Analysis and Comparison of Vibration Signals from Internal Combustion Engine Acquired Using Piezoelectric and MEMS Accelerometers

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Abstract

Condition monitoring of vehicles with internal combustion engine is of immense importance due to high number of vehicles with such engines and their importance to transport and economy. As many persons use a vehicle which is old and inexpensive, a condition monitoring system designed for such vehicles cannot be expensive. Unfortunately, condition monitoring of engines is usually based on the use of vibration signals, which are acquired by accelerometers. Piezoelectric accelerometers are the most commonly used for this purpose, and such accelerometers are not cheap. However, an alternative exists in the form of microelectromechanical systems (MEMS) accelerometers, which are much cheaper, but have narrower frequency characteristics. This paper describes preliminary results of a research on feasibility of use of MEMS accelerometers for condition monitoring and failure detection in internal combustion engines.

Keywords: MEMS accelerometers, vibration signal processing, spectrogram, Wigner-Ville spectrum

1. Introduction

Condition monitoring is a widely-used technique that allows for early detection of machinery faults or failures in order to reduce maintenance costs and downtime. Application of condition monitoring allows to improve reliability and productivity of the equipment and safety of its operators [1]. A comprehensive condition monitoring program includes detection, diagnostics and prognosis.

Condition monitoring usually applies to a number of machines that operate under heavy environmental conditions, like high temperatures, high humidity, high load, etc. Among these machinery, condition monitoring of internal combustion engines (ICE) is a particularly difficult task due to complexity of ICEs [2]. However, it is also very important due to importance of transport for the economy [3].

The age of motor vehicles in use still increases, and the older a vehicle, the higher the probability of its defect or failure; therefore, condition monitoring of vehicles is of vital importance. This, however, requires a special monitoring hardware to be installed in the vehicle permanently. Such hardware cannot be expensive, if it is intended to be installed in old, cheap vehicles.

Although different techniques also exist, diagnostics and condition monitoring of ICEs are mainly based on vibration and acoustic signals [1]. Vibration signals are acquired by means of accelerometers, which need to be installed on a flat surface using screw joints or a special wax. Commonly used piezoelectric accelerometers allow to acquire signals in the frequency range up to 15 kHz, or more. These transducers are not cheap, with prices starting at around $300, and reaching several thousands dollars. This makes application of a system based on such accelerometers in older cars economically unreasonable. Fortunately, less expensive alternative exists in the form of MEMS accelerometers.

Nowadays, microelectromechanical systems (MEMS) is a technology that allows for manufacturing of microscopic devices, particularly those with moving parts. This technology allowed for production of low-cost accelerometers, and recently also microphones [4]. The application of MEMS accelerometers and microphones in a vehicle condition monitoring system seems attractive, even if the accelerometers usually have substantially narrower frequency ranges than piezoelectric devices. However, it is necessary to elaborate on minimum requirements concerning the MEMS accelerometers first, and to compare their performance with piezoelectric accelerometers. Indeed, this paper describes some preliminary results of comparison of cheap MEMS accelerometers and good quality piezoelectric accelerometers in application to ICE monitoring.

2. MEMS accelerometers and controller board

The first stage of the research was to select sensors suitable for data acquisition in the designed application. Regarding the accelerometer, the basic requirements were three-axial measurement and wide acceleration range. However, the greatest concern was the frequency range of the measured acceleration. Unfortunately, the price of MEMS accelerometers is proportional to the frequency range.

Based on analysis of frequencies corresponding to ICE operation in the rotational speed between 0 and 6000 rpm, vehicle's wheel rotational speed, and considering that higher frequencies are generated by rolling bearings, the ADXL345 accelerometer by *Analogue Devices* was selected [5]. This accelerometer is a 3-axial MEMS device, with sampling frequency up to 3.2 kHz, configurable acceleration ranges from 2 to 16 g, and supply voltage from 3 to 5 V. The device is available on a small PCB, simplifying its installation, and comes at a price less than $3.

Two ADXL345 accelerometers were connected to the STM32F407G-Discovery board, which was selected as an optimal choice for rapid development regime. The STM Discovery board is equipped with the STM32F407VGT6 microcontroller, clocked at 168 MHz, what is sufficient to receive the accelerometer's data with 3.2 kHz sampling rate. The project assumed that the device will be installed in a vehicle; therefore, the controller board needed to be protected against harsh environmental conditions, including vibrations, moisture condensation and dust. The simplest solution was to use a plastic case, inside which the controller board was fixed together with additional hardware components, like power supply and flash memory. The design was carefully tested in a number of experiments, using a digital signal analyzer. Figure 1 presents the exploded view of the device, and the MEMS accelerometer fixed to a small piece of rectangular pipe, which simplifies its installation.

