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Characterization of engine's combustion-vibration using diesel and biodiesel fuel blends by time-frequency methods: A case study

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ABSTRACT

Engine knocking and faults usually cause lower efficiency, abrasion in parts, and noise pollution. Various methods have been developed to diagnose faults and detect engine knocking. This research was conducted to study combustion, vibration, and also knocking in diesel engines produced due to the fuels, such as D100, B20, B40, B60, B80, and B100 diesel-biodiesel fuel blends. Therefore, two time-frequency representations (TFR) are used to characterize the non-stationary and noisy vibration signals measured on engine body. For an ideal combustion, the acceleration peak values were found within the frequency range of 0–7 kHz in a TFR diagram. However, each fault in valves and injection units can cause high-frequency vibrations between 7 and 25 kHz for each cylinder in the TFR diagram. It was concluded that the maximum and minimum vibrations were obtained in B40, B20, and D100, B80 fuel blends respectively during full-load engine mode. Moreover, the maximum vibration shocks were obtained for B20 and B40 fuel blends and minimum values were obtained for D100 and B80. The result achieved for B40 fuels blend showed a large amount of combustion energy loss due to the uncontrolled vibrations. However, the smoothest engine performance was obtained for B40 fuel blend.

1. Introduction

Biodiesel fuel is derived from vegetable oils, animal fats, and waste edible oils and is produced by transesterification with methanol or ethanol in the presence of a catalyst. In fact, biodiesel is a methyl or ethyl ester [1,2] and can be blended up to 20% with diesel fuel. In internal-combustion engines, the presence of oxygen in biodiesel fuel reduces the emissions of hydrocarbons, carbon monoxide, and other pollution. However, results obtained from the reported experiments in 2002 showed that the biodiesel had increased 2% of nitrogen oxide (NO_x) emissions for B20 [3].

Various reasons such as combustion and knocking are the main causes of engine vibrations and noise. Compared with spark engines, knocking becomes more rigorous with increasing ignition delay in diesel engines [4]. In this case, knocking creates annoying noises and vibrations, burns the piston crown, and damages to engine parts [5].

Progress in combustion of diesel engines depends on the injection features, such as the number of injections and timings, quantity of fuel, and mean injection pressure. Besides, varying the injection features affects the engine block vibrations [6]. Signal transform methods have been employed to identify knocking from the data captured by accelerometers, which are in time domain, frequency domain, TFR domain [7,8], and wavelet transform [9,10]. TFR transforms are among the novel and practical methods for the analysis of structural health monitoring in vibrating systems. Signal analysis methods have multiple applications in solving vibration problems and diagnosis in rotating machines [11]. For example, Short Term Fourier Transform (STFT) can be used to detect different sources of vibration in an engine. Moreover, this method has been used for identifying normal and abnormal combustion-related knocking in a cylinder block. Using the Fast Fourier Transform (FFT) and FFT-based methods, such as estimated power spectral density, is unsuitable for identifying non-stationary events,

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including cross-terms and systems with rapid changes in time and frequency. However, these methods are fast and have the capability of filtering noises [12]. Considering the literature review, it is necessary to explore the updated procedure.

Previous studies have shown the effect of diesel-biodiesel fuel blends on engine combustion, however, engine knocking has not been investigated carefully in internal diesel engines so far. In this paper, cylinder block vibrations of two types of diesel engines were used in terms of combustion characteristics, knocking, and engine faults.

2. Materials and methods

2.1. Experimental set-up and data acquisition

Two four-stroke diesel engines, a single-cylinder engine (ND130-DT95A), and a six-cylinder engine (Perkins 1006-6) were used for the experiments (Table 1). In these engines, the rotational speed is controlled and stabilized by a governor. These engines are usually used for agricultural tractors. The cylinder firing order is 4-2-6-3-5-1 for the six-cylinder engine. For both engines, valves timing are, IVO 25° before BDC, EVC 28° after TDC, IVC 55° aBDC, and EVO 120° aTDC. A dynamometer was employed to apply the load to the engine (Fig. 1a).

