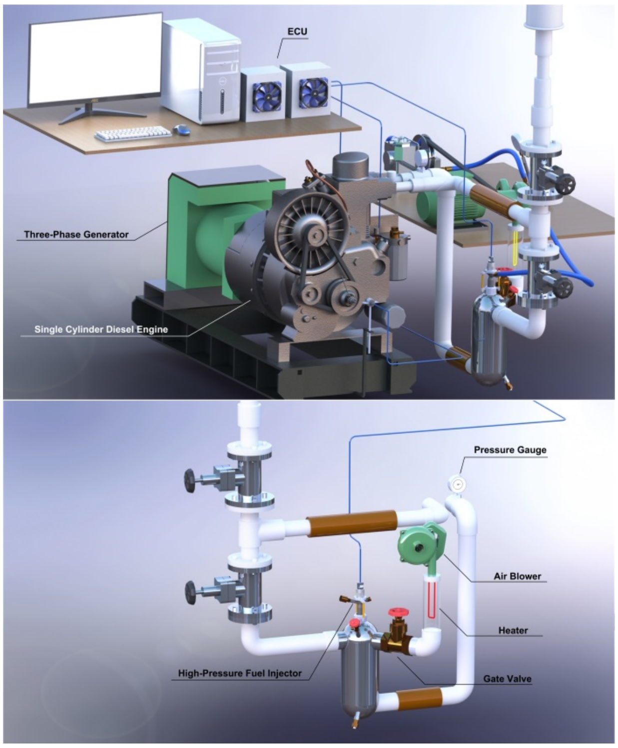

Fig 1. Three-dimensional illustration of the engine lab setup.

2.2 Monitoring Vibratiotions Method

Vibration data were acquired at two modes of engine operation, conventional compression ignition (CCI) and PCCI. The knock sensor, which was employed to monitor vibration, is shown in figure 2. The knock detector is mounted on the engine block and monitors and converts the pinging induced by the knocking action into an analogue signal. Based on past experimental activities, the best positioning for the transducer was chosen because it ensures high sensitivity to the combustion process while having a low sensibility toward other mechanically induced vibrations.

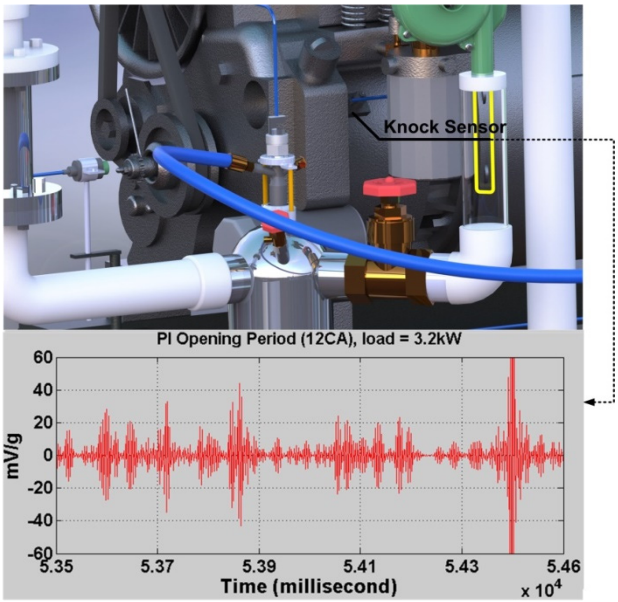

Fig 2. A set up for engine vibrations measurement (above) and sample of time domain signal for PCCI mode (below)

Before the fuel exceeds the knock threshold, the control module compares the signal to the values contained in the standard and intervenes to manage the engine, fuel injection, and ignition to the degree needed. Because of the availability of such a technology, the engine may operate closer to the boundaries of controllable burning, resulting in improved non-conventional engine capability. Time-domain vibration signals were saved in mentioned sampling frequency for recording time of 3 s. Numbers of samples were 100,000. For acquiring vibration signals of the engine, a knock sensor with specifications of FAE – (sensitivity15 mV/g) was used. This high accurate transducer is used to measure frequencies from 1 up to 20 kHz. Figure 2 shows a section of the acceleration-time domain filtered signal on the engine in high load conditions in PCCI operation. This signal is for the conditions engine speed of 1500 rpm. The combustion cycles are observed in this figure. For more resolution of combustion, the signal was passed through a high pass filter. Figure 2 shows the filtered signal that combustions in engine are clearly visible. The data was recorded on a laptop computer. For data acquisition, signal analysis, such as filtering, and the Fast Fourier Transform, LabVIEW and MATLAB software were utilized. The frequency-domain data analysis enabled the extraction of components most relevant to combustion occurrences.

