Injection Fault Detection of a Diesel Engine by Vibration Analysis

Ezzeddine Ftoutou and Mnaouar Chouchane

Abstract In this paper, the potential of vibration analysis for early detection of fuel injection faults in an internal combustion diesel engine, having six cylinders in line, has been investigated. The main sources of vibration of a diesel engine, as well as the mechanism of propagation of these sources to the engine structure have been presented. Using the tarring screw of the injector, the injection pressure in one of the cylinders has been gradually reduced from its nominal value, respectively, by 10 and 50%. Two signals are acquired using an analog-to-digital dynamic acquisition card. The first is the TDC signal in cylinder 1 measured using an inductive sensor. The second is the vibration signal which has been measured, on the cylinder head of the engine using a piezoelectric accelerometer. The vibration signal has been analyzed in the crank-angle domain, the frequency domain using the Fast Fourier Transformation, and in the angle-frequency domain using the Short Fourier Transform. The analysis of the injection fault signals in the three domains showed that in the crank-angle domain, a visual analysis gives limited information; in the frequency domain, the identification of the cylinder with the faulty injector is not possible; and in the angle-frequency domain, the detection of the injection fault and the identification of the faulty cylinder are possible and not complicated.

Keywords Injection fault · Diesel engine · Vibration analysis
Fault detection

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1 Introduction

Early detection of diesel engine faults is essential in order to take early correction actions and avoid costly repair. Injection faults due to defects in a fuel pump, fuel lines, and injectors affect the power of the engine, increase the polluting particles in the exhausted gas, increase the radiated noise, and reduce the life cycle of the engine. Higher injection pressure increases the pollutants in the emission and increases fuel consumption. A lower pressure, however, reduces the engine power and efficiency (Çelikten 2003).

Vibration measurement on the engine block or cylinder head is a non-intrusive method and has been used successfully for fault detection of diesel engines (Chandroth 1999; Antoni et al. 2002; Geng et al. 2003; Antoni et al. 2004; Carlucci et al. 2006; Ftoutou et al. 2012; Ftoutou and Chouchane 2016). Signal processing techniques of the vibration signals are used to extract features sensitive to faults and less sensitive to noise. In the present work, the potential for early detection of injection defaults using vibration signals is investigated. In the experimental work, a six-cylinder in-line diesel engine has been used. The injector pressure of one of the cylinders has been reduced gradually from its nominal value by 10 and 50%. Vibration signal has been analyzed in the angular domain, the frequency domain and angle-frequency domain.

2 Vibration Analysis of an IC Engine

The measured vibration on the engine depends on the excitations and the propagation path. The main sources of excitation likely to affect the engine vibration response include impacts due to piston clearances (piston slaps), fuel injection pressure, high rise of gas pressure during combustion, and the impacts of admission and exhaust valves. Some of these faults affect the vibration signal simultaneously and during a limited portion of the engine cycle. A fault is usually detected by comparing the vibration signal of the faulty engine to the reference signal or signature. In angular domain, the presence of several simultaneous faults makes the separation of the sources a difficult task in time or angular domain. Classical Fourier spectrum is more useful for the analysis of stationary signals associated to rotating machines. For nonstationary engine vibration signals, the spectrum tends to smear frequency components. Joint time–frequency analysis methods or angle-frequency analysis have more potential for source separation since the frequency content of the signal is analyzed during time or angle variation.

3 Internal Sources of Vibration in an IC Diesel Engine

Measured at any point on the internal combustion engine structure, the vibratory signal is composed of a very complex superposition of the contributions of different vibratory sources modified by their respective transmission paths. These sources originate from several internal phenomenon's in the engine and excite the natural modes of the engine. The vibration is amplified at the natural frequencies of the engine. Therefore, the produced vibration and the noise radiated from the engine result from the combination of the excitations and the dynamic response of the structure. Diesel engine vibration is caused by several mechanical and thermal sources applied sometimes simultaneously at different phases of the engine cycle. In the following, the main sources of vibration of a diesel engine, as well as the mechanism of propagation of these sources to the engine structure are described.

