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Kinetic Energy Harvesting in Automotive Applications

J. Happel, Johann Harmstorf, Andre Kneifel, Alexander Raaz, Karl-Ludwig Krieger,
ITEM Universität Bremen, Otto-Hahn-Allee 1, 28359 Bremen, Germany
jakob.happel@uni-bremen.de

Abstract

This publication focuses on the characterization of kinetic energy in the engine compartment of road vehicles to supply autonomous wireless sensor systems. For this purpose multi-dimensional acceleration values were recorded at different installation points and an analysis of the usable engine vibration was performed in the time and frequency domains for multiple installation locations and orientations. Additionally, the frequency distribution of occurring engine speeds were investigated in application-oriented driving situations, and the power spectral densities for city, intercity, and highway driving routes were calculated. Through the evaluation of the measured accelerations with the corresponding OBD data of the vehicle it is possible to estimate the amount of harvested energy for different driving routes. The results serve as a basis for the development of an optimally adapted high efficiency energy harvester for several locations in the engine compartment.

Key words: energy harvesting, automotive, vibrations, engine compartment, wireless sensor node

Motivation

The integration of sensory functions in the motor vehicle is steadily increasing. There are more and more sensors to perform basic and comfort functions in the vehicle. A barrier to innovation in this context is cabling and connectors of the sensors. Although using digital serial bus communication, the total cable length in a modern upper class car is still about 3 km [1] with a weight of approx. 30 kg. The installed cables increase the total weight of the vehicle and, hence, fuel consumption. Furthermore, space is required for the wiring within the vehicle and the relevant components. In addition to the installed cost, cables and connectors are potential weaknesses in the system. Due to the high personnel demand for installation and maintenance, the cabling is a major cost factor.

The performance of autonomous wireless sensor systems crucially depends on their energy supply and energy management. Systems powered by exhaustible energy sources such as batteries always require maintenance. The energy harvest from their immediate environment, however, is an innovative, promising concept for maintenance-free energy supply of autonomous wireless micro systems which can be directly integrated into the monitored components.

In contrast to photovoltaic and thermoelectric power conversion, the kinetic energy harvesting is the only universal way of energy harvesting in engine compartments because vibration energy is always present in varying intensities. By using different conversion principles and an appropriate harvester kinetic energy can be converted efficiently into electrical energy.

The performance of kinetic energy harvesters and thus the performance of the entire micro system, highly depends on its adaptation to the vibration source. For this reason, a detailed analysis of the intended target environment is necessary to ensure high efficiency, which is a basis for successful systems development.

Measuring section and vehicle

A test drive to analyze the vibrations in engine compartment was performed. The measuring system consisted of a NI cDAQ-9178 [2] and three NI 9234 [3] analog input modules with twelve ADC-channels. As acceleration sensors four ADXL335 [4] have been used. The measurement run was performed with a 2008 VW Passat 1.9 TDI. Identical engines are also installed in other vehicles of the Volkswagen Group and, thus, represent a typical 4 cylinder diesel vehicle in Germany.

Prior to the investigation of vibrations in the engine compartment, a possible application for the sensor system had to be defined, to determine the installation location of the sensor system. For this analysis it has been assumed that in a first step only non safety-related-functions with low requirements in terms of latency of data acquisition and wireless transmission can be realized. Levels of fluids such as the windshield washer water are particularly suitable for this purpose and were focused in the investigation. Fig. 2 shows the locations of acceleration sensors mounted in the engine compartment. Sensor 1 is placed on the cooling water tank, sensor 2 on the windshield washer tank, sensor 3 on the cover of the oil filler neck and sensor 4 near the air filter. All four sensors were identically aligned to ensure the comparability of directional dependent accelerations. The orientation of the axes is also shown in figure 2.

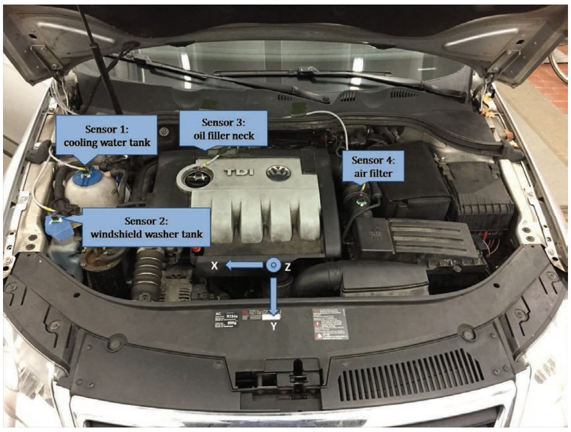

Fig. 1. Installation points of acceleration sensors in engine compartment

The test drive was executed in the area of Bremen. The round circuit with a total length of 137.6 km is divided into three parts: 58.9 km intercity, 53.4 km highway and 25.3 km city driving.

