Comparison of spectral analysis of vibration using commercial knock sensor and 3-axis acceleration sensor

Ł Zieliński¹, D Walczak², K Szczurowski³ and S Radkowski⁴
¹PhD student, Warsaw University of Technology Institute of Vehicles, Warsaw, PL
²PhD student, Warsaw University of Technology Institute of Vehicles, Warsaw, PL
³Doctor, Warsaw University of Technology Institute of Vehicles, Warsaw, PL
⁴Professor, Warsaw University of Technology Institute of Vehicles, Warsaw, PL
E-mail: lizielinski@mechatronika.net.pl

Abstract: With the development of internal combustion engines, engineers attempt to reduce the noise and vibration generated. Due to the high cost of fuel, are increasingly looking for new sources of power in order to reduce costs. In diesel engines, an increasingly popular method is the admixture of propane-butane. This follows because of the price of the fuel as well as to improve the efficiency of combustion. With the development of this type of dual fuel power seems to be a reasonable study of the effects of LPG to generate noise and vibration, as well as an attempt to evaluate the combustion process. Unfortunately, too much addition of LPG causes a phenomenon called knock consisting in abnormal, uneven, explosive combustion of fuels in reciprocating engines. This phenomenon may lead to a reduction in engine performance and permanent damage. Control of the knock detection uses vibration acceleration sensors recording the high frequency ranges. Within the framework of the research conducted by the team of authors, an attempt was made to compare the vibroacoustic signals originating from the commercial knocking sensor with a three-axis acceleration sensor. These signals were subject to a quick Fourier transform in the purpose of analysing the amplitude spectra.

1. Introduction
Searching for alternative sources of supplying the combustion engines is a natural phenomenon in relation to the limited resources of petroleum and to the more and more demanding standards regarding the exhaust gas emissions [1]. Popularity of the specific fuel in a given region depends on the geographic, political, and economic conditions. Additionally, the distribution network of a given fuel is not of lesser importance, enabling the access to the filling-up facilities. The geopolitical system is divided into two poles of gaseous fuels - CNG and LPG. In many European countries, a propane – butane mixture is very popular. This is a result of a low fuel price, wide distribution network, and a relatively cheap method of storing and transport [2].

LPG is a liquid fuel used basically as a replacement for a basic fuel in engines with spark ignition. For the last few years, the tests have been conducted connected with the effect of the LPG addition to the engines with compression-ignition [3-6]. It results from the attempts to replace a part of a diesel oil dose with a cheaper fuel, in order to cause the cost reduction. Significant physicochemical differences of these two fuels induce both advantages and problems related to the use of the diesel oil and LPG [7] during simultaneous powering of the combustion engine. The diesel oil has a property of compression-ignition, thus being an initiator of the combustion process. These fuels have a different flame speed, and therefore a different speed of pressure increase. The current diesel oil supply systems enable a very flexible adjustment regarding the number of doses and their percentage distribution. LPG, however, is a gaseous fuel, fed to the intake manifold and creating the...
mixture of fuel and air during the compression stroke, which in engines with a high compression ratio results in susceptibility to the phenomenon of a knocking combustion, which is disadvantageous during combustion of such a mixture. A high compression ratio causes the increase in the probability of occurrence of this phenomenon as a result of high temperature at the end of the compression phase. The phenomenon of a knocking combustion has a degenerative effect on the engine parts [8], causing its permanent damage.

In the recent years, in Poland and in Europe, the growing interest in installations enabling injection of an LPG addition to the engines with compression-ignition can be observed. The control systems of such installations are based to a large extent on the low amount of information about the current parameters of the engine operation. Reduction or turning off the LPG addition takes place when a specific temperature of exhaust gasses is exceeded or when the information comes from the additional sensor of knocking combustion. Based on the little amount of information, it is difficult to adjust the maximal participation of LPG that will not induce the knocking combustion phenomenon.

The knocking combustion can be observed by means of registering the vibrations of the engine body, and in particular the specific frequency bands of these vibrations. The reason why the authors discuss these issues is the fact of the growing interest in using the information included in generated vibrations and in the acoustic emission [9, 10], as well as the reduction of the acoustic emission as one of the environmental threats. Another emission of vibrations and noise in a dual-fuel engine is generated by the pressure change in the combustion chamber, which correlates with the measured parameters, among others, the torque. This phenomenon seems to be interesting if an attempt to optimise the selected control parameters is taken into consideration, where the optimisation criterion is minimising the vibrations and noise generated by the combustion engine. Within the framework of the research conducted by the team of authors, an attempt was made to compare the vibroacoustic signals originating from the commercial knocking sensor with a three-axis acceleration sensor. These signals were subject to a quick Fourier transform in the purpose of analysing the amplitude spectra.