3. Time Frequency Analysis

Filtering for engine structural oscillations and A-weighting were used to Fast Fourier Transform (FFT) of cylinder vibration–time signals to accomplish the interpretation of the vibrations data obtained by the transducer. These filters' specifications may be found in [7], accordingly. The signal's FFT was calculated utilizing the following equation;

$$X(k) = \sum_{n=1}^{N} x(n)e^{(-i2\pi nk)/N} \tag{1}$$

n = 1,2, 3... N terms, where x(n) represents the discrete data and n denotes the number of samples obtained. Where k=1, 2, 3,...N terms. Equation 2 gives the STFT of the same signal x(n). The window function is W(n), and the discrete frequency variable is (m).

$$S(k,m) = \sum_{-\infty}^{\infty} x(n)W(k-n)e^{(-i2\pi nk)/N} \tag{2}$$

4. Test Methodology and Target Conditions

Commercial diesel is employed as a high reactive fuel throughout this study. During the intake stroke, premixed diesel is injected into the premixing chamber while the injection pressure is (15MPa). Diesel is sprayed directly into the cylinder at high pressure (30MPa). The compositional details of diesel are shown in table 2.

Table 2. Diesel fuel properties.

Fuel	Diesel
Molecular formula	C12-C25
Octane number /RON	0
Oxygen content (wt%)	0
Density(kg/l)	0.845
Low heating value(MJ/kg)	42.5
Enthalpy of vaporization (kJ/kg)	0.27

By altering the fuel premixing ratio, the port injection opening period, Dur PI (°CA), provides for more exact cylinder charge stratification than is possible with standard injection systems. This injection strategy ensures that the amount of premixed diesel entering the cylinder is controlled and reliable. Table 3 is a list of the specific operating criteria that must be met. The trials are carried out in one of the following regimens. The engine was run in the first mode using ordinary diesel combustion in the CCI mode. The premixing chamber system is always closed in this mode. The features of combustion are determined as accurately as possible at various loads while maintaining smooth functioning. The PCCI combustion mode, which uses both the premixing charge preparation system and DI powered with normal diesel, is the second mode. The characteristics of combustion are tested at various loads to prevent the knocking phenomena and to capture all of the characteristics.

Table 3. Port injection experimental conditions for PCCI mode

Parameter	Port Injection Opening Period(°CA)			
	0	5	8	12
P_{PI} (bar)	0	150	150	150
Dur PI (°CA)	0	5	5	12
PI mass content (mg/cycle)	0	0.0139	0.0150	0.0160

For the PCCI technique, the time and duration of the port injection were adjusted to achieve varied diesel premixing ratios. The injection interval was changed to control the charge reactivity. The energy content of each diesel injection could be determined using experimental fuel flow measurement, and the injection time was therefore proportional to charge reactivity.

5. Results and Discussion

Time-domain vibration signals were saved in mentioned sampling frequency for recording time of 3 s. Numbers of samples were 100,000. For acquiring vibration signals of the engine, a knock sensor with specifications of FAE – (sensitivity, 15 mV/g) was used. This high accurate transducer is used to measure frequencies from 1 up to 20 kHz. Figure 3 shows a section of the acceleration-time domain filtered signal on the engine in high load conditions in PCCI operation. This signal is for the conditions engine speed of 1500 rpm. It appears that identifying all engine combustion occurrences in the temporal domain as magnitude from the recorded engine vibration signal is possible. Rapid charge spontaneously combustion and pressure wave inside the combustion chamber contributes to the intensity of knocking combustion.

