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Condition Monitoring of a Small Four-stroke Petrol Engine using Vibration Signals

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Abstract

This paper concerns with condition monitoring method of a small, four-stroke, petrol engine using vibration signal based on time domain and crank angle domain analysis techniques. Acquired vibration signals on the engine can be used to study engine processes and abnormal conditions in the engine cycle such as intake/exhaust valve operations, ignition process, combustion process, etc. In this study, vibration signals were used to study mechanical and fluid flow processes in the engine cycle. Vibration signals were applied to monitor abnormal conditions of intake/exhaust valve clearances and spark plug gap and also can be possible to develop to monitor more complex small to large petrol engines.

Keywords: condition monitoring, vibration signals, fault condition, intake/exhaust valve clearances and spark plug gap

1. Introduction

Condition monitoring technology for diesel engines has been developed in recent years. Diesel engine manufacturers and third-party vendors have developed engine monitoring techniques to determine performance of diesel engine operation. A typical monitoring system is applied microprocessor based instrument with analysis software to monitor engine combustion characteristics, intake/exhaust valve operation, piston motion, cylinder and liner conditions. Measurement techniques using non-intrusive sensors (i.e. accelerometer, microphone, etc.) provide information in time domain and frequency domain. These information related engine processes can be used to identify existing or impending problems by comparing detected deviations between a normal condition and an achievable condition in the engine cycle [1-10]. A

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challenge of the engine monitoring system used in industry has to face with a large amount of recorded data that acquired using a commercial or an in-house developed software. These data can be analyzed using exist signal processing techniques to reduce number of data and also to obtain some useful information to monitor engine conditions. Typical engine monitoring systems are faced with gathering and interpretation of data from a number of different sources such as maintenance history, vibration analysis, spectrum analysis, logged operating data, inspection data, engine analysis, and oil analysis. Currenly, a condition monitoring system has been developed to integrate techniques to reduce data from various sources that acquired into a centralized system in order that accessible information can be produced for using in a preventive maintenance program.

The mothod for enhancing analysis process is studied in this paper in order to monitor a small, four-stroke, single cylinder, petrol engine using vibration signals. The physical aspects of combustion characteristics of spark ignition engine are crucial performance indicators and are covered in depth using vibration signals and top dead center (TDC) signal. Analysis techniques and data reduction schemes produce measuring parameters that are used to analyse engine states. Vibration signals were acquired from an accelerometer attached on a surface of the cylinder head of the engine using LabVIEW program. These signals were analyzed by using time domain analysis techniques to determine various statistical parameters. Then, the engine states could be predicted. Furthermore, vibration signals detected on a petrol engine are composed of various events that associated with some mechanical and fluid flow processes in the engine cycle. All events are combined to create complicated vibration signals. These signals could be mapped onto various processes associated with intake/ exhaust valve operation, combustion and spark ignition and are described in this study.

2. Signal Analysis

A vibration pattern analysis is the evaluation of vibration signal related to TDC signal and can give a detail of various mechanical conditions in the engine cycle associated with gas leaks or mechanical impacts. The mechanical impacts, such as valve closure, produce sharp vibration amplitudes [1,11-14]. The gas leaks, on the other hand, typically occur over a longer period of time and produce lower amplitudes. In addition, gas leaks are usually affected by changing pressure in the cylinder. Roughness or friction also produces vibration that is characterized by a noisy low amplitude pattern [1,11-14]. The vibration pattern analysis of a four-stroke, petrol engine involves the determination of the presence and absence of expected events associated with the engine processes which occur as a measurable amplitude at a specific time. Abnormal events based on mechanical experience and the maintenance history of the engine operation can be predicted using an engine knowledge. Thus, specific regions of the vibration pattern can be isolated. The potential faults can be identified with the vibration pattern by comparing with a baseline normal condition pattern.

Signal analysis techniques used in this paper were based on time domain and crank angle domain. The analysis techniques were used to describe some useful parameters such as statistical parameters and energy content from acquired vibration signals. All parameters are defined as follows.

Root mean squre (RMS)

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{N} x_i^2}{N}} \tag{1}$$

Variance (var)

$$\mathrm{var} = \sigma^2 = \frac{1}{N}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2 \tag{2}$$

Skewness

$$\mathrm{skewness} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_i - \bar{x}}{\sigma}\right)^3 \tag{3}$$

Kurtosis

$$\mathrm{kurtosis} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_i - \bar{x}}{\sigma}\right)^4 - 3 \tag{4}$$

Energy content

$$E_x = \int_0^t \left|x(t)\right|^2 dt \tag{5}$$

Where, N is a number of data,
x_i is an element of data $x(t)$
$\bar{x}$ is a mean value of data $x(t)$, and
σ is a standard deviation of data $x(t)$.