2. Testing stand
The testing stand employed in this paper is a SEAT Cordoba6L vehicle, equipped with the modified dual-fuel engine based on the unit marked 1.4 TDI AMF.

The engine of the tested vehicle was adapted to the dual-fuel operation by means of mounting an additional LPG installation with injectors located in the intake manifold tubes. The gas is injected sequentially, supplying all cylinders one by one (Fig.1). Additionally, the compression ratio was decreased from 19.5 to the value of 18.5, by means of using a thicker gasket and increasing the space of the combustion chamber by means of the mounting sleeves for the installation of the glow plugs with the pressure sensor (Fig.2).

Figure 1. Glow plug mounting sleeves PSG. Figure 2. LPG injection nozzle.
During the tests, the head vibrations (the B&K and knock sensors) were registered among other parameters, as well as the excess oxygen ratio (\( \lambda \)), the air temperatures in the intake and exhaust manifolds, fuel doses, amount of air, pressure in the intake manifold, pressure inside the combustion chamber (PSG), rotational velocity, engine load, torque, and many others. During the tests, the LabVIEW environment was used to register all measured signals. For the registration of vibrations, a knock sensor (Bosch 0 261 231 004) (Fig.3) was employed, and for the registration of accelerations - a three-axis vibration sensor (B&K, 4504 type), (Fig. 3). The signals were sampled with the frequency of 51.2 kHz, and every measurement lasted 5 seconds. The measurement cards NI 9234 were used for the measurement-taking (Fig. 4). The whole vehicle situated on the chassis dynamometer is shown in the last picture of this chapter (Fig. 5). The tests were performed for different LPG shares and for various rotational velocities.

![Figure 3. Installation of sensors: a combustion knock sensor and a three-axis acceleration sensor.](image3.png)

![Figure 4. Measurement setup.](image4.png)

![Figure 5. Tested vehicle on the chassis dynamometer.](image5.png)

![Figure 6. Acceleration axis layout of the three-axis sensor](image6.png)

3. Result analysis
Analysing the obtained measurements of signals connected with the dual-fuel engine’s vibroacoustic activity, the amplitude-frequency analysis was conducted in the first step. In the first stage, the low frequency band, in which changes related to the ignition and combustion of the air-fuel mixture processes can be seen, was the main focus. The result is shown in Figures 7-18.
Figure 7. Amplitude spectrum, 1500 RPM, LPG share (0-50%), X-axis vibration sensor.

Figure 8. Amplitude spectrum, 1500 RPM, LPG share (0-50%), Y-axis vibration sensor.

Figure 9. Amplitude spectrum, 1500 RPM, LPG share (0-50%), Z-axis vibration sensor.

Figure 10. Amplitude spectrum, 1500 RPM, LPG share (0-50%), knock sensor.

Figure 11. Amplitude spectrum, 2000 RPM, LPG share (0-50%), X-axis vibration sensor.

Figure 12. Amplitude spectrum, 2000 RPM, LPG share (0-50%), Y-axis vibration sensor.

Figure 13. Amplitude spectrum, 2000 RPM, LPG share (0-50%), Z-axis vibration sensor.

Figure 14. Amplitude spectrum, 2000 RPM, LPG share (0-50%), knock sensor.
The harmonics of the frequency corresponding to the mixture ignition indicate the decrease in vibration amplitude with the growing LPG share, apart from the last measurement for the greatest participation of the gaseous fuel, which was examined, i.e. 50% LPG. Both the spectra for the individual vibration directions of the acceleration sensor, as well as the spectrum of the signal from the knock sensor, do not indicate unequivocally the occurrence of knocking combustion. The next step consisted in accomplishing spectra for the broader frequency band. According to relation 1, the estimated frequency corresponding to the occurrence of knock combustion amounts to approximately 7 kHz. This relation was developed on the basis of the empirical data for the engines with the spark ignition, in which the resonance frequency of knock is described by the relation:

$$f[kHz] = \frac{180\theta}{3.14 \cdot piston \ diameter \ [mm]}$$

$$\theta$$

Figure 15. Amplitude spectrum, 2500 RPM, LPG share (0-50%), X-axis vibration sensor.

