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Original Article

Condition monitoring of valve clearance fault on a small four strokes petrol engine using vibration signals

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Abstract

This paper studies condition monitoring technique of a small four strokes, single cylinder petrol engine using vibration signal analysis based on time domain, crank angle domain, and signal energy. Vibration signals are acquired from the cylinder head of the engine and used to describe engine processes such as intake/exhaust valve operations, ignition process, and combustion process. In this study, vibration signals have been applied to monitor various fault conditions in the engine such as intake and exhaust valve clearance faults. Vibration signals acquired in time domain could be mapped onto crank angle domain using top dead center signal. Time domain techniques were used to analyze vibration signals so that the main events related to the engine operations could be described easily. Using energy analysis technique, all fault conditions could be also identified. For future work, signal analysis techniques must be developed and the detected signals should be compared with other signals such as pressure signal in order to verify the accuracy of the results.

Keywords: condition monitoring, valve clearance, vibration signals, fault condition, time domain, signal energy

1. Introduction

In the past decades, many successful efforts have been made to use vibration analysis as a means for condition monitoring of rotating machinery. A number of methods such as statistical analysis and time domain analysis have shown a high potential for the early detection of malfunctions and diagnosis of machines (Long and Boutin, 1996; Girdhar *et al.*, 2004). However, the use of vibration signals in applications with internal combustion engines (diesel and petrol engines) is quite difficult due to the complexity of the vibration signals and large amount of data. It was early realized that any effective approach dedicated to internal combustion engines would have to cope with the highly transient nature of their vibrations (Autar, 1996; Long and Boutin, 1996; Gill *et al.*, 2000). These gave little scope to the classical methods, which usually assume stationary (time invariance of statistical properties) of the vibrations and so cancel out all time information. This paper introduces an approach, which takes into account the non-stationary nature of the vibration signals produced by a small four strokes petrol engine. The idea is to rephrase the prospect of vibration monitoring of a small four strokes petrol engine into a very general framework of cyclic stationary processes, which is perfectly suited for describing the physical phenomena generated on a cyclic basis.

Non-intrusive sensor measurement techniques (i.e. vibration measurement technique) provide information in time domain and crank angle domain. This information related engine processes can be described to identify existing or impending problems by detecting deviations from a normal or an achievable condition in the engine cycle (Autar, 1996; Long and Boutin, 1996; Gill *et al.*, 2000). A challenge of engine monitoring system used in industry is that it has to face with a large amount of recorded data that acquired using

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commercial or in-house developed software. These data can be analyzed using exist signal processing techniques to reduce the number of data and to obtain some useful information for monitoring the engine conditions. Ideally, a condition monitoring program should mature to integrate techniques to reduce data from all sources and channels into a centralized system that produces information accessible to all levels of the preventive maintenance.

This paper has studied vibration analysis methods based on time domain analysis for a condition monitoring of a small four strokes, single cylinder petrol engine with a capacity of 125 cm^3 using vibration signals. The physical aspects of combustion characteristics of the spark ignition engine are very crucial for the engine performance and can be described using actual vibration signals and a reference signal or a top dead center (TDC) signal. The analytical technique and data reduction can produce a normalized measure that can be used to analyze the states of the engine.

In this research, vibration signals were acquired on a small petrol engine using LabVIEW program. Vibration signals were acquired using an accelerometer with a magnetic clamp attached on the surface of cylinder block of the petrol engine. A proximity sensor was used to record the TDC signals. For the signal analysis, vibration signals were mapped from time domain into crank angle domain. Typical vibration signals detected on the petrol engine are related to the main events associated with some mechanical and fluid flow processes in the engine cycle. Thus, vibration signals can be mapped onto various processes associated with intake/exhaust valve operation, combustion and spark ignition processes. For fault diagnosis, vibration signal can be analyzed using signal energy, which is described in this study.