These analysis methods can be applied to complicated signals. Thus, the mechanical and fluid flow processes in the engine cycle can be described from vibration signals.

3. Experiment

In this study, a small petrol engine was run at normal speed of 1500 rpm with various simulated conditions such as normal, intake/exhaust valve clearance fault and spark plug gap fault conditions. All fault conditions were simulated on the engine. In this work, the engine was a four-stroke, single cylinder, petrol engine (Tiger brand) with capacity of 100 cc. Two signals acquired using LabVIEW program were vibration signal and TDC signal. Vibration signal was detected using accelerometer and TDC signal was detected using proximity sensor given one pulse per revolution.

A schematic diagram of a data acquisition (DAQ) system for monitoring the engine is described in Figure 1. This system consists of an external located accelerometer with a charge amplifier, a TDC sensor, a connecting block, and a DAQ card with in-house developed LabVIEW software installed in a notebook computer. In this study, National Instruments (NI) DAQ card, 12-bit, PCMCIA-6024E was used to acquire and digitize both vibration and TDC signals. Both signals were records with sampling frequency of 100 kHz and saved into files for later analysis. The vibration signal was measured using accelerometer attached on the cylinder head stud of the small petrol engine as shown in Figure 2. An aluminum clamp was used to hold Bruel & Kjaer accelerometer, Model 4371 at the same axis of the engine piston. A proximity sensor was installed to measure one pulse per revolution from the crankshaft of the engine as shown in Figure 2. This TDC signal gave two pulses every one engine cycle which were represented the piston positions at TDC of the power and intake strokes. In the analysis, all parameters were calculated using Equations (1)-(5). Each parameter was averaged over 100 engine cycles.

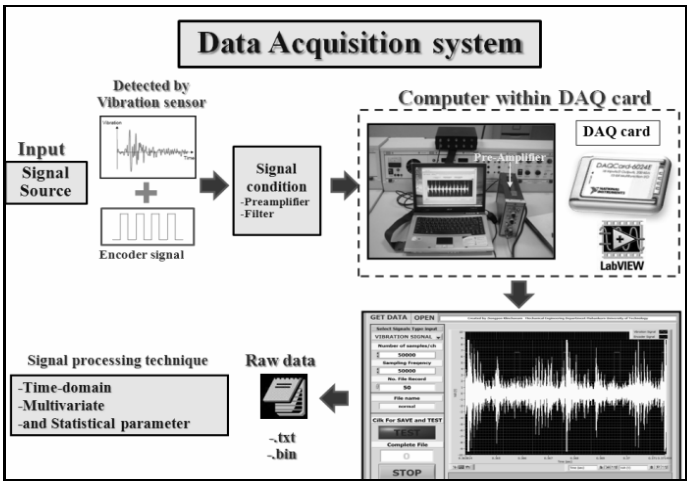

Figure 1 A schematic diagram of a data acquisition system.

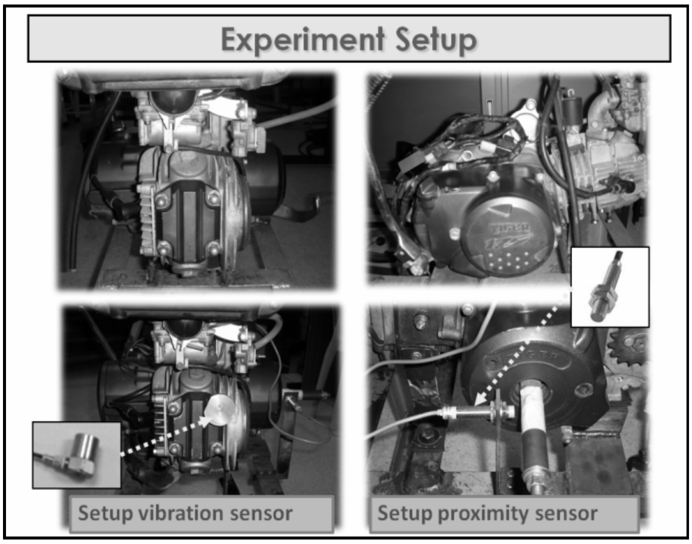

Figure 2 A small four-stroke petrol engine and sensors.