In this study, six fuel blends, B20, B40, B60, B80, pure biodiesel (B100), and pure petrodiesel (D100) were prepared and used. Biodiesel used in this research was produced from waste cooking oil based on ASTMD 6751-09 standard in biodiesel laboratory of Bioenergy Research center, Tarbiat Modarres University (TMU), Iran. Using the Gas Chromatography (GC), the percent of saturated and unsaturated fatty acids were determined. The fatty acid profile of the fried vegetable oils used in this work is summarized in Table 2. According to this composition, 75.69% of used biodiesel are unsaturated fatty acids and only 24.31% are saturated fatty acids. Due to the more unsaturated fatty acids, the cetane number of fuel is low [13].

Table 3 shows the petro-diesel and biodiesel fuel specifications, measured based on ASTM standard. Also, the optimum range for produced biodiesel in ASTM 6751 standard is provided. The cetane numbers of used fuel blends are varied from 58.2 (D100) to 62.5 (B100).

To acquire the engine vibration signals, three accelerometers (made by CTC (AC102-1A), 0–15 kHz) were used. A proximity sensor was used for measuring the angle of engine crankshaft. So, the angle of the crankshaft was recorded simultaneously during the vibration measurement. In this process, the proximity sensor was coupled to the end of the crankshaft. The proximity sensor's pulses and accelerometers vibration signals were transferred to a switchboard. The switchboard output signals were transferred to an analogue-to-digital (A/D) converter (model Advantech, USB-4711A by sampling rate of 150 kHz). After that, the output data cable was connected to the computer USB port to transfer the data (Fig. 1b). The accelerometers' mounting directions were in three orthogonal axes, namely vertical, lateral (for piston slap vibration), and longitudinal (perpendicular to the other axes), respectively (Fig. 1). Data acquiring time was 1 min with the sampling rate of 50 kHz for each experiment after stabilizing the engine. In this interval, the enough vibration data was saved for several engine's working cycles. Starting point of data collection was set with top dead center (TDC) of the piston (No.1) by the proximity sensor. The experiments were conducted in idle and under-load engine conditions. For idle mode, the engine was run at 1000, 1200, 1400, 1600, 1800, 2000, and 2200 rpm. For under-load mode, the engine was run at 1400, 1600, 1800, and 2000 rpm that were under full load.

2.2. Signal analysis for combustion and knock detection

2.2.1. Short-term fourier transform (STFT)

In STFT, first, a signal is divided into small-time sections. Then, Fourier transform is performed for each section to develop a spectrum. The STFT is calculated using Eq. (1):

$$F(\omega,\tau)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty}x(t)h(t-\tau)e^{-j\omega t}\mathrm{d}t \qquad (1)$$

where *h(t)* is a central windowing function at time *t*, which provides the conditions of Eq. (2):

$$\int_{-\infty}^{+\infty}h(\tau)\mathrm{d}\tau=1 \qquad (2)$$

Spectrogram or energy density spectrum of the STFT is derived from Eq. (3):

$$STFT(\omega,\tau)=|F(\omega,\tau)|^2=\left|\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty}x(t)h(t-\tau)e^{-j\omega t}\mathrm{d}t\right|^2 \qquad (3)$$

For the discrete-time analysis, the STFT is defined as Eq. (4):

$$STFT(m,\omega)=\sum_{n=-\infty}^{+\infty}x[n]h[n-m]e^{-j\omega n} \qquad (4)$$

2.2.2. Morlet scalogram distribution

Morlet scalogram is the square of wavelet transform and is calculated using Morlet wavelet. Wavelet transform uses windowing, which is different from the constant window applied in the short-time Fourier transform. The wavelet function for input signal $x(t)$ is defined as Eq. (5):

Table 1
Technical specifications of two different diesel engines.

Engine ND130-DT95A	Engine Perkins 1006-6
Manufactured by Daedong, Korea	Manufactured by Motorsazan, Iran
Number of cylinders, 1	Number of cylinders, 6
Direct injection	Direct injection
Fuel injection time, 22° before TDC	Fuel injection time, 22° before TDC
Common power in 2200 rpm, 7.3 kW	Maximum power in 2200 rpm, 82 kW
Maximum power in 2400 rpm, 9.5 kW	Maximum torque in 1200 rpm, 431Nm
Maximum speed, 2400 rpm	Maximum speed, 2300 rpm