2. Signal Processing

The analysis of vibration patterns is an evaluation of vibration relationship to a crankshaft angle and is to obtain the understanding of various mechanical processes in the engine cycle associated with mechanical impacts or gas leaks. Mechanical impacts, such as valve closure, produce sharp vibration patterns. Gas leaks, however, typically occur over a longer period of time and have lower amplitudes (Autar, 1996; Long and Boutin, 1996; Gill *et al.*, 2000). Gas leaks are usually affected by the changing pressure in the cylinder. A roughness or friction also produces vibration pattern that is characterized by a noise with low amplitude (Autar, 1996; Long and Boutin, 1996; Gill *et al.*, 2000; Antoni *et al.*, 2002). The vibration pattern analysis of the four strokes petrol engine involves the determination of the presence and absence of expected events associated with the engine processes, which occur at measurable amplitudes and at a specific time. Abnormal events based on the mechanical experience and the maintenance history of the engine operation can be predicted using the engine knowledge, then, specific regions of the vibration pattern can be separated. Potential faults can be defined with the vibration pattern. Anomalies in the signal pattern can be detected by comparison with a baseline normal condition pattern.

The signal analysis techniques used in this study are based on time domain, crank angle domain, and signal energy. Typical vibration signals are acquired on time domain and can be converted into crank angle domain using a reference signal that gives the TDC signal of an engine. Thus, the main events related to the petrol engine processes can be identified. To obtain more information from the vibration signals, the signal energy technique is applied to improve signal resolution so that various fault conditions can be identified. The signal energy (E_x) can be calculated, as follows:

$$E_x = \int_0^t x^2(t)dt \qquad (1)$$

where $x(t)$ is time domain waveform at time, *t*.

In this work, the signal energy can be used to analyze vibration signals or acceleration signals detected from an accelerometer, thus the engine state can be described by the time domain techniques. This work applied numerical methods of trapezoidal rule to evaluate the area under the curve of the signal energy.

3. Experiment

A small, single cylinder, four strokes petrol engine, Tiger brand, with capacity of 125 cm^3 was used and run at a speed of 1500 rpm, no load and with various conditions such as the intake and exhaust valve clearance fault conditions as shown in Figure 1. Typical spark plug gap used in this engine was 0.8 mm. All fault conditions were simulated on the engine as follows:

- Simulated fault at the intake valve (IV) with various intake valve clearance fault conditions i.e. IV Fault 1 = 0.8 mm, IV Fault 2 = 2 mm and IV Fault 3 = 3 mm. The typical intake valve clearance of this engine was 1.5 mm.
- Simulated fault at the exhaust valve (EV) with various exhaust valve clearance fault conditions i.e. EV Fault 1 = 1 mm, EV fault 2 = 2.5 mm and EV fault 3 = 3 mm. The typical exhaust valve clearance of this engine was 2 mm.

The vibration and TDC signals were acquired from an accelerometer and a proximity sensor, respectively using

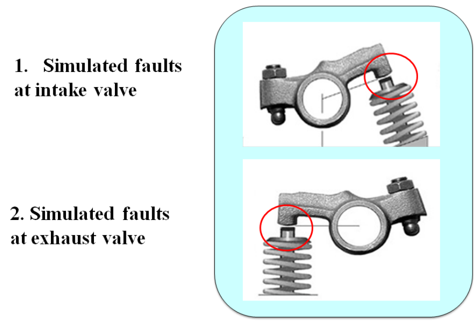

Figure 1. Testing conditions.