3.1 Combustion Forces

During the phase of combustion, a significant and brief increase of the pressure in the engine cylinders occurs. The combustion causes a descending motion of the pistons and the rotation of the crankshaft. The combustion force is sometimes described as comparable to a hammer stroke and depends on the power demand of the engine. Excitations due to combustion forces are periodic and spread to frequencies up to several kHz (Lecelère 2003). The shock of the combustion pressure applies a direct excitation on the engine head (1), Fig. 1. This path constitutes the first way of propagation. On the other hand, the shock due the sudden pressure rise excites the mobile components (piston-rod-crankshaft) in two ways

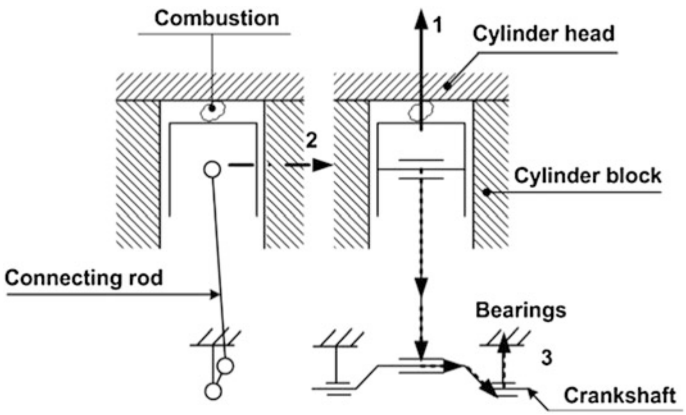

Fig. 1 Combustion force

- the transverse excitation (2), Fig. 1, is transmitted through the piston to the cylinders while conjugating with the piston slap,
- the vertical excitation (3), Fig. 1, propagates through the mobile parts to the crankcase bearings.

3.2 Piston Slaps

Piston slap is another important source of vibration in diesel engines. It is caused by the inversion of the inertia forces of the piston in the neighborhood of the top dead center (TDC). Piston slap results from the succession of two strong shocks. One shock is applied by the upper part of the piston while the other shock is applied by the lower part of the piston. The piston slap vibration covers a large range of frequencies that spread up to several kHz.

3.3 Inertia Forces

The alternating motion in the engine excites the moving parts (piston, rod, and crankshaft) by the action of the highly variable inertia forces. The inertia forces are quasi-harmonic and results into mechanical vibrations in the low frequencies, up to the first few lower harmonics of the rotating speed of the crankshaft (Lecelère 2003). The inertia forces vibration depends on the engine regime, its geometry, and the mass and inertia of the moving parts. The inertia forces are transmitted to the cylinders by the pistons at positions in the neighborhood of the TDC, at the time when friction forces are inverted and vary significantly in time. The inertia forces are also transmitted to the crankshaft bearings through the crankshaft.

3.4 The Injection Forces

The injection of diesel fuel under a high pressure (about 270 bars for the engine used in this study) during a very short time (some micro-seconds) creates a mechanical shock. Furthermore, the spring of the needle of each fuel injector is also a source of secondary importance contributing to cylinder head vibration.

3.5 The Distribution System Forces

Distribution system vibrations are generated by the impacts of the intake and exhaust valves on their seats as well as the excitation of the valve tails by the rocker arms. The camshaft generates vibrations which are transmitted to the upper part of the engine through the rockers and the rocker arms. Gas flow in the manifolds and through the intake and exhaust valves and the gearing of the distribution belt or gears are also additional sources of vibration.

4 Measurement Set Up

In this study, an internal combustion diesel engine having six cylinders in line, a power of 260 CV at 2200 rpm and a maximum torque of 1020 Nm at 1200 rpm are used. The fuel is injected directly into the combustion chambers at a pressure of 270 bars in the following order 1-5-3-6-2-4. A piezoelectric accelerometer has been used for the acquisition of the vibration signal. The signal provided by the accelerometer is first amplified by a charge amplifier and then connected to an analog input channel of a PC plug-in acquisition card. A second input channel of the acquisition card has been used for the reference signal used to identify the TDC of cylinder 1. Figure 2 shows, from top to bottom: TDC signal and vibration signal. The time interval between two pulses is equal to the period of one engine cycle (two crankshaft revolutions, i.e., 720° of crankshaft rotation).

