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INFLUENCE OF OPEN/CLOSED VOLUME TYPES ON SENSOR MATRIX DESIGN FOR VIBROACOUSTIC STUDY OF VEHICLES

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Abstract

Environmental protection involves various complexities, like reduction of vibroacoustic pollution generated by motor vehicles. This type of pollution, generated from vehicle operations, presents significant challenges in mitigation efforts. According to this, it results the need to develop a methodology aimed at identifying and analysing the sources of noises and vibrations typical of both normal vehicle functioning and component failures. These sources mainly concentrate within the engine compartment. Thus, the configuration of the sensors to analyze the vehicle noise and vibration behaviour should be adapted to the identified categories of open or closed vibroacoustic volumes. The goal of this study is to demonstrate, by practical experiments, that in case of an open volume, accelerometers should predominate in the sensors array, whereas for a closed vibroacoustic volume, a more balanced distribution with microphones may be appropriate. This classification of vibroacoustic volumes serves as basic criteria for the design of sensors network in vibroacoustic studies of vehicles.

Key words: automotive, diagnostic, noise, pollution, vibration

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1. Introduction

The noises and vibrations generated by motor vehicles are addressed in international specialized literature under the abbreviation NVH (Noise, Vibration, and Harshness) (Festa et al., 2021), and they are the subject of a complex analysis which highlights that the impact of NVH is classified into the following branches (De Roo, 2011):

- Social impact*:* this affects both the population living in the area where the NVH generated by vehicles occurs and the drivers/servants of the vehicles;
- Environmental impact*:* this is reflected on both beings or man-made buildings and other constructions;
- Economic impact*:* this affects the direct costs of medical care for people, whose health is impacted by NVH, as well as costs associated with the rehabilitation of road infrastructure and the repair of vehicles damaged as a result of NVH.

The social impact includes:

- Health status of the population (Darshana et al., 2013), e.g., temporary and/or permanent hearing loss; tinnitus - the perception of sounds without correspondence to an external sound source - and/or ear fullness; communication difficulties; anxiety; condition agitation; reduced performance; insomnia; tiredness; increased blood pressure/hypertension; changes in gastrointestinal function.
- The health status of the driver of the vehicle (Sitnik et al., 2013), e.g., difficulties in maintaining balance - motion sickness; pain in the neck and

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occipital area - associated with overstraining the back muscles to prevent head movements as a result of vibrations applied to the human body.

The impact on the environment is about of:

- The development of plants and animals in areas exposed to NVH generated by motor vehicles.
- Buildings and constructions located in the immediate vicinity of operating motor vehicles, in terms of affecting their structure.
- Road infrastructure, in terms of accelerating the aging process and increasing wear and tear (Kirillov et al., 2014).

The economic impact can be highlighted as follows:

- The ACEA (Association of European Automobile Manufacturers) estimates that approximately 4% of revenues are invested in research and development in the field of NVH, as could be observed in the Table 1 (De Roo, 2011).

This means that developing a method to study and analyse the NVH generated by motor vehicles, with the capability to highlight the fault status of the main vehicle components, could be a way to address environmental concerns.

2. Vibroacoustic diagnosis of vehicles approach

2.1. The need for vibroacoustic diagnosis of vehicles

In the automotive domain, diagnosis is utilized to identify the state of defect in components or systems, which is referred to as the state of fault. Depending on the category, faults can exhibit preliminary symptoms or may appear suddenly. Electrical faults are characterized by a lack of preliminary symptoms and are relatively easy to detect through the measurement of electrical resistance, voltage, or current for an individual component or an integrated component in a circuit. Typically, detecting mechanical faults requires an invasive method, which includes the removal and dismantling of the component for dimensional measurement and/or inspection (e.g., connecting rod of an internal combustion engine). In the case of hydraulic or pneumatic faults, preliminary signs such as abnormal specific noise or vibration may be observed. However, for a proper diagnosis, similar to mechanical faults, there are cases that require the use of invasive measurements of pressure or flow. Traditionally, diagnosing mechanical, hydraulic, and pneumatic faults necessitates more time and resources than electrical faults. An example of combining the noise analyzing with another diagnostic method is the study conducted by Metro de Madrid, which involved recording acoustical parameters of the overhead electrical line to determine the critical wear section of contact wires (Gonzales et al., 2008).