4. Results and Discussion

Typical main four strokes of the petrol engine are intake, compression, power and exhaust strokes as shown in Figure 3. The main mechanical events in the engine cycle are valve opening/closing events of intake and exhaust valves associated with the intake and exhaust strokes, respectively. For the intake stroke, intake valve is approximately opened at 10-20 degrees before top dead center (BTDC) and closed at approximately 51-56 degrees after bottom dead center (ABDC). For the exhaust stroke, the open/ closed positions of the exhaust valve occur at approximately 47-57 degrees BTDC and 15-21 degrees ABDC, respectively [15].

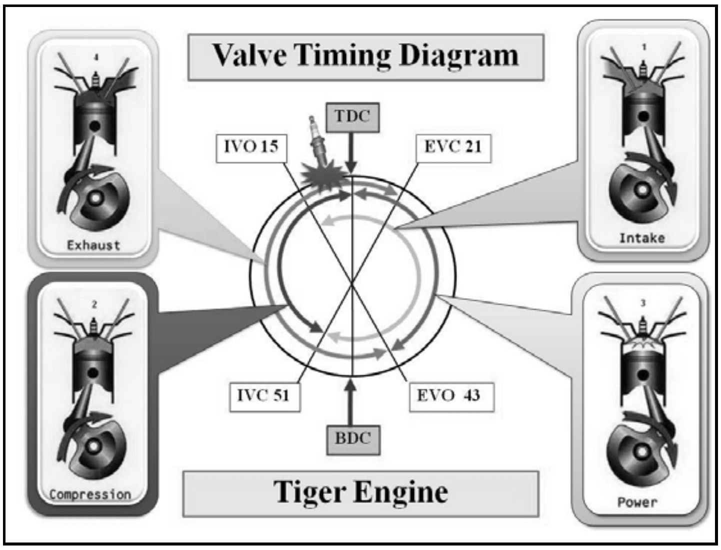

Figure 3 Typical valve timing diagram of a small four-stroke petrol engine.

It is difficult to identify valve timing locations and other valve operations with typical vibration signals. The use of TDC signal can help to eliminate the aforementioned problem. The vibration signals can be mapped onto a crank angle domain using a TDC pulse given one pulse per revolution. Vibration and TDC signals were recorded at engine speed of 1500 rpm with various simulated conditions as shown in Figures 4-7. Amplitude of vibration signal and TDC location are shown on the vertical and horizontal axes, respectively. Crank angle at 0 degree represents piston position at TDC of the intake stroke. All four main strokes as seen in Figures 4-7 are intake, compression, power and exhaust strokes which are associated with crank angle at 0-180, 180-360, 360-540 and 540-720 degrees, respectively. IVO, IVC, EVO and EVC represent intake valve opening, intake valve closing, exhaust valve opening and exhaust valve closing events, respectively. It can be seen that the vibration signals are more complicated and the main valve operation events are the strongest events as shown in Figures 4-7. The vibration signals show other small and unclear events which may come from other sources inside the engine such as ignition process, combustion process, piston movement and ancillary equipment.

The vibration signals shown in Figures 4-7 help us to gain better understanding about the operations of the petrol engine and can be used to identify abnormal conditions. Typical vibration signal acquired from the engine at the normal condition is shown Figure 4 with the intake valve clearance of 1.5 mm, the exhaust valve clearance of 2 mm and the spark plug gap of 0.8 mm. The

Valve operation events such as IVO, IVC, EVO and EVC can be seen clearly approximately at 705(or -15), 231, 497, 21 degrees after top dead center (ATDC) of the intake stroke. The spark ignition event occurs approximately at 360 degrees ATDC but this event is unclear with small amplitude. This event is composed of spark ignition and combustion processes. The combustion process may be identified in the vibration signal at crank angle of 360-400 degrees.