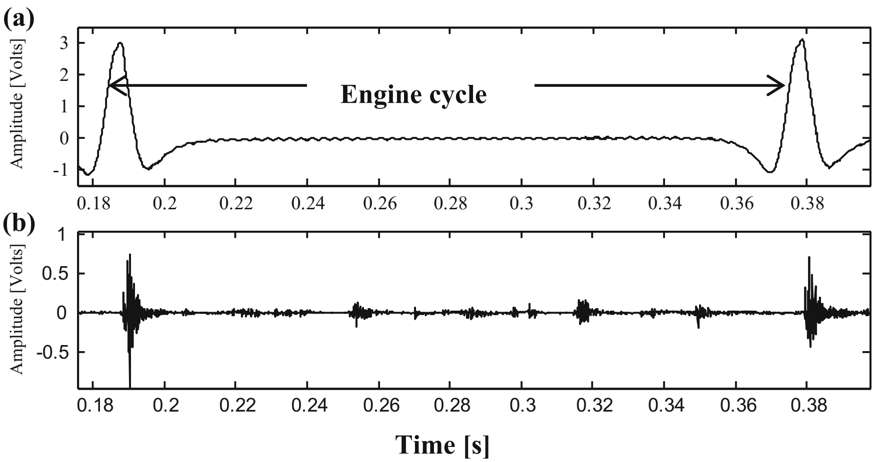

Fig. 2 Measured signals. **a** the TDC signal and **b** the vibration signal

5 Analysis in the Time Domain

In the time domain, a visual analysis gives usually limited information. Figure 3 represents three signals corresponding to the three sstudied cases (nominal injection pressure and pressures reduced respectively by 10% and 50% for cylinder 6). Each signal covers one cycle (two crankshaft rotations). Every signal contains 4096 samples.

Statistical analysis of one cycle signal can be used to compute scalar parameters such as maximal value, the mean, the root mean square, Skewness, the Kurtosis, and other parameters (Ftoutou et al. 2012). These parameters can further be computed for segments of the divided signals. For example, the signals shown in Fig. 3 contain six events and may therefore be divided into six segments. The vibration due to the combustion in the cylinder 6 is more sensitive to the injection faults induced into this cylinder. The scalar parameters for the interval highlighted in Fig. 3 are expected to have larger variation caused by the simulated faults. The statistical analysis of the vibrations signals is not presented in this paper.

The reference vibration signal corresponding to the no-fault state measured on the cylinder head is shown in Fig. 3a. The reference signal corresponds to an idle speed of 500 rpm and no applied charge. The vibration level when any one of the pistons reaches its TDC is significantly higher for a crank-angle rotation of about 10°. These vibrations, occurring six times per cycle, are essentially due to fuel injection and combustion pressure and can be visually detected. The accelerometer used for vibration measurement has been fixed in the vertical direction between cylinder 3 and 4. Thus, the vibrations due to combustion in these chambers are the highest respectively at an angle 240° and 600°. The vibration due to cylinders distant from the accelerometer has a lower energy. Figure 3b, c show the vibration

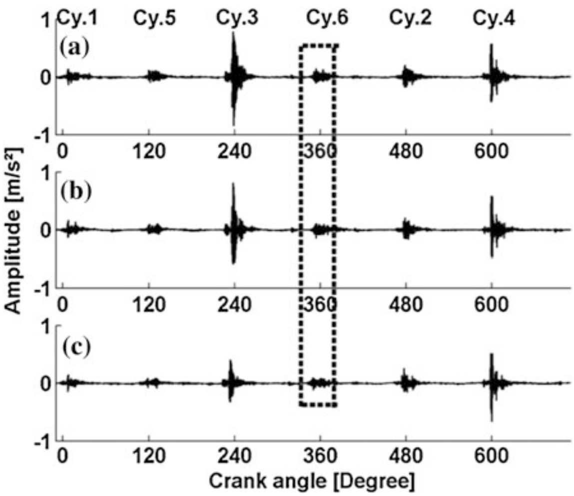

Fig. 3 Vibration signals in the time domain. **a** For a nominal injection pressure, i.e. 270 bars, **b** for an injection pressure reduction of 10% and **c** for an injection pressures reduction of 50%