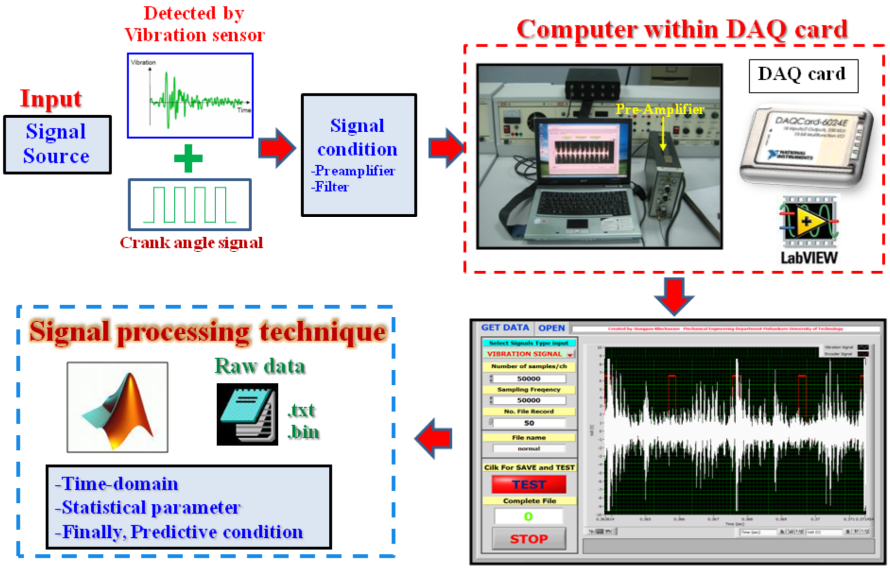

Figure 2. Schematic diagram of a data acquisition system.

LabVIEW program. A schematic diagram of data acquisition (DAQ) system is shown in Figure 2. This system consists of an accelerometer with a charge amplifier, a proximity sensor, a terminal 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 crank angle signals, which were recorded with a sampling frequency of 100 kHz and then saved into digital files for later analysis. The vibration signals were measured from an accelerometer attached on the cylinder head stud of the small petrol engine as shown in Figure 3. An in-house designed aluminum clamp was used to hold the Bruel & Kjaer accelerometer, Model 4371 at the same axis of the piston motion and the proximity sensor was attached to measure one pulse per revolution from a shaft connected with the main crankshaft of the engine as shown in Figure 4. This crank angle signal gives two pulses every one engine cycle, which is represented the piston position at TDC of the intake and power strokes, respectively. All calculations were averaged over 2000 engine cycles.

4. Result and Discussion

It is difficult to identify the engine processes such as valve operation and ignition processes using typical time domain vibration signals acquired from the petrol engine. The crank angle signal or TDC signal can help to identify the main events of the engine as mentioned above. The vibration signal can be mapped onto a crank angle domain using a crank angle signal given a pulse per revolution as shown in Figure 4. This signal was recorded at engine speed approximately 1500 rpm and no load. At this speed, the engine ran

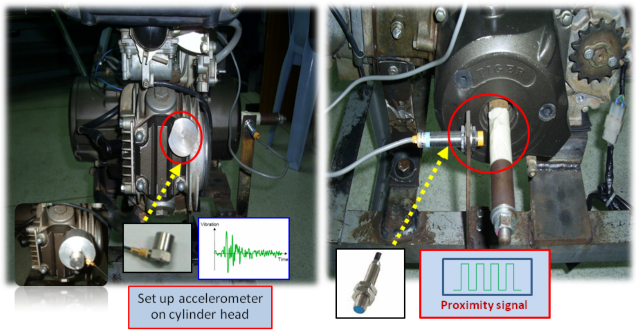

Figure 3. Small four strokes petrol engine testing rig.

smoothly than other speeds with a variation of ±100 rpm. Signal amplitude was slightly varied with speed but the locations of the engine events were the same. Vibration signal amplitude and crank angle are shown on the vertical and horizontal axes, respectively. Crank angle at zero degree represents a piston position at TDC of the intake stroke. All four main strokes described in Figure 4 are intake, compression, power and exhaust strokes associated with crank angles at 0-180, 180-360, 360-540 and 540-720 degrees ATDC (After Top Dead Center), respectively. Valve operation events are the strongest events as seen in Figure 4. IVO, IVC, EVO, and EVC represent intake valve opening, intake valve closing, exhaust valve opening, and exhaust valve closing events, respectively

The recorded vibration signals can help to understand the engine processes of the small four stokes petrol engine and also can be used to identify abnormal conditions from the running engine. For greater resolution, amplitudes of each recorded vibration signals as shown in Figures 5-6 were