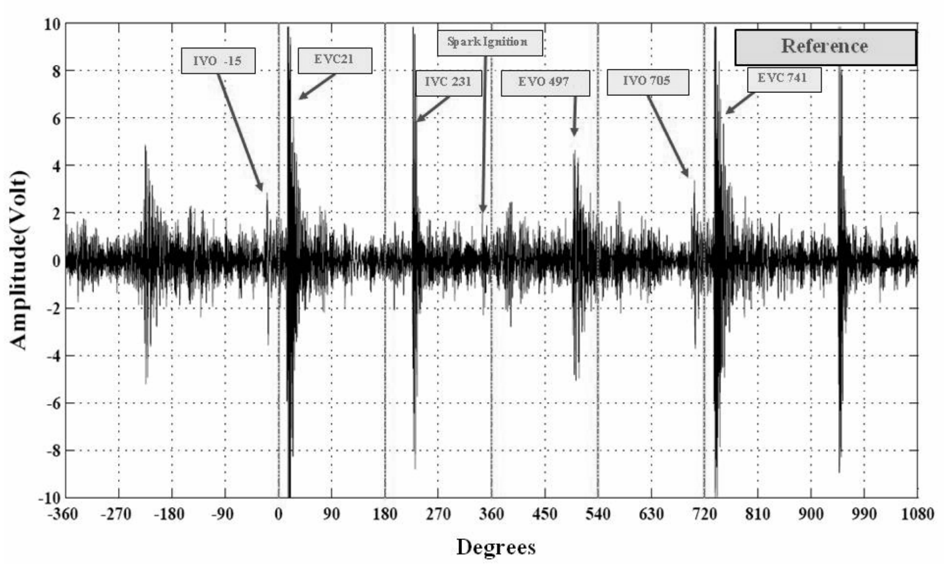

Figure 4 Vibration signal acquired from the engine for normal condition.

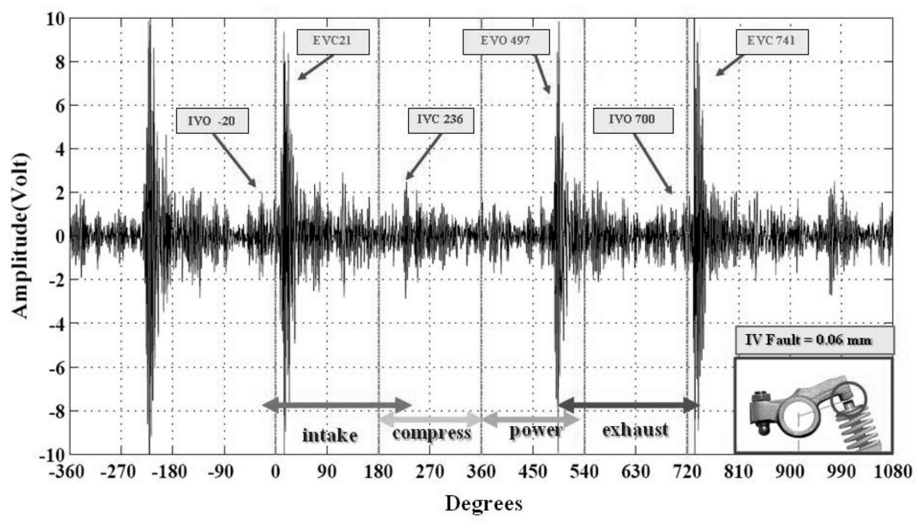

Figure 5 Vibration signal acquired from the engine for intake valve clearance fault condition.

A fault condition of intake valve clearance was simulated by reducing clearance between rocker arm and intake valve. For the intake valve fault, the intake valve clearance was set about 0.06 mm. It can be seen that IVO event in Figure 5 has small amplitudes and is difficult to identify. This may be because the intake valve opening impact may not have enough energy to produce high vibration amplitude. The exhaust valve fault was simulated by reducing clearance between rocker arm and exhaust valve. The exhaust valve clearance was set around 0.08 mm for the exhaust valve clearance fault condition. The vibration signal for the exhaust valve fault condition is shown in Figure 6. Typical exhaust valve of the engine was closed at 21 degrees ATDC at the normal condition. For fault condition, the exhaust valve event seems to disappear and exhaust valve was not closed completely at 21 degrees ATDC.