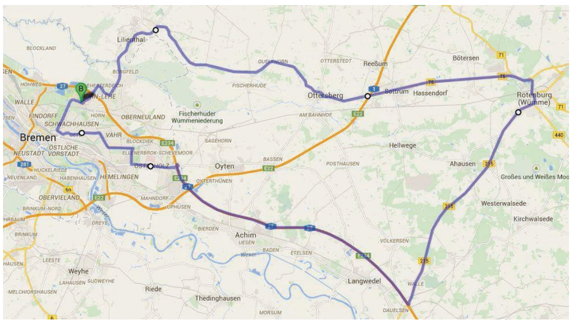

Fig. 2. Round circuit for measurement run

Analysis of engine vibrations: installation point

First, the relation between measured acceleration and the respective installation point of sensors has to be analyzed. For this purpose, a comparison of acceleration data of the x-axis during intercity driving was performed for all four sensors. The measured acceleration is shown in the top of figure 3 while the corresponding engine speed, vehicle velocity and engine load are shown at the bottom plots.

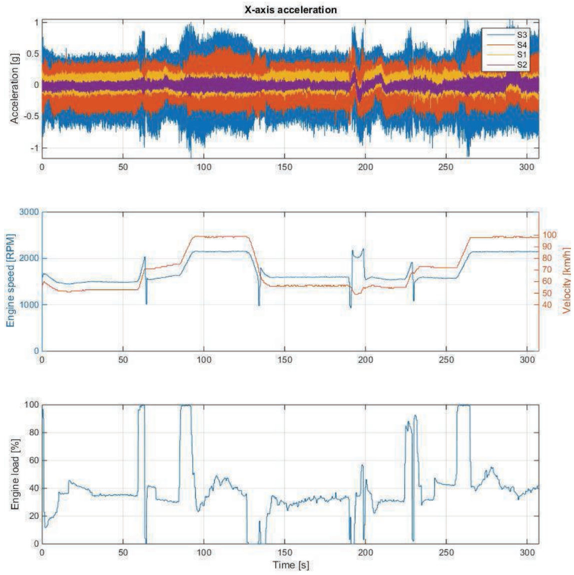

Fig. 3. Comparison of acceleration amplitude between different installation points

As seen in figure 3, the measured acceleration values depend on the installation point. While the amplitude of acceleration of sensor 3 is in the range of 0.5 g to 1 g, the amplitudes of sensors 1, 2, and 4 decrease according to their distances between mounting positions and engine.

Furthermore, figure 3 shows that the measured accelerations strongly depend on the engine speed. With increasing engine speed accelerations for all installation points are significantly increasing. Also, correlations between the measured data and the engine load can be identified. Especially for sensor 3 (oil filler neck) the amplitude of the acceleration increases significantly at high engine load (Fig. 3, t = 65 s), whereby the engine speed is directly related to the engine load.

In figure 4 the acceleration spectral density of sensor 1 is plotted versus time. Furthermore, the engine speed and vehicle velocity are depicted in the bottom plot.

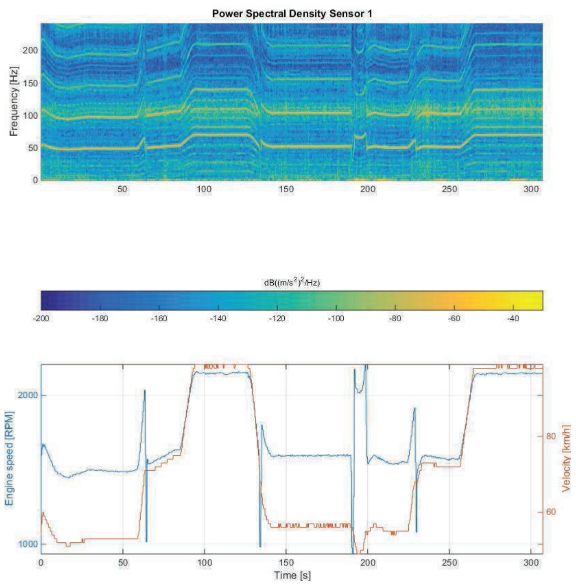

Fig. 4. Acceleration spectral density of sensor 1

As shown in figure 5, one can identify a clear relation between engine speed and acceleration spectral density. The distance between the fundamental and harmonics is equidistant at about 50 Hz for all sensors, with the exception of sensor 3, which also contains frequencies with high power density in the range between the harmonics.