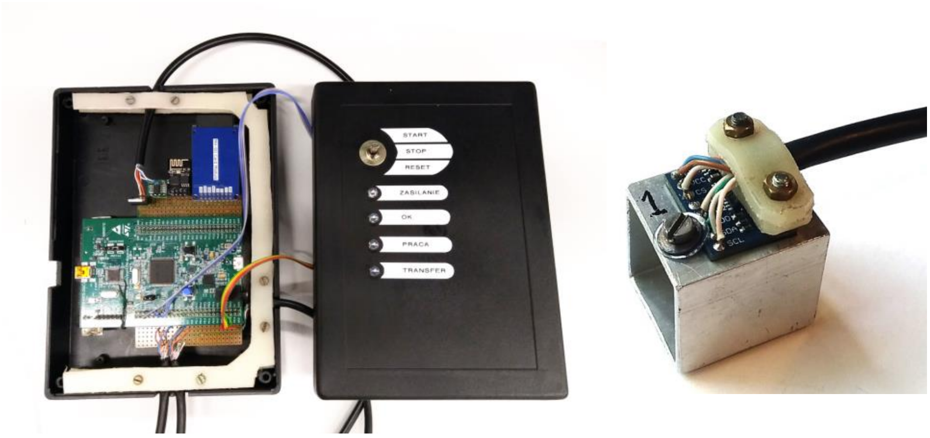

Figure 1. The controller board in its casing (left)
and the MEMS accelerometer mounted on a piece of rectangular pipe (right)

3. Measurement setup

To evaluate quality of the signals from MEMS accelerometers, good-quality piezoelectric devices needed to be used as reference accelerometers. For this purpose, the PCB 622B01 accelerometers were selected, which are high-quality ceramic shear devices, with frequency range 0.2 Hz to 15 kHz. The PCB 622B01 accelerometers will be further referred to as the "reference accelerometers". The reference accelerometers were connected to a National Instruments NI-9234 sound and vibration input module. The acquired signal was downsampled (using a proper decimation technique, i.e. with anti-aliasing filtration) to 3.2 kHz.

The accelerometers were installed on a passenger vehicle's internal combustion engine chassis, using a wax. One accelerometer was placed on the screw securing the cylinder head cover. The other was placed on the lower part of the engine's block. The measurements were acquired with the first set of accelerometers, and the engine was cooled down, so the wax could work again. Then, the second set of accelerometers was waxed in the same positions, and the second set of measurements was acquired. The results presented and discussed below are based on the measurements from the accelerometers placed on the cylinder head cover only.

Each experiment was began with starting the engine and allowing it to run idle for several seconds. Next, the engine rotational speed was slowly increased, up to 5000 rpms, and than slowly decreased to idle. Finally, a small engine defect was introduced, in a form of one cylinder misfire, by unplugging one of the engine's sparks. Figure 2 presents the time plot of the signal acquired from the MEMS accelerometer during the experiment.

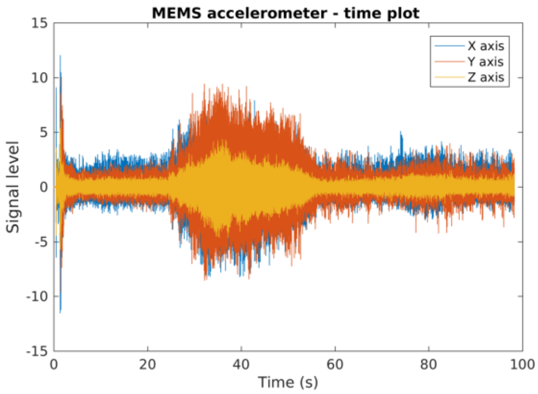

Figure 2. Time plot of the signals acquired from the MEMS accelerometer

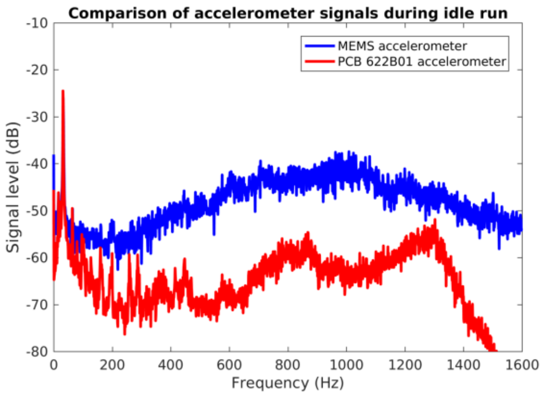

Figure 3. Spectra of the accelerometer signals during ICE idle run

4. Results

The first analysis considered the part of the signal when the engine was running idle. The engine's rotational speed was approximately constant; therefore the analysis could have been performed by plotting power spectra of the signals from the accelerometers, as presented in Fig. 3. Each spectrum was obtained by dividing the acquired signal into six segments and averaging the spectra of each segment.

