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The effect of piston scratching fault on the vibration behavior of an IC engine

Ashkan Moosavian [a,b], G. Najafi [a,*], Barat Ghobadian [a], Mostafa Mirsalim [b]

[a] Biosystems Engineering Department, Tarbiat Modares University (TMU), Jalale-E-Aleahmad Highway, Tehran, Iran
[b] Workshops, Engine and Vehicle Labs Unit, Irankhodro Powertrain Company (IPCo), Tehran, Iran

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ABSTRACT

Two-body and three-body abrasive wear which are the main wear modes in internal combustion (IC) engines, might occur in the area between piston and cylinder and could cause different failures of piston and cylinder such as scratching and scuffing. These failures could reduce the engine performance and cause the engine breakdowns in their severe form. This paper investigates the effect of piston scratching fault on the vibration behavior of an IC engine with the purpose of developing a practical way for the early detection of this fault. To this end, vibration test was conducted on the engine under two states namely, healthy and faulty. To generate the faulty engine state, scratching fault was simulated by cutting a groove into the piston skirt. Short-time Fourier transform (STFT) and continuous wavelet transform (CWT) were employed in the analysis stage. The results showed that piston scratching fault caused a significant increase in the maximum, mean and energy of the engine vibration. The results of CWT method demonstrated that piston scratching fault excited the frequency band of 3–4.7 kHz of the engine vibration. The obtained results indicated that piston scratching had significant and detectable effects on the engine vibration. Hence, the vibration analysis could be used as an effective tool for detection of piston scratching fault in IC engines.

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1. Introduction

Internal combustion (IC) engines are the main component of powertrains, which generates necessary power for vehicles. IC engine as the heart of vehicles, comprise of a lot of different components and mechanisms performing particular tasks. Performance, efficiency and durability of the engines are among the main issues for automotive engineers. Together with the development of technical knowledge, the progress of advanced components and mechanisms in terms of design and materials, and increase in the power and efficiency, the engines' life and durability faces a significant challenge due to hard working conditions. Nowadays, parallel with the increase in engines' performance, power and speed, there is a huge demand for longer service intervals of the engines.

Piston as one of the main components in IC engines, always exposes high thermal and mechanical loads, and reciprocates continuously in a very tight area into cylinder. Due to this hard working condition, this component has high potential to failure. Among the different failure modes, the piston faults caused by wear mechanisms are common and various [1,2].

There are three important wear mechanisms in IC engines namely corrosion, abrasion and adhesion [3]. Abrasion occurs during the running-in period of engine which is a dominant wear mechanism for piston/cylinder system. Abrasive wear is damage to a component surface caused by the motion of a harder surface or hard particles trapped at the interface. Hence, there are two types of abrasive wear, namely, two-body and three-body abrasive wear. Two-body abrasive wear takes place when a hard surface slides on a softer counter surface. Hence, two-body abrasive wear could be happened when two sliding metal surfaces contact to each other. Three-body abrasion occurs when wear is produced by free hard particles trapped at the area between the two sliding surfaces [4].

Abrasive wear could be a root cause of different piston faults such as scratching, scoring, scuffing and seizing. As a result of these failures, the piston/cylinder system might seriously be damaged, and the engine will need to be overhauled which is costly indeed [5]. Due to the undesirable and destructive effects of abrasive wear on engines, it is essential to develop and propose practical ways to reduce the risk of its occurrence. In recent years, many successful methodologies have been developed for decreasing the probability

* Corresponding author at: P.O. Box: 14115-111, Iran.
E-mail address: g.najafi@modares.ac.ir (G. Najafi).

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of this fault occurrence, which have been most based on the design and material solutions. For example, Cho et al. [6] have investigated the effects of surface roughness and coatings on the tribological behavior of piston skirt surfaces. To this end, three different surface roughness and two graphite and diamond-like carbon (DLC) have been studied. They have showed that DLC coating provides better tribological performance. Krak et al. [7] have studied the resistance of surface treated 8625 alloy steels against scuffing fault. In this research, the scuffing resistance of non-treated, carburized, nitrocarburized and carbonitrided 8625 alloy steels has been compared. Olander et al. [5] have tested the scuffing resistance of grey iron and plasma sprayed cermet coating for marine 2-stroke engines. Tamura et al. [8] have studied the tribological properties of tungsten carbide containing DLC (WC-DLC), hydrogenated DLC (H-DLC) and B_4C coatings in boundary lubrication condition. They have found that H-DLC coating provides the lowest friction coefficient.

