Development of a measuring system for the analysis of vibrations sent from engine to passenger seat

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Abstract: The present paper aims at developing a measuring system for vibrations analysis of engine cylinder cover and passenger seat fixing device. Such a system is useful for analyzing the correlation, if any, between the vibrations generated by internal combustion engine and those felt by the passenger (which create a certain degree of discomfort).

1. Introduction
Considering the current existence of multiple and accessible sensors and acquisition boards, it is now possible to easily study the vibrations produced by an internal combustion engine. Moreover, due to the electronic control of engine parameters, we now have new possibilities of studying the engine’s dynamical behavior. The present paper aims at developing a measuring system for vibrations analysis of engine cylinder cover and passenger seat fixing device. Such a system is useful for revealing the correlation, if any, between the vibrations generated by the internal combustion engine and those felt by the passenger (which create a certain degree of discomfort).

2. Experimental research
The main purpose of this paper is to develop a low price measuring system, which can allow the analysis of vibrations transmitted from internal combustion engine to passenger seat.

In order to accomplish this goal, there have been used the following constituents: 2 MEMS accelerometers of type ADXL345 and 2 Arduino Mega 2560 data acquisition boards. The first measuring system was placed on the engine, with the accelerometer being attached to the engine cylinder cover (figure 1a) and the second measuring system was placed inside the vehicle, with the accelerometer being attached to the passenger seat attachment rail (figure 1b).

To validate the accuracy of the measuring system, there have been considered multiple functional situations of engine such as: engine start, constant engine speed of 2000 rpm, constant engine speed of 3000 rpm. Also we have to mention that the tests were conducted considering a parked vehicle thus neglecting vibrations determined by road irregularities [3]. If vibrations would have been measured in case of a moving vehicle, it could have been used as a mathematical model the one developed in paper [7].

The measured data was processed using a software which allows a comparative analysis of vibrations obtained at engine level and at passenger seat level, considering the same functioning conditions [2], [4].
The obtained results revealed a correlation between the vibrations recorded by the two accelerometers, but, as expected, there were also some major differences between vibrations average values, which represents a validation of the proposed measuring system.

Figure 1 depicts the measuring system attached to engine (figure 1a) and passenger seat (figure 1b).

![Image 1](image1.jpg)

Figure 1.

A series of limitations of the measuring system were introduced by the maximum data acquisition frequency of the microcontrollers (in this case of 1 Hz), on one hand, and by the accelerometers measuring precision, on the other hand. Also, considering the fact that our data acquisition board was not provided with internal storage capabilities, this led to the impossibility of real-time data storage and required a permanent connection between the board and a laptop, which represents a drawback of the proposed measuring system. However, this limitation could be eliminated by attaching a microSD card or a Bluetooth device to our board.

3. Data statistical processing

Engine vibrations are caused mainly by the following aspects [1]:

- The cylinder pressure due to combustion is not constant through the combustion cycle;
- The slider-crank mechanism does not output a smooth torque even if the pressure is constant (e.g., at top dead centre there is no torque generated);
- The motion of the piston mass and connecting rod mass generate alternating torques often referred to as "inertia" torques.

In terms of vibrations that affect passengers, specialty literature mentions multiple parameters specific to vibration phenomenon that should be taken into account when analyzing effects on human body [5]:

- Frequency;
- Amplitude, acceleration or vibration energy.

Due to the fact that the paper focuses mainly on the comparison of values of acceleration obtained from experimental tests, the formula of vibration acceleration is [5]:

\[ a = A \cdot \omega^2 = (2 \cdot \pi \cdot f)^2 \cdot A \quad [m/s^2] \]  

(1)

where \( A \) – vibration amplitude [m], \( \omega \) – vibration pulsation [s\(^{-1}\)], \( f \) – vibration frequency [Hz].
Also, excitation frequency is given by formula [6]:

\[ f = \frac{2 \times N \times I}{60 \times C} \quad [Hz] \]  

(2)

where \( N \) – engine idle RPM, \( I \) – number of cylinders, \( C \) – engine cycle.

In figure 2 [7] are presented factors which induce vibrations (such as road irregularities, driveline excitation shaft, engine or transmission) and the vehicle’s parts and elements which can damp vibrations (such as rubber mounts, vehicle suspension etc.). The graph highlights the track of different vibrations sent from point of origin to passenger or driver [7], [8].

Figure 2.

Following, there are presented some graphical examples of vibrations produced by an internal combustion engine, considering different functional situations.

For example, in Figure 3 there are shown the acceleration values on the \( OX \) axis (vehicle’s transverse direction), while in Figure 4 there are shown the acceleration values on the \( OY \) axis (vehicle’s longitudinal direction) and on the \( OZ \) axis (vehicle’s vertical direction), obtained in case of engine start.

