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Fault detection of injectors in diesel engines using vibration time-frequency analysis

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ABSTRACT

In CI engines, injector spraying into the combustion chamber has extreme importance in fuel atomization and knocking control in the CI engines. Knocking and malfunction of engines due to faulty injectors can lead to efficiency reduction, damages, and acoustic noise. Much research is developing methods of engine knock detection. Hence, injector fault detection has not been addressed specifically, this research is focused on the subject and corresponding vibration amplitudes and frequencies, likely to cause the knock phenomenon. Welch test, Short-Term Fourier Transform (STFT), Wigner-Ville Distribution (WVD), and Choi-Williams Distribution (CWD) were employed for detailed scrutiny of vibrations generated by an under-load engine. For an ideal combustion, the acceleration peak values should be placed in the range of 0–10 kHz in time-frequency (TFR) diagram. While a faulty injection unit can cause components at higher frequency, between 10 and 25 kHz, in TFR diagram for each cylinder, and this can effects on the engine performance. Regarding the results which are presented in this research it infers that, in real-time performance monitoring of an engine, the STFT technique is more efficient for fault diagnosis of fuel injection nozzles and knock detection. By comparing vibration response of healthy and faulty injectors, the RMS and kurtosis of the faulty injectors showed an increase of 12.9% and 20.6% respectively.

1. Introduction

Knocking-combustion studies is important due to engine durability, fuel consumption, and power density, as well as noise and emission performance [1]. Combustion pressure changing and knock are the main source of engine vibration and noise. In spark ignition (SI) engines, ignition of fuel mixtures farther from the flame front causes knocking due to rapidly releasing an uncontrolled energy. This causes a rapid and irregular increase in gas pressure, which develops knocking. In compression ignition (CI) engines, by fuel injection into the combustion chamber at the high-compression ratio, the fuel mixture ignites with a delay [2,3]. Current SI engines suffer from conventional knock and super-knock [1]. Compared with SI engines, knocking is more rigorous in CI engines when the ignition delaying increases [2,3]. In this case, the knocking generates annoying noise and vibration, burns the piston crown, and damages engine parts [4].

Vibration-based condition monitoring (VCM) has applied successfully for detection and differentiation of faults generated in rotating machines, via mounted accelerometers on bearing pedestals [5]. Vibration or acoustic signals derived from reciprocating engines are cyclostationarity. A cyclostationary signal is one that exhibits some hidden periodicity of its energy flow along with stationary random signals [6]. Impact excitations, time-varying transfer properties and non-stationary random response are typical characteristics of the reciprocating engine vibration. These characteristics of the engine vibration make its dynamic analysis and signature extraction much more difficult than that of the rotational machinery [7]. Induced mechanical vibrations of engines can interfere with the knocking detection process. For example, valves closure impact often produces high-frequency vibrations that fall inside the knocking detection window in the signal processing. The valve closure impacts depend on their clearance, which control their upraising speed over the camshaft. Thus, these impacts take place at different intensities, and therefore, can disturb knocking detection process [8].

There are several methods for capturing information on engine knocking by instruments. Measuring the combustion pressure inside a cylinder is one of the most reliable methods, since other sources of mechanical vibrations do not affect this method. Nevertheless, due to its difficult implementation and high costs, mostly accelerometers are used for knocking detection [8–10]. To do so,