Despite of the proposed methodologies to control the abrasive wear mechanism, the risk of its occurrence has remained yet in engines, especially in the area between piston and cylinder. In other words, it has not been proposed yet a definite solution to stop completely this wear mechanism. Thus, it is required to develop a method for detection of this fault in engines. By equip the engines with such diagnostic method, the fault could early be detected and correction actions could be done to control it. This procedure prevents the fault progression and increases the health level of the engine [9]. Nevertheless, a few studies have been conducted in this field. For example, Wakatsuki et al. [10] have presented a diagnostic system based on the temperature measurement to detect scuffing on the cylinder liner of a large two-stroke diesel engine. To this end, a thermocouple type temperature sensor installed on the cylinder liner surface was used. Jena and Panigrahi [11] have proposed a sound-based diagnostic method to detect motor bike piston-bore fault. They have employed continuous wavelet transform (CWT) technique using complex Morlet wavelet function in signal processing method stage. It has been shown that the high intensity zones in the CWT plot with the frequency of 15.6 Hz can be attributed to the piston-bore defect, which is corresponds to engine firing frequency at idle speed. Hase et al. [9] have conducted an investigation on early detection of seizing fault caused by adhesive wear in journal bearing using acoustic emission. They have illustrated the changes in the amplitude of AE frequencies over the experiment time using time-frequency plots. In these plots, it can be observed that the seizure fault causes significantly the amplitude of AE frequencies to be changed, especially around 0.5 MHz. They have mentioned that features of AE frequency spectrum are dependent on the wear mechanism, and changes in amplitude and frequency of AE signals are important information for early detection of seizure.

One of the most common and promising method in fault detection area is vibration analysis which is effectively utilized in engine fault diagnosis. Each rotary machine has some unique vibration characteristics representing its health condition. If a failure occurs in the rotary machine, its vibration characteristics may change. In vibration analysis, these changes are found by some methods like signal processing. Then, the changes are attributed to that failure [12,13]. In abrasive wear, the contact and rubbing between the piston and cylinder surfaces could generate vibration and noise. So the use of vibration analysis and obtaining the vibration characteristics of wear could be a proper way for detecting this fault in IC engines.

We tried previously to identify the piston scuffing fault caused by three-body abrasive wear using vibration analysis [14]. To this end, CWT technique was employed to obtain the vibration characteristics of the scuffing fault. In that research, it was shown that the piston scuffing excited the engine vibration in the frequency band of 2.4–4.7 kHz.

Further to the previous study, the current work as a new research, investigates the effect of another type of piston fault namely piston scratching fault on the engine vibration, and tries to find the vibration characteristics caused by this fault. The differences between the current and previous studies are in the failure mode and its severity. The severity of the fault studied in the current work is less than that in the previous work.

In this research, two experiments were conducted on a real IC engine in healthy and faulty conditions in which the engine vibrations were measured during the tests. In the analysis stage, the vibration characteristics caused by piston scratching fault were obtained by comparing the obtained results of short-time Fourier transform (STFT) and continuous wavelet transform (CWT) methods for the healthy and faulty conditions. The flowchart of the proposed procedure is illustrated in Fig. 1.

2. Experimental work

2.1. Experimental setup

The experiments were performed on an inline four-cylinder spark-ignition (SI) engine. The engine specifications are given in Table 1. In order to control the engine speed and load, a 190 kW Horiba-WT190 eddy-current dynamometer was coupled with the engine. More than thirty equipment in conjunction with different sensors were employed to run and control the engine such as engine speed, torque, throttle position, water temperature, oil pressure, ambient temperature, crankcase pressure and exhaust manifold temperature sensors. All sensed engine parameters were captured during the experiments.

To measure the vibration signals, a PCB accelerometer type 357B11 was horizontally installed on the engine cylinder block in front of the cylinder#3 liner. The accelerometer sensor specification is given in Table 2. The vibration signals passed through a Brüel & Kjær (B&K) NEXUS conditioning amplifier type 2692 low noise version with a high bandwidth which has comprehensive high and low-pass filtering facilities. The data acquisition system consisted of an Advantech PCLD-8710 terminal board and data acquisition card type PCI-1710. The signals were recorded in a computer using MATLAB software. In this research, all signals were sampled with a 50 kHz sampling frequency. Fig. 2 shows a schematic and real experimental setup.

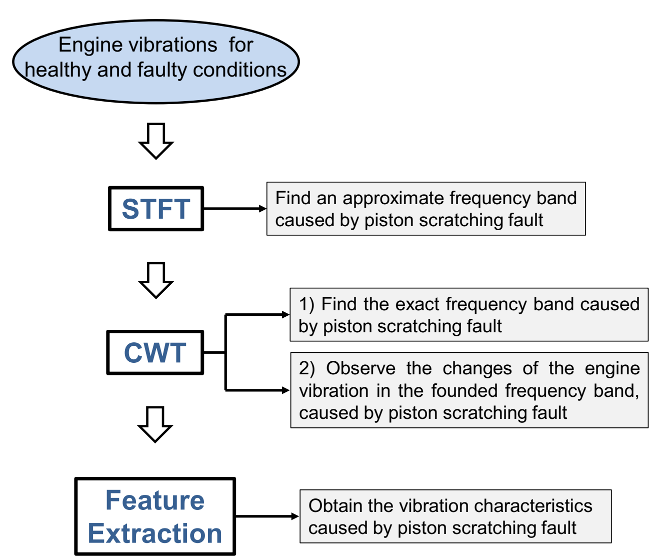

Fig. 1. The flowchart of the proposed procedure.

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