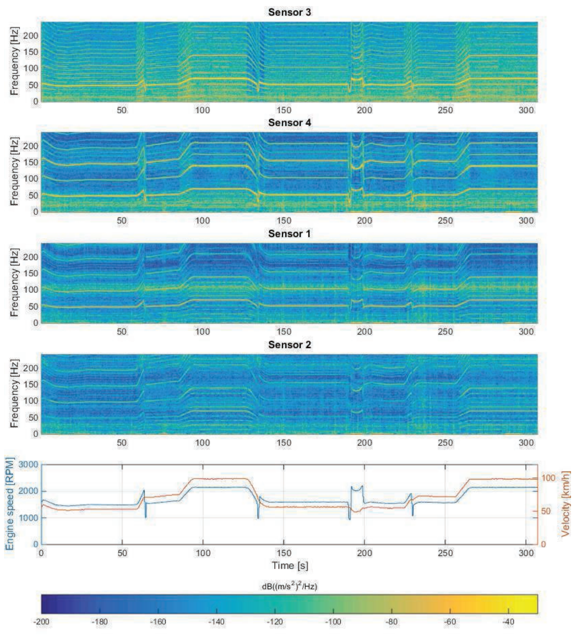

Fig. 5. Acceleration spectral density for different installation points

Analysis of engine vibrations: directional dependence

To allow an optimal positioning of the harvester within a predetermined installation space, the preferred direction of the vibrations has to be considered. Hence, an analysis of the vibration direction was performed using a three-axis acceleration measurement.

For this analysis the same route as for the study of the installation locations was chosen. Sensor 3 (oil filler neck) has been used for evaluating the directional dependency because of its high acceleration values in combination with higher influence of the engine load.

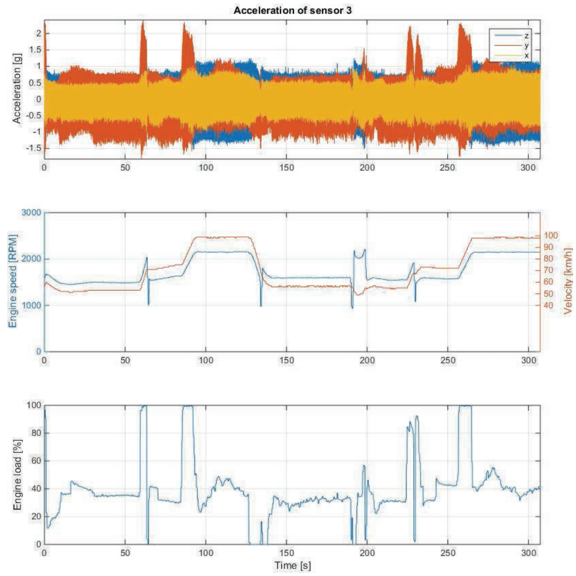

Fig. 6. Directional dependent acceleration of sensor 3

Figure 6 shows the measured acceleration for all three axes of sensor 3. As mentioned before, a strong dependency between engine speed and measured accelerations can be identified, whereby the amplitude of acceleration increases with rising engine speed. Furthermore, a high acceleration in the y-direction is present at high engine load (see Fig. 6, time t = 70, t = 90 etc.), in contrast to x- and z-axes. On an overall basis, we measured the minimum accelerations in x-direction. The maximum accelerations in any of the directions can be observed on the z-direction if the engine speed is about 1600 RPM and above. At engine speeds below 1600 RPM or the engine operates at high load of approx. 40 %, the maximum can be observed on the y-direction.