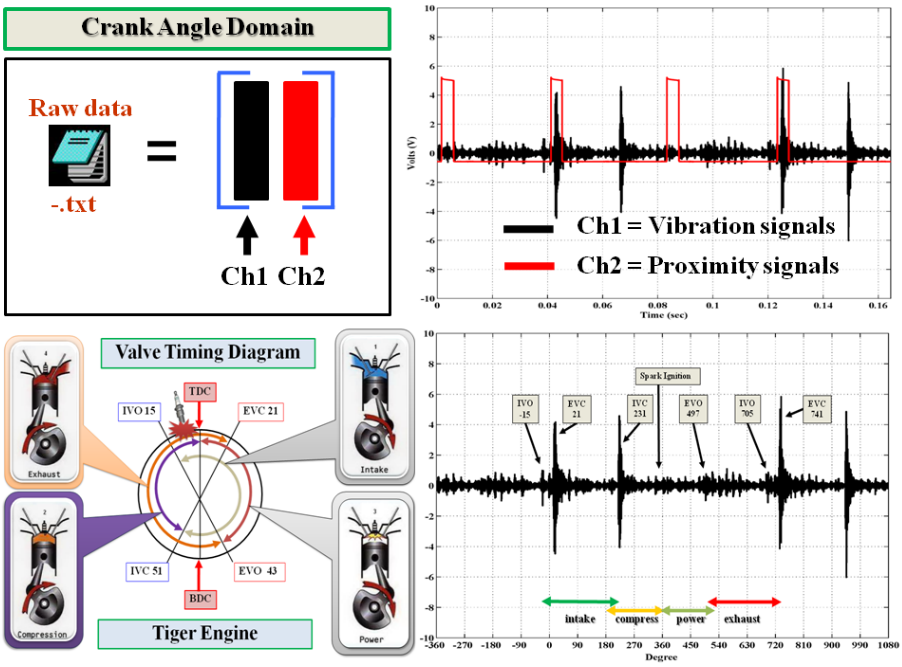

Figure 4. Typical valve timing diagram of a small four strokes petrol engine and a signal mapping technique from time domain to crank angle domain.

enveloped so that signal amplitudes can be easily compared. Each example of an enveloped signal of each testing condition was mapped onto crank angle domain using the TDC signal. Typical vibration signal acquired from the engine at normal conditions are shown in Figures 5(A) and 6(A) with the engine set-up parameters such as intake valve clearance of 1.5 mm, exhaust valve clearance of 2 mm, and spark plug gap of 0.8 mm. The main operation events such as IVO, IVC, EVO, and EVC can be seen clearly at around 705 (or -15), 231, 497, and 21 degrees ATDC, respectively. It can be seen that IVC and EVC events are greater than other events because the closing impact of both valves produces more signal amplitudes than other engine processes. Typical spark ignition event occurs at approximately 345-355 degrees ATDC and is difficult to identify them easily as seen in Figures 5(A) and 6(A) because this event is unclear with small signal amplitude close to noise level. Various simulated faults of intake valve clearance can be seen in Figures 5(B)-5(D). When intake valve clearance is greater than at normal condition, the IVO event is delayed around 2-5 degrees and the IVC event occurred earlier, around 4-9 degrees, as seen in Figures 5(C)-5(D). As seen in Figure 5(B), valve clearance is smaller than at normal condition. The intake valve is opened early at approximately 700 (or -20) degrees ATDC. The intake valve closing is delayed at around 236 degrees ATDC. This IVC event is difficult to identify because valve clearance is too small. Thus, the closing impact may have not enough energy to produce high amplitudes of the vibration signal. For various simulated faults at exhaust valve clearance, the EVC events for normal conditions occur at the location around 21