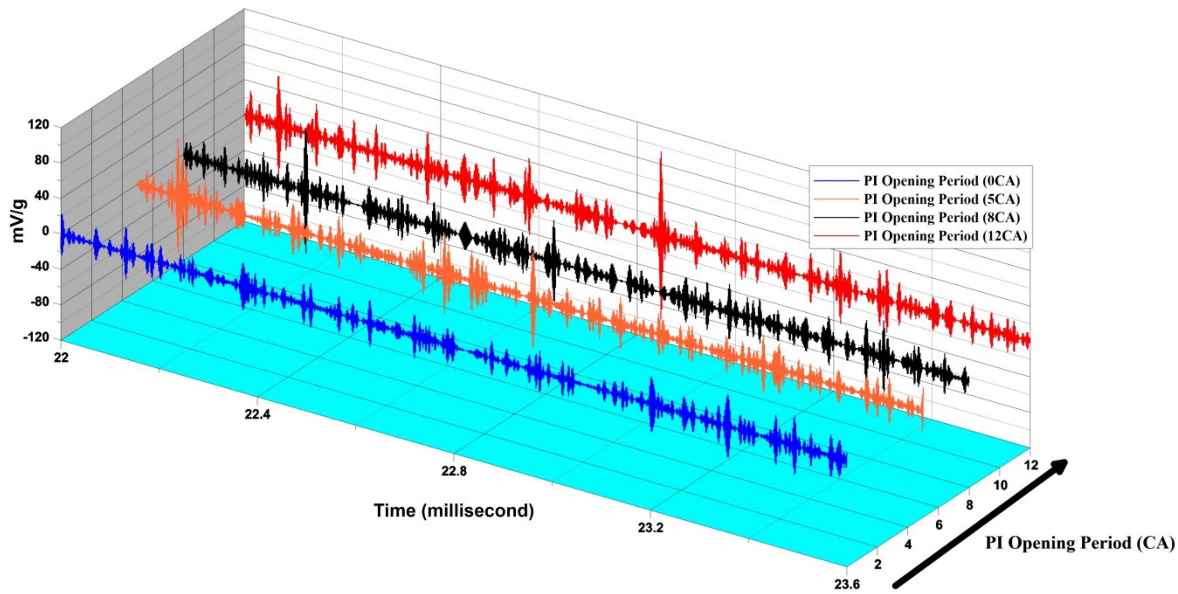

Fig 3. Filtered time domain knock sensor signal for engine at 3.2 kW brake power

For interpreting the reasons for increasing vibration, it could be referred to that; the combustion speed is highly correlated to the acyclic uncontrolled combustions which result in a high temperature inside the cylinder. The above observations show that chemical kinetics and piston compression for the cylinder charge affect auto-ignition time and combustion length in PCCI engines. At higher premixing ratio, the PCCI combustion occurs very rapidly with a high rate of heat release and in-cylinder pressure leading to noise and vibration.

These knock related pressure vibrations can be isolated by filtering and further processed in the time domain. The increasing knock intensity of the cycles from the bottom to the top is indicated by the different amplitudes. It is critical to determine the frequency of the incidents. To do so, the discrete Fourier transform must be used to analyses the signals. The rate of pressure increase is related to the presence of strong frequency signals in combustion noise [8]. In other words, the apex of pressure rise rate is responsible for the majority of combustion acoustic intensity. The maximum magnitude of AHRR and combustion vibration has significant connections [9, 10]. This is illustrated in figure 4, which exhibits cylinder vibration spectral response for all premixing ratio levels related to CCI and PCCI at high load conditions. The data are shown as a graph having frequency on the horizontal dimensions and dB on the perpendicular axis. The vertical axis represents the component intensity, which is indicated in decibels (relative dB). In the spectral analysis, the knock modes, such as those with high energy content, are highly influenced by changes in the premixing charge.

The first cavity mode (16Hz) responds with its amplitude to knock most intensively. But typically, the higher harmonics are responsible for the excitation of structural vibrations and thus can serve better for knock detection. The resonance frequencies depend on the dimensions of the combustion chamber and on the sound velocity of the cylinder charge. For simple cylindrical chamber geometries, the frequency calculation procedure is easy.