Figure 16. Amplitude spectrum, 2500 RPM, LPG share (0-50%), Y-axis vibration sensor.

Figure 17. Amplitude spectrum, 2500 RPM, LPG share (0-50%), Z-axis vibration sensor.

Figure 18. Amplitude spectrum, 2500 RPM, LPG share (0-50%), knock sensor.

Figure 19. Amplitude spectrum, 2000 RPM, LPG share (0-50%), Y-axis vibration sensor.

Figure 20. Amplitude spectrum, 2000 RPM, LPG share (0-50%), Z-axis vibration sensor.
In the spectra for the broader frequency band, a greater vibroacoustic activity in the range of 5-7 kHz can be observed, especially for bigger LPG shares, i.e. 30% and 50%. The results of this analysis indicate the symptoms of knocking, unequivocal statement of the occurrence of this phenomenon, however, is not possible. The greatest amplitudes, however, can be observed on the signal from the Z-axis and the signal from the knock sensor.

The next step was determining spectra of the proportionality constant to the vibration energy, understood as a product of the square of the amplitude and the frequency. The results are shown in Figures 26-30. As can be observed, with all measurement directions, as well as on the combustion knock sensor, the increase in amplitudes of the determined constant was registered. Selection of information proved to be a very interesting task, which was carried out by the sensor in the direction of “Z” Fig. 26 and 29. As can be observed, a proper setting of the measurement direction can serve as a filter for information regarding the occurrence of vibrations from the range of knocking combustion. This information is more unequivocal in the context of the knocking combustion occurrence.
The last stage presented in this paper is the analysis of the knocking combustion occurrence with the use of the summation of amplitudes of the subsequent spectral lines of the vibration energy ratio so as to illustrate the increase in vibration energy in specific frequency ranges. The plots of the summed up values of the energy lines are shown in the plots below.
The curves shown in Figures 31-36 indicate, in which frequency ranges the highest increase in vibration energy can be seen, this increase is connected with the rapid increase in pressure caused by knocking combustion. The rapid pressure growth in the engine with the compression-ignition (significantly higher pressure and faster increase than in the engine with the spark ignition, for which the phenomenon of knocking combustion is much better investigated) makes it difficult to unequivocally indicate the knocking combustion occurrence. The best method consists in measuring the combustion pressure in the chamber during the engine operation. Unfortunately, these measurements are also flawed with significant disorders and they require more precise analyses, which is proved by the research results carried out so far.

In order to assess, if knocking combustion took place, the velocity of pressure increase is determined \[11\], whose task is defining the limit, when the combustion is normal, and when knocking combustion starts. The analysis presented in \[11\] does not take into account many factors influencing the velocity of the pressure increase, hence the need of additional tests and analyses.

4. Conclusions
The analysis of the vibration accelerations in the low frequency band does not enable the recognition of the occurrence of the knocking combustion in the process of combusting the mixture of fuel and air. In this band, other information can be found, related to the combustion process, which is not used in the presented task. Moving the analysis to the higher frequency band enables observations of the range, in which the amplitudes of the vibration accelerations grow, which can be connected with the occurrence of the knocking combustion, the unequivocal proof, however, causes interpretation problems.

Introduction of the proportionality constant to the energy of vibration significantly improves the interpretation possibilities, especially if it is subject to additional transformations.

A very important realisation is a phenomenon of information filtering dependent upon the direction of registering the vibration accelerations. Certain procedures require additional processing like filtering signals, cutting out bands, or different type of information preselection. In the discussed case of selecting
the direction of registration, the band related to knocking combustion was vividly marked at one of the measurement directions, which allows for additional conclusion-drawing, that does not include a series of preliminary signal processing.
A credible proof of the occurrence of knocking combustion in the given frequency ranges are observations of pressure inside the combustion chamber.

5. Abbreviations
LPG – liquefied petroleum gas
SOI – start of injection
CI – compression engine
PSG – pressure sensor glow plug
B&K – Bruel&Kjaer
NI – National Instruments
f – frequency
RPM – revolutions per minute

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