The fundamental engine frequency, equal to double the engine rotational speed, is clearly visible in the figure. As the engine idle run was at around 950 rpm, the frequency is equal approximately 32 Hz. A number of harmonics can also be observed in both the reference and the MEMS accelerometer signal. It can also be noticed that the MEMS accelerometer produced a substantially higher level of signal in frequency range between 200 and 1200 Hz. (The decreasing level of the reference accelerometer spectrum is due to anti-aliasing filtration performed during the signal decimation).

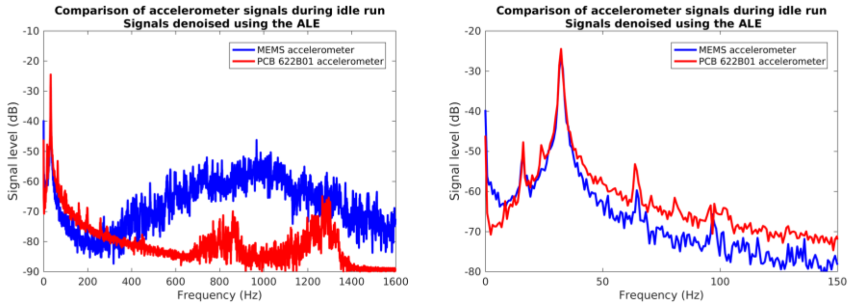

Figure 4. Spectra of the accelerometer signals during ICE idle run after de-noising using the ALE (left). Zoomed part of the spectrum (right)

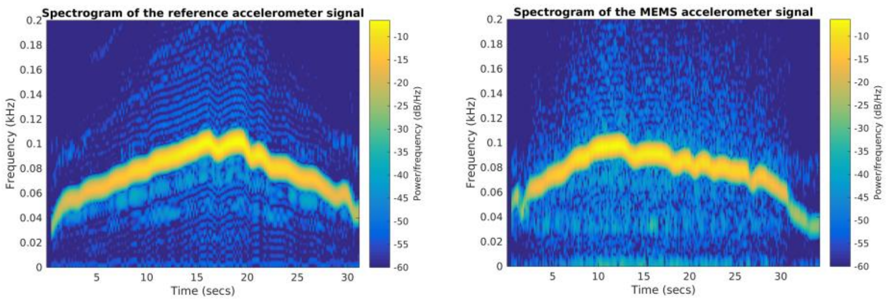

Figure 5. Spectrograms of the accelerometer signals during up-down engine run after denoising using the ALE. Reference sensor (left), and MEMS sensor (right)

A simple technique to enhance signal quality is called the *adaptive line enhancer* (ALE) [6]. This technique proved very effective in extracting sinusoidal signals embedded in a large amount of noise. Therefore, both the signals were filtered using the ALE with 1000 parameters. Figure 4 shows the spectra of the signals thus processed. It can be noticed that the enhancement worked very well, and the spectra show a very good level of similarity in the frequency range between 0 and 150 Hz. However, the levels of the signals differ significantly in the frequency range between 400 and 1300 Hz. This is probably due to poorer quality of the MEMS accelerometers, and it needs to be further researched.

As the ALE technique worked well, it was also applied for the part of the signal, when the engine's rotational speed was increased up to 5000 rpm, and decreased down to idle. However, the signal obtained during this phase cannot be treated as stationary, and therefore time-frequency analysis should be applied. One of the simplest and well-known techniques of time-frequency analysis is the spectrogram [7]. Spectrograms of the signals acquired with the reference and MEMS accelerometers are presented in Fig. 5. For clarity of the presentation, only the frequency range from 0 to 200 Hz has been shown. In this range, the fundamental frequency of the engine is clearly visible. Moreover, the spectrogram of the reference sensor signal shows also a number of other curves, which may depict harmonics of the fundamental frequency. These curves are not visible in the MEMS sensor signal, which appears to contain more noise.

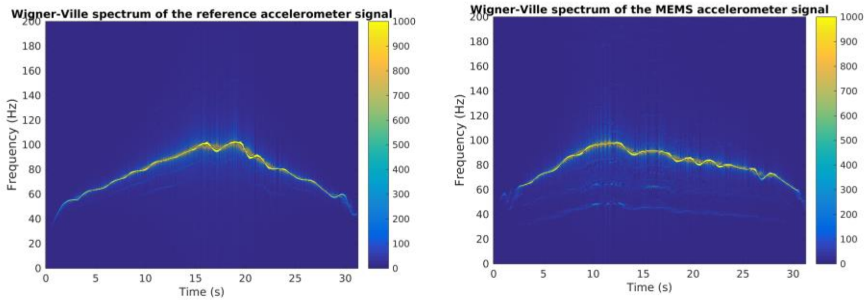

Figure 6. Wigner-Ville spectrum of the accelerometer signals during up-down engine run after de-noising using the ALE. Reference sensor (left), and MEMS sensor (right)