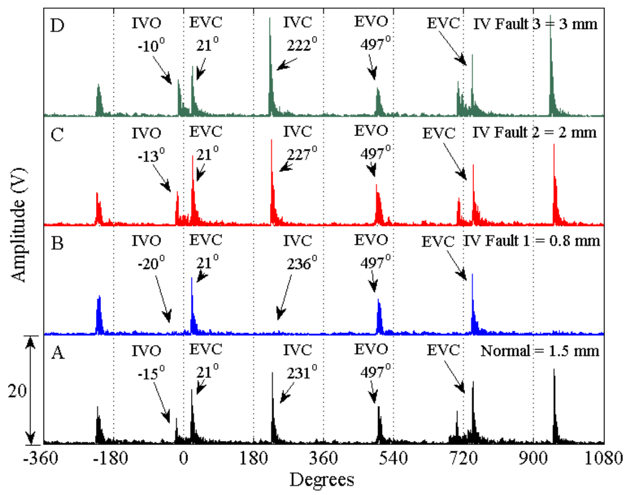

Figure 5. Various vibration signals acquired from the engine speed at 1500 rpm (A) Normal (B) IV Fault 1 (C) IV Fault 2 and (D) IV Fault 3.

degrees ATDC as seen in Figure 6(A). It can be seen that when the exhaust valve clearance is higher, the larger signal amplitude of the EVC event can be seen in the vibration signal. When exhaust valve clearance is greater than at normal condition as seen in Figures 6(C) and 6(D), the EVO event is delayed and the amplitude of this event can be seen clearer than at normal state (Figure 6(A)) and at exhaust valve clearance of 1 mm (Figure 6(B)). This may be because the increasing valve clearance is leading to the rising in-cylinder

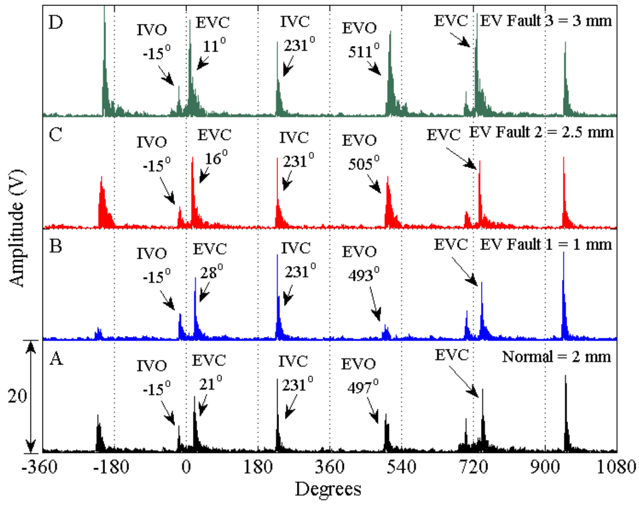

Figure 6. Various vibration signals acquired from the engine speed at 1500 rpm (A) Normal (B) EV Fault 1 (C) EV Fault 2 and (D) EV Fault 3.

pressure when the piston is moving forward to TDC of the exhaust stroke. Thus, the activity of the exhaust gas gives more energy to produce more information in the vibration signal. For an exhaust valve clearance of 1 mm as seen in Figure 6(B), the EVO event is difficult to identify. This may be because in-cylinder pressure may not have enough energy to produce a vibration signal. When the exhaust valve clearance is greater than at normal condition a delayed opening of the exhaust valve and the early closing of exhaust valve can be seen as shown in Figure 6(C)-6(D). However, when the exhaust valve clearance is smaller than at normal condition, the exhaust valve is opened earlier and closed later as seen in Figure 6(B). It can be noted that when intake or exhaust valve clearance of the engine has greater or smaller clearance than at normal condition, it will result in a late valve opening and early valve closing with greater signal amplitude or early valve opening and late valve closing with smaller signal amplitude, respectively. Typical spark ignition events as seen in Figures 5-6 occurred at approximately 315-405 degrees ATDC. The spark ignition event cannot be identified and the amplitude of this event is close to the noise level because the spark ignition and combustion processes, which are the main activities of this event, gave signal amplitude less than the closing impact of valve.