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signals were converted using various methods such as FT (Fourier Transform), TFR transforms like STFT, WVD, CWD, ZAMD, WT (wavelet transform), etc. [11–13]. TFR analyses are among the novel and practical methods for structural health monitoring in vibrating systems [14]. TFR approach can be used in analyzing the behavior of some systems. This method has been used for analysis of friction-induced vibrations in engines. With any variation in a system, a frequency change occurs in the TFR analysis caused by vibration [15]. For example, STFT can be used to detect different sources of vibration in an engine. Further, this method has been used for identifying normal and abnormal combustion-related knocking in a cylinder block. Using the FFT and FFT-based methods, such as estimated power spectral density, is unsuitable for identifying non-stationary events, including cross-terms and systems with rapid changes in time and frequency. Nevertheless, these methods are fast and capable of filtering noises [16]. Lee et al. developed a method of knock detection using cylinder pressure, block vibration and sound pressure signals from a SI engine. Knock intensity greatly varies with engine operating conditions, knock sensor locations and fuel characteristics [17]. Taghizadeh et al. studied the combustion, vibration, and knocking in diesel engines produced due to different levels of diesel-biodiesel fuel blends by time-frequency methods. Each fault in injection units and incorrect spraying causes the knocking phenomenon and high-frequency vibrations between the 7 and 25 kHz [18]. Rizzoni and Chen detected knock in an internal combustion engine using time-frequency distributions. They presented an improved knock detection scheme capable of tracking variations in the knock resonance frequencies. Experimental results obtained from a single-cylinder engine were used to validate the proposed method [19]. Bares et al. analyzed the frequency spectrum of the pressure signal of an engine using FFT and a window function in two locations near the maximum heat release and near the end of combustion, and the result was compared with the classical maximum amplitude pressure oscillation (MAPO) definition. Results showed that the proposed knock index definition can avoid the strong knocking events and reduces engine vibration [20]. Wang et al. used the Wigner-Ville distribution (WVD) of vibration signals for different states of valve train and displayed it as TFR diagram. Moreover, probabilistic neural networks (PNNs) were employed to classify the time-frequency diagrams after normalization. By these methods, the fault diagnosis of the valve train was associated to the time-frequency (TFR) diagram [21]. Molinaro et al. carried out the knocking recognition in engine vibration signal using the wavelet transform [22]. For low signal-to-noise ratio at high engine speed, signal parameters extracted using wavelet transform improve knocking detection [22]. Antoni et al. developed a cyclostationarity methodology for condition monitoring of internal combustion engines based on angular sampling and cyclic signal processing [23]. Cerdá et al. performed knock detection in diesel engines based on time-frequency analysis of cylinder pressure signal using Choi-Williams Distribution (CWD) via [24]. Chauvin et al. studied real-time combustion parameters of HCCI-diesel engine obtained from the knock sensor [25]. Ettefagh et al. developed a parametric model-based filter to measure the knock intensity of a SI engine. The filter were designed based on advanced parametric modeling method and decomposition of the non-stationary random vibration signals [26]. In recent years, higher-order spectra (HOS) methods like bispectrum and trispectrum have been successfully applied for faults diagnosis in vehicles and rotating machines [5,27,28]. The final targets of such techniques are to achieve a significant reduction in the number of vibration transducers installed at each bearing pedestal, without losing valuable information needed for the diagnosis [5,27]. The order bispectrum analysis also eliminates the effects of rotating speed change on the vibration signal [29].

Diesel engine's injection process is necessary for optimal engine operation in terms of efficiency, power, and torque and reduction of emissions. In general, this process is highly depend on the condition of injection pump and fuel injector. Combustion progress in diesel engines is depend on the characteristics of injection process like the number of injectors and their timing, fuel quantity, and mean injection pressure. Therefore, any changes in characteristics of injection process can effects on the engine block vibrations [30]. It is difficult to extract these information through measuring parameters such as needle position, vibration, or acoustic properties of direct air-borne measurements [31]. Elamin et al. done the identifying of injector faults in a diesel engine using acoustic emission (AE) technique. The AE signals were recorded and processed in the angular, frequency, and jointed angular-frequency domain. The results of angular-frequency analysis was shown that AE can clearly monitor the changes in the combustion process due to its high signal to noise ratio compared to other methods [32]. Jianmin et al. monitored a diesel engine fuel-injection system through vibrations analyzing. The results revealed that vibration signal can potentially be employed for fault diagnosis and obtain information such as crash strength [33]. Albarbar et al. used adaptive filtering to conditioning the injector impact excitations via air-borne acoustic signals. Based on the results, Wigner-Ville distribution (WVD) were useful in analyzing the injector needle impacts [31,34]. In another research, Albarbar et al. investigated the characteristics of diesel engine air-borne acoustic signal by time-frequency domain analysis, and the energy levels within the injection process in the frequency band of 9–15 kHz [34]. Siano and Agostino employed discrete wavelet transform (DWT) to analyze the cylinder block signals of a SI engine for knock detecting. They used a Multi-Resolution Analysis (MRA) and conventional index MAPO for pressure data. The research had very similar results for the both methods [35]. Flett and Bone studied a fault detection and diagnosis (FDD) system for a diesel internal-combustion engine valve train with deformed valve spring faults and abnormal valve clearance faults. Five classification methods were implemented experimentally to monitor valve closing and combustion impacts. The FDD approach using the Naïve-Bayes classification method produced the best performance. The detection and classification accuracy values for multiple faults were 99.95% and 92.45%, respectively [36].

A literature review showed the lack of research focused on the injection fault detection in CI engines using time-frequency analysis. Most of works that studied engine knock detection and therefore, identification of injector faults has not been addressed specifically. In this study of this vibration signal of a six-cylinder diesel engine were evaluated using time-frequency analyses. The experiments were conducted for detection of faulty injectors as well as engine's knocking. The proposed diagnostic method in this paper can detect the faulty injectors through knocking phenomenon. Finally, this research introduced and evaluated a fast and reliable approach for injector fault detection in diesel engines.

2. Materials and methods

2.1. Experimental set up

A direct injection, four-stroke six-cylinder, diesel engine (Perkins 1006-6) was used for experiments. To apply the load on the engine a dynamometer, model Σ5 made by NJ-FROMENT Co, was employed (Fig. 1a) as experimental setup. In this research, the engine was run with two series of healthy and faulty injectors. Injectors which were worked for more than 6 years and did not spray well, were chosen as faulty injectors. Although these faulty injectors did not significantly effect on the engine performance. It