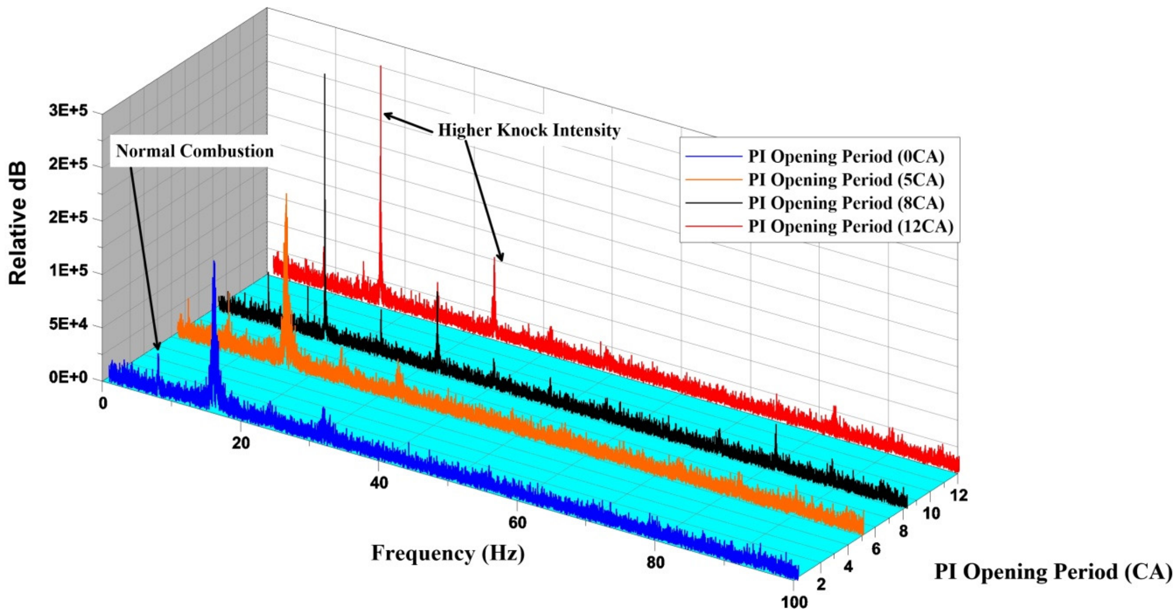

Fig 4. Cylinder pressure spectra of knocking combustion cycle.

Knock detection reliability is improved by evaluating knock strength using a squared structural vibration signal. Figure 5 depicts the difference in knock strength between the two levels: integration of squared and rectified signals in a predetermined time window. It is clear that a higher amount of premixing ratio results in a stronger knock signature. When in-cylinder pressure shock waves occur, the knock-related structural vibration pattern often begins promptly with high amplitudes. The knock-induced high-frequency cylinder vibration also exhibits this property (see Figure 3).

The best way to show knock behavior under various knocking engine circumstances is to advance the ignition timing. On the basis of cylinder vibration signals, the effect of auto-ignition advance on the knock intensity of subsequent combustion cycles is indicated. A few knocking cycles arise stochastically at the knock boundary ignition time. To obtain the efficiency benefits of improved ignition timing without risking damage to the engine, a controller must recognize the threshold level.

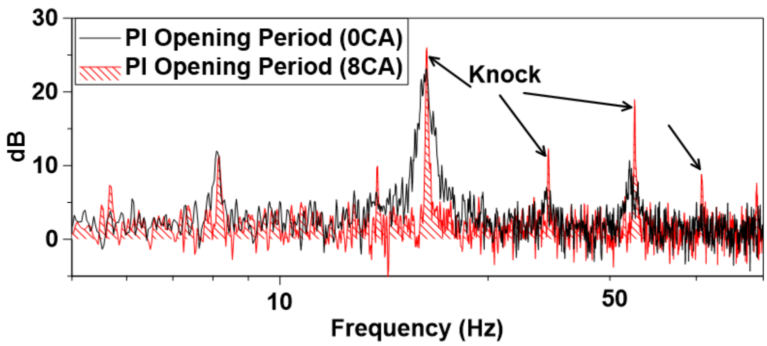

Fig 5. Correlation of cylinder vibration energy at non knocking, knock borderline and heavy knocking engine condition

6. Conclusion

In a DEUTZ F1L511, one cylinder diesel engine, vibrations were tested in conjunction with normal diesel combustion. Port fuel injection (PI) was used to create the premixed charge, while direct injection (DI) was used to create the conventional diesel charge. Comprehensive engine testing was done to see how different factors affected PCCI ignition, pollutants, and efficiency. The significance of PCCI concept is demonstrated and contrasted to CCI combustion, with the following summary:

- To separate the elements mostly linked to the combustion activity from the knick transducer signal, an appropriate high-pass filter was constructed.
- The premixing ratio affects the combustion related vibrations; as premixed content in the cylinder increases, the quantity of sharp combustion increases due to the high level of charge homogeneity. Thus, the ignition delay is reduced as well as the pressure rise rate during early stage of combustion.
- Accelerated oxidation of the fuel/air combination was caused by the premixed charge. PCCI combustion results in accelerated combustion, which shorten combustion duration and, as a result, marginally lowers combustion efficiency.

These findings are exciting because they motivate researchers to look into diesel-fuelled PCCI engines for improved dependability and effectiveness. In a summary, this research will add to the current premixed charge combustion information in a diesel engine (PCCI mode) by revealing the vibrational and ignition properties of the PCCI engine.

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