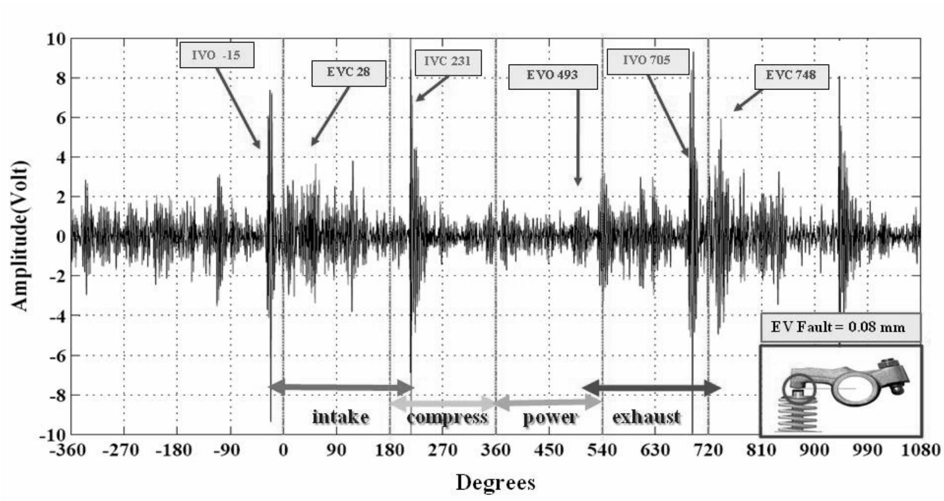

Figure 6 Vibration signal acquired from the engine for exhaust valve clearance fault condition.

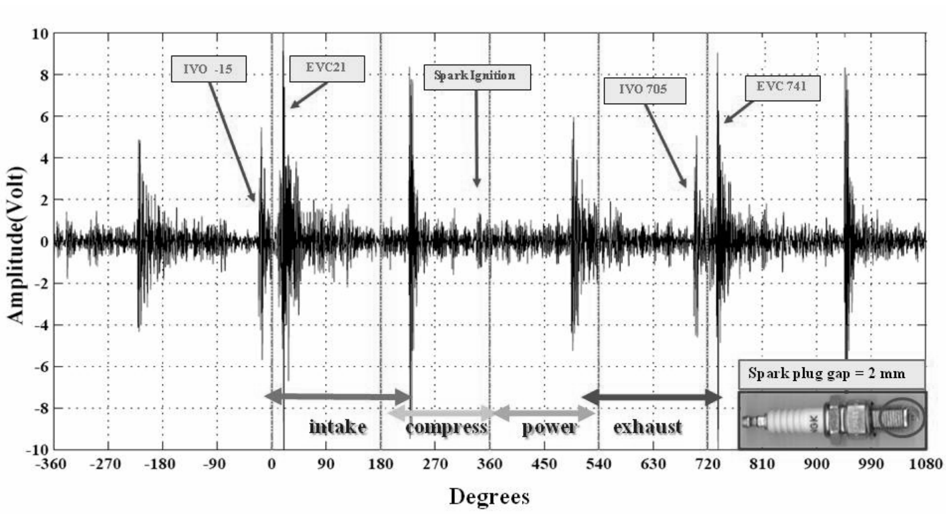

Figure 7 Vibration signal acquired from the engine for spark plug gap fault condition.

The spark plug fault was simulated by increasing spark plug gap which was about 0.8 mm for normal condition and 2 mm for fault condition. It can be seen that the signal amplitudes between the compression stroke and the power stroke at around 360-450 degrees ATDC as shown in Figure 7 are smaller than at normal condition. For the spark gap fault condition, the ignition process was delay and sometimes it is difficult to identify because signal amplitude is unclear and closed to noise level. In addition, the activities of mechanical and fluid flow processes disappear during the exhaust stroke (around 540-700 degrees ATDC). This may cause by fault ignition or no ignition processes so that the mechanical impacts and fluid flow processes inside the cylinder may have not enough energy to produce any event as seen in Figure 7.

5. Conclusions

It has been demonstrated through a range of experimental results that the vibration monitoring technique shows a possible technique for investigating of the behavior of a four-stroke petrol engine. Typical finding from a small, four-stroke petrol engine i.e. intake/exhaust valve operation and spark ignition events can be applied to determine more complicated engine such as a medium or large, four-stroke, four-cylinder, petrol engine. The vibration signal can be used to detect engine operation processes in the engine cycle. Typical recorded vibration signals consists of both burst and continuous signals which associated with mechanical and fluid flow activities in the engine cycle.

This study has shown that a simple, non-intrusive vibration measurement technique offers information of the behavior of running engine mechanism. The benefit of this non-intrusive technique is no detrimental effects to engine performance and requires little or without engine modification. With further development, vibration monitoring technique could prove to be an alternative tool for monitoring of engine performance and could significantly aid condition based monitoring strategies.

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