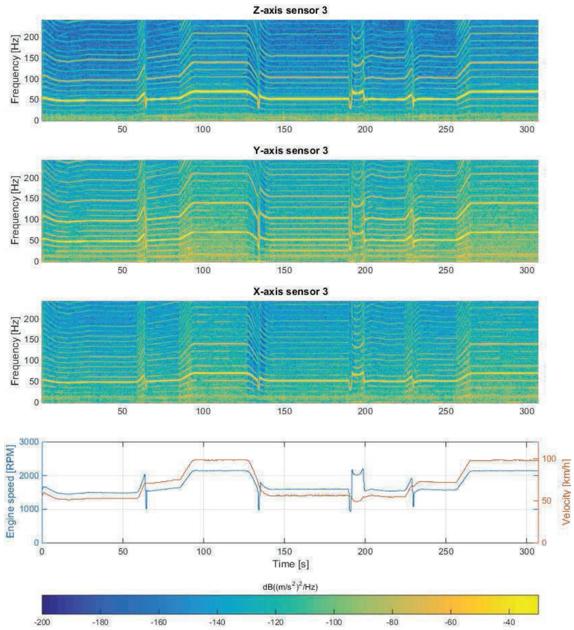

Fig. 7. Acceleration spectral density of directional dependent of sensor 3

In figure 7 the power density spectra for acceleration in three axes is depicted. All three spectra show fundamentals with high power densities, which are highly correlated with the shape of the engine speed curve. However, the acceleration plot of the x-axis is dominated by the fundamental frequency at 50 Hz, while the harmonics have significantly lower power densities. In spite of this, the harmonics of y- and z-axis have high power densities. The highest power density has been measured at a fundamental frequency of about 50 Hz in z-direction.

Analysis of engine vibrations: route sections

In this section the relation between measured accelerations and the respective route sections is evaluated. As an example, in figure 8 the y-direction accelerations of all four sensors are plotted for city, intercity, and highway driving routes, respectively.

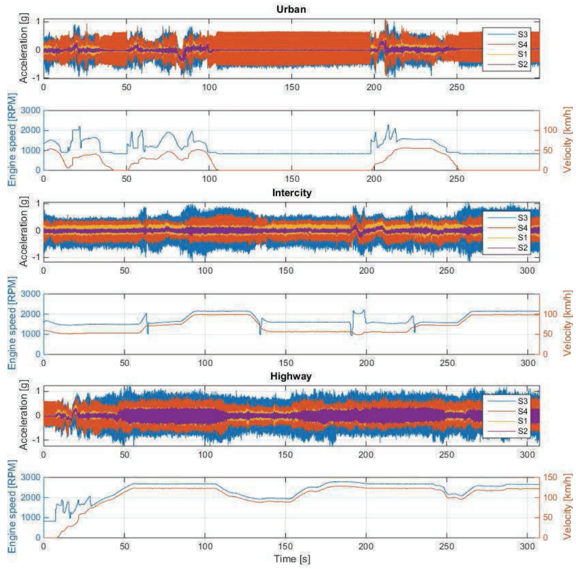

Fig. 8. Accelerations for different driving route sections

Comparing the different sections it can be noted, that the measured accelerations of all four installed sensors generally increase with increasing engine speed, as mentioned before. Nevertheless, high accelerations in the area of air filter were measured, even if the engine is idle (see Fig. 8, city, t = 150s).

The z-axis of sensor 3 (oil filler neck) has been chosen exemplarily for the plot of acceleration spectral density for different driving sections, as it has previously exhibited the highest acceleration values.

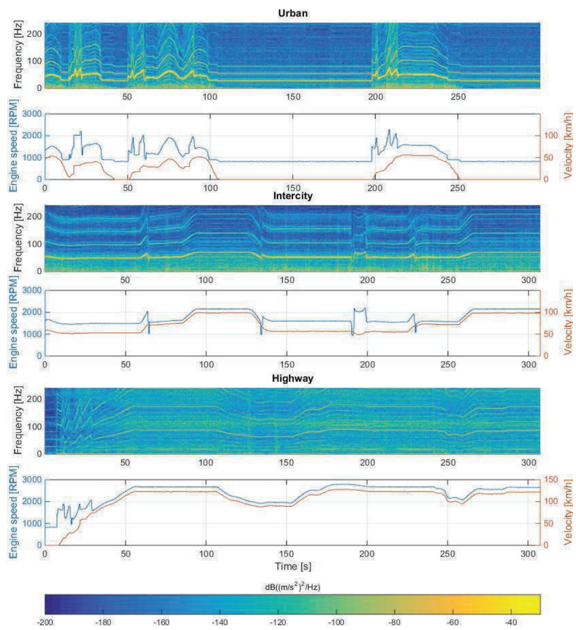

Fig. 9. Acceleration spectral density for different driving sections

As depicted in Fig. 9, all acceleration density spectra show the already known relationship between engine speed and frequencies with high power density. Moreover, the frequency of the fundamental oscillation increases with engine speed. At idle engine speed of 840 RPM the fundamental is at about 28 Hz, while at engine speed of about 2000 RPM, it is at about 88 Hz.