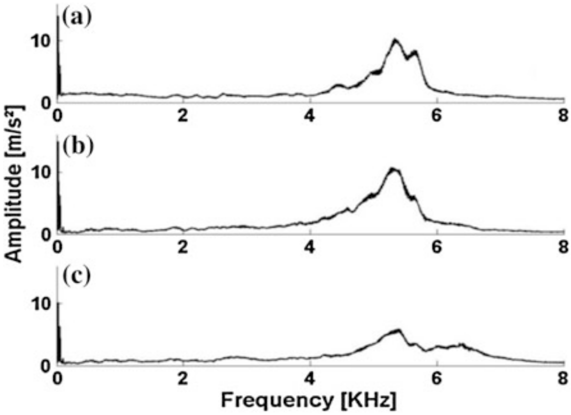

Fig. 4 Frequency spectrum of the vibration signals of Fig. 3. **a** For a nominal injection pressure, i.e. 270 bars, **b** for an injection pressure reduction of 10% and **c** for an injection pressures reduction of 50%

signals when the injection pressure at cylinder 6 is reduced respectively by 10% and 50%. The effect of these induced faults in the angular domain is hardly noticeable.

6 Frequency Analysis

The vibration signals in the frequency domain are obtained using the Fast Fourier Transformation (FFT). Figure 4 shows the spectrum of the reference case (no fault) and the spectrum of each of the two faulty cases. Each spectrum has been average over 100 spectrums of 100 successive cycles. Each cycle contains 4096 samples. The FFT bloc size is 4096, which is equal to the number of samples in one cycle.

Figure 4a–c shows the vibration spectrum of the signals of Fig. 3. High vibration energy can be observed between 4 and 6 kHz. Even though a reduction of the pressure by 50% has reduced the vibration energy in this frequency domain, it is not possible from this spectrum to determine which cylinder has a faulty injector.

7 Time–Frequency Analysis

For stationary signals, frequency analysis is a useful and the most frequently used signal processing tool. The frequency content of nonstationary signals, however, varies with time and therefore time–frequency analysis tools should be used for a more in depth analysis. Parametric and nonparametric approach can be used for frequency analysis and time–frequency analysis. The parametric approach fits a model to the data and has the advantage of not being prone to spectral leakage due to signal truncation. The Short Fourier Transformation (STFT), used in this work, is a basic time–frequency method. It permits the processing of a signal by decomposing the signal into short blocs and computing the spectrum of each bloc.