In order to obtain more information about the petrol engine processes, the vibration signals were analyzed using signal energy technique. The signals shown in Figures 7-8 were calculated using Equation (1). Signal energy of vibration signal was calculated for every crank angle degree to cover the engine cycle. It can be seen that the energy plot of each testing condition can be seen easier with a smooth signal. The typical events shown in Figures 7-8 can be identified by comparing them with the valve timing of the test engine, which are IVO, IVC, EVO, and EVC events. These valve events can be seen clearly at approximately 705, 231, 497, and 21 degrees ATDC, respectively. Using signal energy technique, the main valve operation events can be identified easier than those shown in Figures 5-6. All the findings as described in Figures 5-6 also can be seen in Figures 7-8. The plot of signal energy of each condition can be compared with the baseline signal energy at normal condition so that various valve clearance fault can be investigated easily. Using the energy technique, however, the spark ignition event cannot be identified. This is because the spark ignition and combustion activities may not have enough energy as mentioned before.

From the results described above, all main events of engine operation as seen on the crank angle domain using

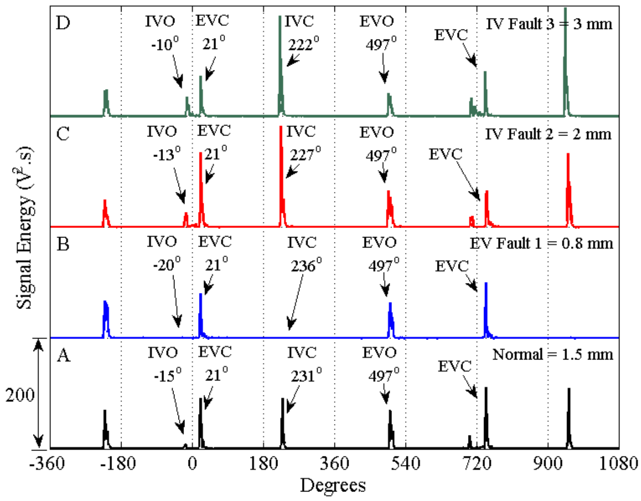

Figure 7. Various signal energy with the engine speed at 1500 rpm (A) Normal (B) IV Fault 1 (C) IV Fault 2 and (D) IV Fault 3.

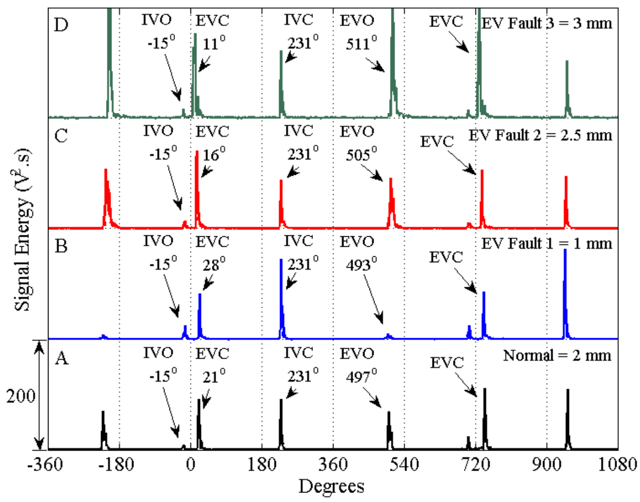

Figure 8. Various signal energy with the engine speed at 1500 rpm (A) Normal (B) EV Fault 1 (C) EV Fault 2 and (D) EV Fault 3.

signal energy technique can be used to analyze by considering only the main components. The signal energy shown in Figures 9-10 was windowed only the main events and the window size was approximately 90 degrees for each main event such as 0-90, 180-270, 450-540, and 630-720 degrees for the IVO, IVC, EVO, and EVC events, respectively. The signal energy of each testing condition was averaged over 2000 engine cycles. Figure 9 shows the signal energy of the IVO and IVC events of various test conditions N, F1, F2 and F3 is referred to Normal, Fault 1, Fault 2 and Fault 3 conditions with various intake valve clearances of 1.5, 0.8, 2 and 3 mm, respectively.