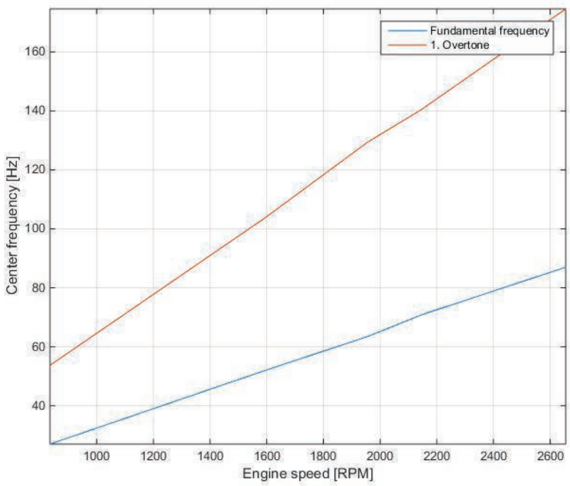

Fig. 10. Relationship between the center frequency of fundamental / 1. overtone and engine speed

To achieve a high efficiency the natural frequency of the harvester has to be tuned to the excitation frequency of the vibration source. The high efficiency range in commercial kinetic energy harvesters is narrow and therefore, should be ideally suited to the vibration source. However, it was pointed out in the previous sections, that the usable fundamental frequency with high power density heavily depend on engine speed.

Focusing only on the relation between engine speed and power spectral density is not sufficient for an application-oriented development. Therefore, also specific application scenarios with varying frequency distribution of engine speeds occurring in application-oriented driving situations have to be taken into account.

Figure 11 shows the histograms for the existing engine speeds during different route sections, as well as for the entire measurement run.

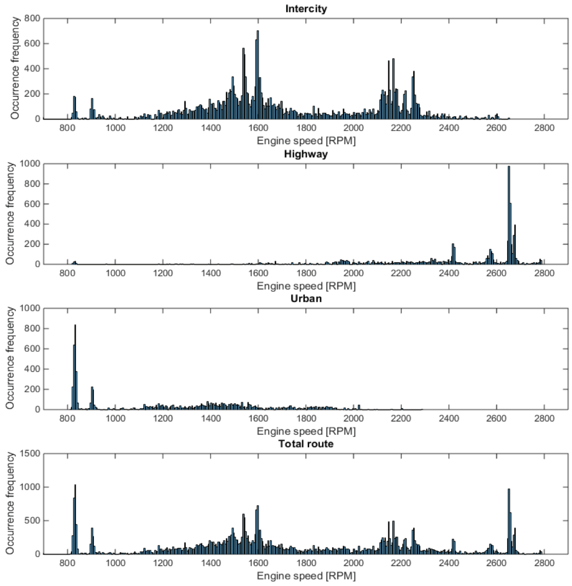

Fig. 11. Histograms of engine speeds for different driving route sections

As depicted in the histograms of figure 11, a characteristic expression for certain speed ranges occur in each driving section. These are 1590-1600 RPM for intercity driving, 2650-2660 RPM for highway and 830-840 RPM for city routes. The histograms of city and highway driving are dominated by certain engine speeds according to typical vehicle velocities of these route sections (typ. 0 km/h and typ. 130 km/h). In contrast to city and highway, the histogram of engine speeds of intercity route sections with villages (typ. 50 km/h), zones with speed limits (typ. 70 km/h) and free sections (typ. 100 km/h) is spread wider. The measured accelerations for certain engine speeds during the test drive are shown in table 1.

Tab. 1: Acceleration for different engine speeds

Engine Speed [RPM]	Part of the entire route [%]	Center frequency [Hz]		Average acceleration [m/s^2]			
		Fundamental frequency	1. Overtone	S1	S2	S3	S4
830-840	2.56	27	53.7	0.4434	0.4464	2.6369	10.6537
1590-1600	1.77	52	103.8	2.0611	0.7073	5.8056	4.1899
2650-2660	2.41	87	174	3.5787	3.4051	8.5210	7.2319

Conclusion and outlook

In this publication we analyzed engine vibrations in the engine compartment based on the distribution, the directional dependence, and different route sections. It has been shown that the amplitude of the measured accelerations, as well as the frequency of fundamentals in the power density spectrum strongly depend on the engine speed and engine load.

Using the results an optimal adaptation of the energy harvesters natural frequency can be performed for individual route sections. Thus, the harvester is able to operate within a maximum time interval at a high efficiency.

Using the gained knowledge, the amount of energy yield for each installation point of an kinetic energy harvester can be predicted. The results are used as the basis for a system design of a self-powered wireless sensor system in an engine compartment. This paper therefore provides a contribution to transfer existing energy-harvesting techniques into automotive applications.

References

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