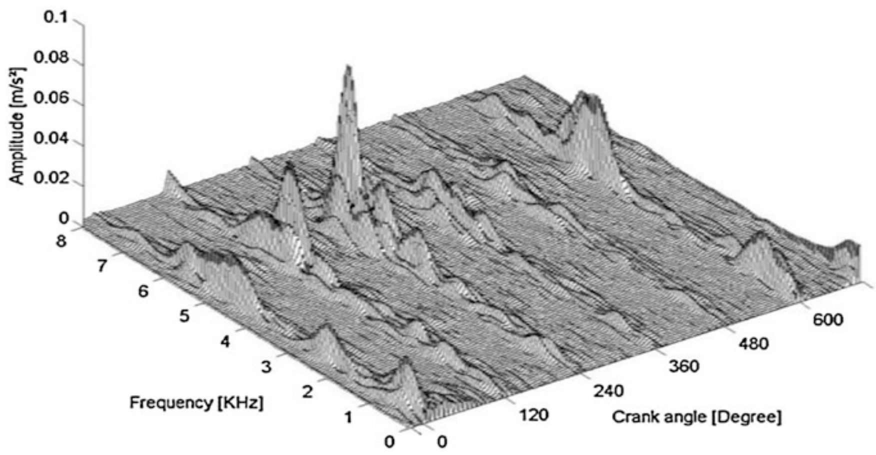

Fig. 5 Angle-frequency representation of the reference signal

Different type of windows can be used to reduce spectral leakage. A Gaussian window is usually used. Certain overlaps of bloc samples are frequently applied in order to reduce information loss since the window function time–frequency analysis methods are used to determine the frequency content at each time (Chandroth 1999; Stankovic and Böhme 1999; Antoni et al. 2002; Antoni et al. 2004; Carlucci et al. 2006; Wang et al. 2008; Ftoutou and Chouchane 2016). For the engine vibration, angle-frequency analysis in which time is replaced by the crank angle is more useful and has been used in this research work. Angle-frequency spectrum, Fig. 5, is given for the reference no-fault state. Large vibration levels occur at crank angles integer-multiple of 120°, when the piston of each cylinder reaches the top dead position and immediately afterward during combustion. The vibrations at these angles are significantly larger in the 4–6 kHz frequency domain and last about 10° especially for cylinders 3 and 4. Low frequency vibrations, due probably to the motion of the pistons and other moving parts, appear particularly away from the TDC positions and reach a maximum frequency around 50 Hz. It is expected that an increase of crankshaft and piston bearing gaps affect particularly these lower vibrations. An injection fault, however, is expected to affect higher frequency vibration. Figures 5, 6, and 7 show the angle-frequency spectrum of the reference signal and those with 10 and 50% pressure reduction of the injector of cylinder 6. By examining these figures, around the 360° angle, multiple peaks in the 4–6 kHz region, which are affected by the injection pressure alteration, are observed.

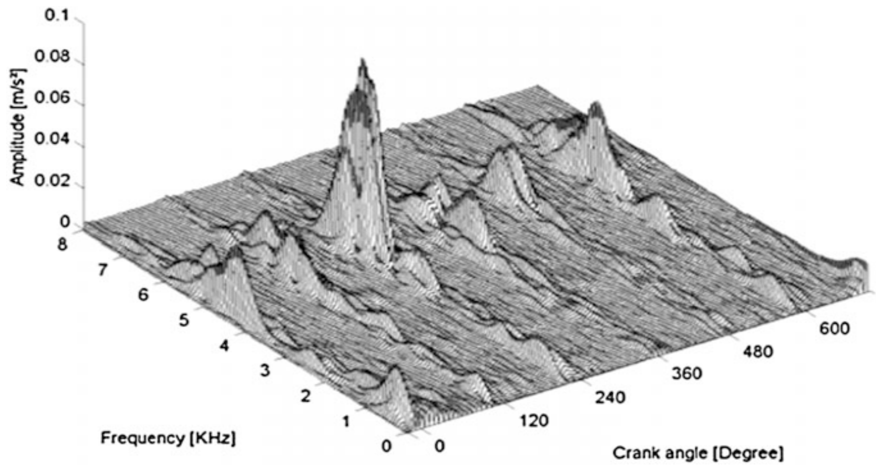

Fig. 6 Angle-frequency representation for pressure reduction of 10%

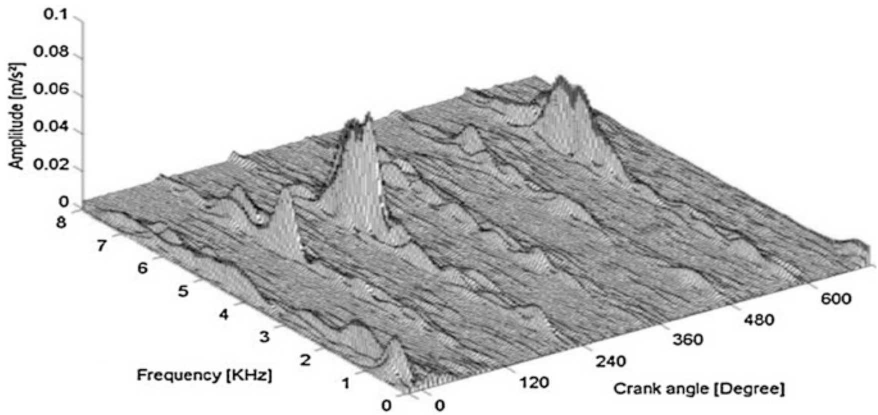

Fig. 7 Angle-frequency representation for a pressure reduction of 50%

8 Conclusion

Angle-frequency representation of the vibration signal measured on the cylinder head are shown to be useful for the detection of injection faults. This type of representation has the potential of separating several sources of excitation occurring at the same time but having different frequency content. Further research work can be oriented toward the extraction of features from the angle-frequency spectrum. The engine faults may then be identified using these features.

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