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Diesel engine fuel injection monitoring using acoustic measurements and independent component analysis

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ABSTRACT

Air-borne acoustic based condition monitoring is a promising technique because of its intrusive nature and the rich information contained within the acoustic signals including all sources. However, the back ground noise contamination, interferences and the number of Internal Combustion Engine ICE vibro-acoustic sources preclude the extraction of condition information using this technique. Therefore, lower energy events; such as fuel injection, are buried within higher energy events and/or corrupted by background noise.

This work firstly investigates diesel engine air-borne acoustic signals characteristics and the benefits of joint time–frequency domain analysis. Secondly, the air-borne acoustic signals in the vicinity of injector head were recorded using three microphones around the fuel injector (120° apart from each other) and an independent component analysis (ICA) based scheme was developed to decompose these acoustic signals. The fuel injection process characteristics were thus revealed in the time–frequency domain using Wigner–Ville distribution (WVD) technique. Consequently the energy levels around the injection process period between 11° and 5° before the top dead centre and of frequency band 9–15 kHz are calculated. The developed technique was validated by simulated signals and empirical measurements at different injection pressure levels from 250 to 210 bars in steps of 10 bars. The recovered energy levels in the tested conditions were found to be affected by the injector pressure settings.

1. Introduction

The increasing interest in environmental problems has necessitated the improvement of engine performance, and reduction of noise and pollutant emissions. One of the key components, which determine engine torque, emissions, noise quality and fuel consumption, are the fuel injection equipment and the intake management system. The effects of the injection timing on the engine emissions and exhaust gas have been studied in [1]. Injection pressure, fuel quantity, injector opening and closing timings are the keys to the ideal injection process condition monitoring system. These parameters should be kept at their optimum values to reduce the fuel consumption and pollutant emissions, and increase the output power. However, measuring these parameters could not be done without fixing sensors and introducing a permanent damage into the system which may influence these parameters, e.g. needle lift and injection pressure measurement. Injection process induced noise and air-borne acoustic signals have been sporadically studied for many years. However, previous work has focused on topics other than the noise radiated from the injector itself [2–4]. The moving mass inside the injector is a small in the order of 15 g, and this mass takes a very short time, in the order of 1–3 ms, from the fully open to fully closed position. There is a distinct opening and closing vibrations and acoustic signals for most injectors. The opening vibrations and induced acoustic signals are due to the moving mass hitting the upper stop and

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the closing ones are due to the moving mass hitting the seat. As a result, the acoustic signals induced by the diesel injector are very short click, with broad frequency content, and radiated from the surface of the injector itself or transmitted through the fuel system or the engine block. Unfortunately, these diagnostic signatures are dominated by the other energy sources and corrupted by background and interference noises.

Most of the work in the literature on diesel fuel injection has been devoted to describing the noise and vibration generated by the fuel pumps and fuel lines. Injector dynamics, needle movements and their resulting vibrations were studied by Gu and Ball [5,6]. They described the vibration characteristics of injectors by three series of transients during an injection cycle; fluid excitation commencing prior to needle impact, needle opening impact and needle closing impact. The injection process was also studied by Gill et al. [7] using acoustic emission and has achieved better results than vibration signatures in detecting the pressure build up activities prior the opening of the needle valve. The injection and exhaust valves opening and closing events were also studied using acoustic emissions in [8]. In this work the injection induced air-borne acoustic signals measurements were recorded remotely and ICA based scheme was developed to monitor injector operation parameters. Fig. 1a shows engine (four cylinders, direct injection) air-borne acoustic signals measured using a microphone located 1 m above the floor and 1 m away from the cylinder manifold with the engine running at an average speed of 1000 rpm (16.7 Hz) and with no load [9–11].

The air-borne acoustic signal shown in Fig. 1a was enhanced by averaging. In practice, it is frequently the case that with a repeated signal, the signal to noise ratio can be improved by averaging, particularly where the corruption of the signal is due to unwanted noise occurring as a result of random events. Time-domain averaging is a way to reduce the content of undesired components in a signal.

The main feature could be observed from the acoustic waveform, shown in Fig. 1a, is four peaks corresponding to the engine firing sequence and these represent combustion events in the cylinders 3, 1, 2 and 4 respectively. What makes the waveform complicated and difficult to extract information from is the numerous frequency components superimposed on each other. In the associated power spectrum, shown in Fig. 1b, four peaks can be seen; the first at twice the frequency of revolution (33.4 Hz), the second at four times the frequency of revolution (66.8 Hz), the third at 100 Hz and the fourth at 470 Hz. The amplitudes of any higher harmonics can be ignored because they contain considerably less energy than the first four leading terms. Each cylinder experiences fuel injection and combustion once for every two complete revolutions of the crankshaft. Thus the number of 'combustions' per single revolution of the camshaft will be equal to (number of cylinders)/2. Here there are four cylinders, so there will be two combustion processes during each complete revolution of the camshaft, and the corresponding noise peak will occur at twice the fundamental frequency ($2 \times 16.7 \approx 33$ Hz). The amplitude of this peak is highly dependent on the combustion conditions. The second peak (67 Hz) is probably due to closing knock of the valves, which occur twice per crankshaft revolution, every second revolution in each cylinder. By increasing the load the amplitude of both of these peaks increase. The third peak at 100 Hz, which corresponds to

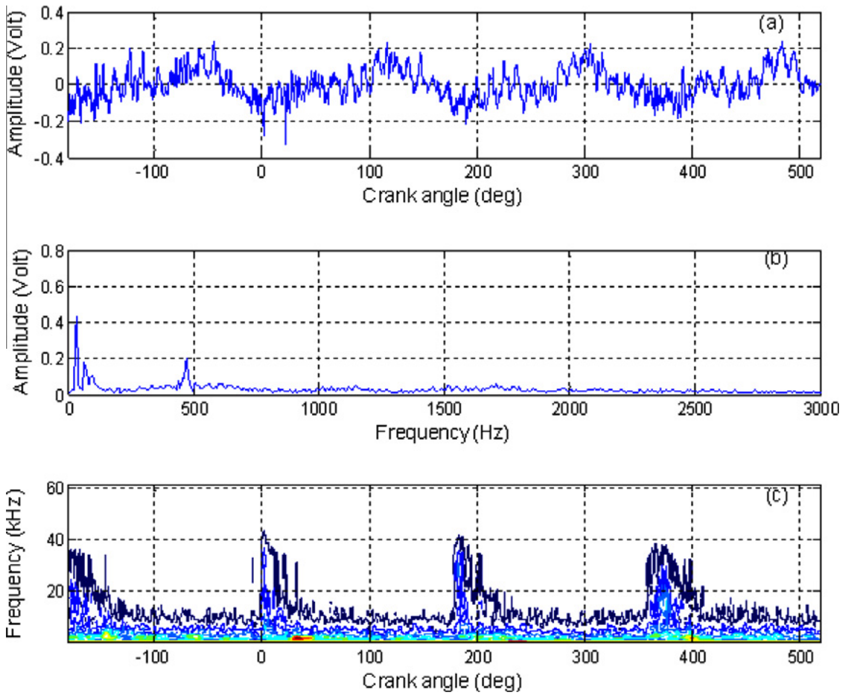

Fig. 1. Air-borne acoustic signal representations at zero load and 1000 rpm, microphone 1 m from the engine and 1 m above laboratory floor (a) time domain (b) frequency domain (c) time–frequency contour plots.