If we analyze the two graphs, we can notice that the values corresponding to the accelerations on the vertical direction (\( OZ \) axis) are close to the value of the gravitational acceleration (approximately 9.81 m/s\(^2\)), while the accelerations measured on the other two directions are much higher at the engine level than those measured at the passenger seat level. For the analysis of the vibrations transmissivity from the engine to the passenger seat, we computed the mean value between the values recorded at the two placement locations of the accelerometers.
The average value of attenuation degree on \(OX\) axis, from engine to passenger seat, during tests, was approximately 5, denoting an attenuation of the vibrations sent from the engine to the passenger seat of 5 times. If the maximum value of acceleration recorded at the engine level, on the \(OX\) axis, was 4.5 m/s\(^2\), the maximum value of acceleration recorded on the same direction but at the passenger seat level was 0.42 m/s\(^2\). Comparing the values obtained on the \(OX\) and \(OY\) axes, it can be noticed that the values in the last case were higher, the maximum value of accelerations on the \(OY\) axis being 10.2 m/s\(^2\), while at the passenger seat level the maximum value was 0.68 m/s\(^2\). The time period when we recorded the highest acceleration values lasted for approximately 1 second.

Figure 3.

Figure 4.
In Figure 5 are presented the acceleration values on the $OX$, $OY$ and $OZ$ axes, obtained in case of an engine functioning at a constant engine speed of 2000 rev/min. From the analysis of the graph, it can be observed that the values recorded on the $OZ$ axis (measured at the engine and passenger seat levels) were close to the value of the gravitational acceleration. Likewise, it can be noticed that the vibrations amplitude at the engine level was higher than the one measured at the passenger seat level. The maximum acceleration on the $OX$ axis, at the engine level, was $2.567 \, \text{m/s}^2$, while at the passenger seat level it was $-0.192 \, \text{m/s}^2$; on the $OY$ axis, the maximum value of engine vibration was $6.781 \, \text{m/s}^2$, and the maximum value of passenger seat vibration was $0.076 \, \text{m/s}^2$.

By analyzing the average acceleration values recorded on the two axes, it was observed an attenuation of the vibrations sent from engine to the passenger seat, on the $OX$ direction, of approximately 32.91 times, and on the $OY$ direction of approximately 40 times.

![Graph showing acceleration values on $OX$, $OY$, and $OZ$ axes](image)

**Figure 5.**

In Figure 6 there are presented the acceleration values on the $OX$, $OY$ and $OZ$ axes, obtained in case of an engine functioning at a constant engine speed of 3000 rev/min. Comparing the acceleration values obtained at the two constant engine speeds (2000 rev/min and 3000 rev/min, respectively), it can be noticed that the values recorded in case of a constant engine speed of 3000 rev/min are higher; for example, the maximum acceleration value at the engine level, on the $OX$ axis, was $7.086 \, \text{m/s}^2$, while the maximum acceleration value at the passenger seat level was $0.115 \, \text{m/s}^2$. On the $OZ$ axis, we can observe that the acceleration values were close to the gravitational acceleration value, while on the $OY$ direction...
the maximum acceleration value was 6.55 m/s² (at the engine level), and 0.076 m/s², respectively (at the passenger seat level).

By analyzing the average acceleration values recorded on the two axes (OX, and OY, respectively), we observed an attenuation of the vibrations sent from engine to the passenger seat, on the OX direction, of approximately 8.575 times, and of 9.05 times, on the OY direction.

This paper's novelty consists of the development of a measuring system with a decent accuracy related to its price. At the same time, the measuring system can be further used for performing a comparative analysis of the vibrations generated by an internal combustion engine running with conventional fuel (petrol) and alternative fuel (liquefied petroleum gas). Also, by making use of the included accelerometers, we can also measure the rolling and pitching motions of vehicles running on different road categories.

![Graph showing values of acceleration on x, y, and z axes for engine and passenger seat (constant engine speed: 3000 rev/min)](image)

**Figure 6.**

### 4. Conclusions

In order to validate the adequate functioning of proposed measuring system there have been analyzed vibrations sent from engine to passenger seat, in different functional situations. Conclusions issued out of this study are the following:

- these boards (such as Arduino) have multiple advantages, starting with the fact that they are easy to program (using a programming language similar to C++);
- the price is accessible;
- there is a large number of sensors and actuators compatible with such platforms in the market, which allows measuring a wide variety of vehicle parameters;
- due to small sizes of data acquisition boards and sensors, it is easy to dispose them in the measuring area;
- besides all these advantages, these boards also have some limitations, especially regarding data acquisition frequency (which in this case was 1Hz);
- cables used to connect sensors to acquisition board have a drawback which is more common to appear in case of high vibrations, namely the cables may determine loss of connection.
The measuring system can be improved by using an external supply for the acquisition board (during these tests the acquisition board was powered directly from the laptop) and by attaching a Bluetooth device which can assure real time data transmission to a laptop or a device able to register data on a microSD card.

Data accuracy is considered acceptable, mainly in case of use for educational purpose. On the other hand, for research purpose, the measuring system is not recommended because of the poor measuring accuracy, needless to say that in the market there are more advanced equipments but at higher costs.

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