The signal energy of the N IVO, and N IVC events at normal condition as seen in Figure 10 is 50.53 and 331.11 V^2s, applying the trapezoidal rule method for calculating the area under the curve of the vibration signal with the window size as mentioned before. It can be seen that when the valve clearance is greater than at normal condition, the signal energy of the IVO and IVC events are greater than at normal condition. The signal energy of the IVC events is greater than the IVO events for all testing conditions.

For the simulated tests of the exhaust valve clearance fault conditions as shown in Figure 10, the results of the signal energy are similar as discussed in the various intake valve clearance conditions. The reference energy for the N EVO and N EVC events are 133.40 and 292.50 V^2s. The signal energy of both EVO and EVC events seems to increase with increasing exhaust valve clearance. From Figures 9 and 10, it can be seen that the energy of the IVO, IVC, EVO and EVC events could be used as indicators to identify fault conditions of valve clearance by comparing the signal energy of the current state with the normal state.

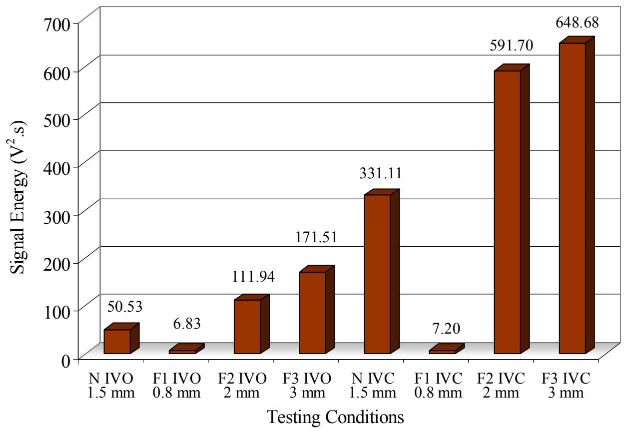

Figure 9. Signal energy of the IVO/IVC events with various testing conditions.

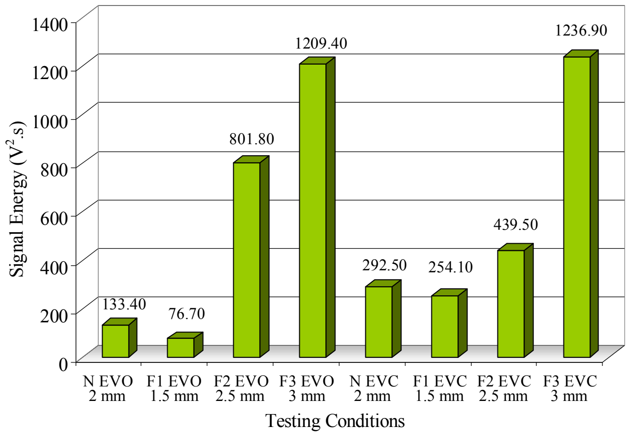

Figure 10. Signal energy of the EVO/EVC events with various testing conditions.

5. Conclusions

It has been demonstrated through a range of experimental results that vibration technique shows a potential for investigating the behavior of a four strokes, petrol engine. Typical recorded vibration signals consist of both burst and continuous signals associated with mechanical and fluid flow processes in the engine cycle. The vibration signal and crank angle signal could be used to map the main event (i.e. valve operation and spark ignition events) in the engine cycle. However, the knowledge of engine processes and signal processing techniques are necessary. The energy analysis based on time domain technique could be used to describe the main events by windowing the vibration signal so the engine condition could be identify easily. Using an accelerometer and a proximity sensor attached on the engine, both detected vibration and TDC signals could be used to investigate valve clearance fault conditions using signal energy applied to the main valve operation events as the indicators by comparing them with the baseline signal energy of the normal conditions. This may also be applied to monitor other four strokes, four cylinders petrol engines. For the future work, it is necessary to use more powerful techniques to improve the accuracy of an engine state monitoring system and the detected vibration signal should be compared with other signals such as acoustic or pressure signals in order to verify the accuracy of the results.

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