The main disadvantage of the spectrogram is its poor resolution, what is clearly visible in Fig. 5, where the power of the signal is spread over a range of frequencies. Therefore, a better distribution was used in the form of the Wigner-Ville spectrum [7] – see Fig. 6. In the Wigner-Ville spectrum, the engine's fundamental frequency is easily visible and can be precisely determined. Moreover, the spectrum of the MEMS sensor signal does not appear so noisy, and both the spectra show a couple of subharmonics. On the other hand, the harmonics, which were clearly visible in the spectrogram of the reference sensor signal, disappeared. Nevertheless, the overal quality of the result is much better in case of the Wigner-Ville spectrum, compared to the spectrograms, and both the signals present comparable amount of details.

Finally, the last part of the signal was analyzed. It was the part where the engine defect, in the form of one cylinder misfire, was introduced. As the engine was running at approximately the same rotational speed, this parts of the signals can be considered to represent stationary processes, and can be analyzed by the means of their spectra. The spectra are presented in Fig. 7.

Comparing the spectra in Fig. 7 with the spectra of the engine without the defect, presented in Fig. 4, reveals that the spectra show more frequency components when the engine is defected. However, the components probably are subject to small frequency fluctuations, usually referred to as frequency smearing [8]. The smearing makes a particular frequency component to appear as an increased variance of the spectrum. Averaging of the spectra can flatten such variance, and using more averaged segments can make such frequency components unrecognizable.

More differences between the ICE in idle run and the ICE with the defect are visible in the zoomed part of the spectra, showing the frequency range between 0 and 150 Hz. When the engine was running without the defect (i.e. in Fig. 4), four sinusoidal components were clearly visible in this frequency range. On the other hand, when the engine experiences one cylinder misfire, between eight and ten sinusoidal components can be recognized. Particularly clearly visible, and with high level, are the three sub-harmonics of the main frequency – the components with frequencies 8.19, 15.36, and 23.55 Hz. What is important, these components are visible in both the reference and the MEMS accelerometer signals. This proves that the MEMS accelerometer can provide with signals of quality sufficient for condition monitoring of the engine.

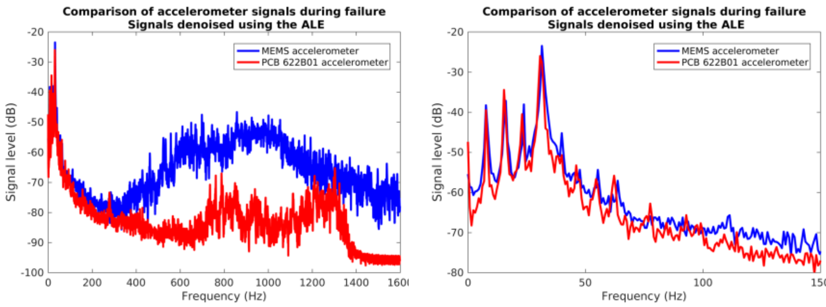

Figure 7. Spectra of the accelerometer signals during ICE one cylinder misfire, after de-noising using the ALE (left). Zoomed part of the spectrum (right)

5. Conclusions

The research reported in this paper considered the application of MEMS accelerometers to condition monitoring of internal combustion engines. MEMS accelerometers are recently very popular sensors, with application in many areas of life, including cellphones, smart watches, toys, and others. For this purpose, MEMS accelerometers are generally cheap, especially comparing to high-quality piezoelectric devices. However, the price is correlated to the frequency range and signal quality.

In this research, the ADXL 345 MEMS accelerometer was compared with the PCB 622B01 device. The former comes at a price of less than $3, the latter costs around $350. The ADXL 345 accelerometer has a frequency range from 0 to 1.6 kHz. Its overall performance in the tests was good. The signals acquired with both the accelerometers had comparable quality in the frequency range up to 200 Hz. Above this frequency, the MEMS accelerometer produced a higher level of wide-band signal, which was probably measurement noise. Nevertheless, both the signals allowed to recognize an increased level of harmonics when a small defect of the engine, in the form of one cylinder misfire, was introduce.

The signals acquired from both the accelerometers during engine's run-up and run-down were processed by Wigner-Ville spectrum estimate as well. In both cases the Wigner-Ville spectrum presented similar level of details.

To conclude, the ADXL 345 MEMS accelerometer is certainly suitable for condition monitoring of an ICE, if the frequency range up to 200 Hz is sufficient. Further research is necessary to confirm its usefulness in higher frequency range.

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