Automotive vibroacoustic presume two categories of NVH: air-borne and structure-borne, with an accepted frequency limit of 300-500 Hz. Below this limit, structure-borne NVH predominates; above it, air-borne NVH becomes dominant. This implies that technicians, for classical vibroacoustic diagnosis, must rely not only on their sense of hearing but also on their sense of touch. In cases where a human operator is replaced by an modern method based on an electronic system for monitoring, it is necessary to use a combined array of sensors. This array must include microphones for recording air-borne signals and accelerometers for detecting structure-borne NVH.

Table 1. General effect of reducing the motor vehicle noise levels

Involved parties	*+/-*	*Effect*
1. The public affected by road traffic noise	+	a) Improved sleep, reduced stress, improved health and quality of life; indirectly, savings on health and effectiveness at work and school.
	+	b) Increased property value.
	+	c) Improved living, work and recreation environment.
2. Road authorities, national and local authorities	+	a) Reduced need for noise abatement programmes (barriers, road surfaces, sound insulation) and cost saving; easier planning of new or upgraded roads.
	+	b) Less local protest.
	+	c) Less need for regulation and enforcement.
3. Health authorities and government	+	a) Reduced healthcare costs.
4. The automotive industry	+	a) Improved environmental image as a sales point.
	-	b) Increased costs for extra noise control including design, testing and materials; in particular for lorries, buses and trucks.
	-	c) Balancing of noise requirements with other design constraints such as weight, fuel consumption, exhaust emissions, cooling and space.
	-	d) In some cases, conflict with sound perception of SUVs, sports and luxury cars.
	-	e) Tampering or cycle beating may occur to avoid noise reduction cost/effort.
5. Consumer market	-	a) Cars: small price increase.
6. Professional market	+	a) Some market advantage for new fleets, for example rental cars and vans, taxis, buses, delivery or municipal vehicles in urban environment or quiet areas. Benefits from tax incentive programmes or privileged access to sensitive areas.
	-	b) Price increase, mainly for lorries, trucks and buses.

The sound is complementary to the vibration signal, and in diagnostics for vehicles by the vibroacoustic method with a human operator, the useful limits are generally as follows (Wang, 2010):

- sound in audible frequency range of 30 to 4.000 Hz.
- vibration in tactile frequency range of 30 to 200 Hz.

Main sources of NVH on the vehicle are described in Fig. 1 and in the corresponding Table 2, with corresponding target limit according to legislation 997/EEC.

Global vibration of the vehicle is felt by passengers and driver at different level of lack of comfort as is depict in Table 3. That means in case of vibroacoustic diagnosis by technician must be necessary to follow some precise test steps:

- slow acceleration, for identifying the speed interval related to the NVH issue referring to the target fault;
- neutral coast down speed, for detection of faults like worn wheel bearing/suspension bushings/U-joints in case all-wheel drive;
- downshift, for target faults in driveline (clutch, transmission or propeller shat);
- torques converter lockup (in case of automatic transmission), for target fault at lockup clutch;
- steering, for detection of faults like worn steering gear/hydraulic issue in the power steering/driveline mounts;
- neutral run-up, for separating fault of engine to that coming from drive train;
- engine loaded, for target faults like fuel injection/air intake/ignition system;
- engine accessory, for isolating faults from belts/pulley/tensioner.

For driver and passenger, vibration level from the vehicle can be useful information in case of diagnosis if the service technician is using the correct questions like:

- in which drive condition is manifesting the NVH complain (like acceleration or deceleration modus);
- if is constant frequency and amplitude, or varies depending of vehicle speed;
- if the NVH complain is appearing in the warm up phase of engine or transmission;
- if during time the amplitude of NVH was increasing;
- if the vehicle is put into neutral on driving how is affected the NVH complain.

In normal vehicle operation, the driver and passenger are exposed to a certain level of NVH environment. Exceeding the limit affects perception and the symptom described in Table 3 appears as: A - No effect on comfort; B - Slightly uncomfortable; C - Moderately uncomfortable; D - Uncomfortable; E - Very uncomfortable; and F - Extremely uncomfortable.

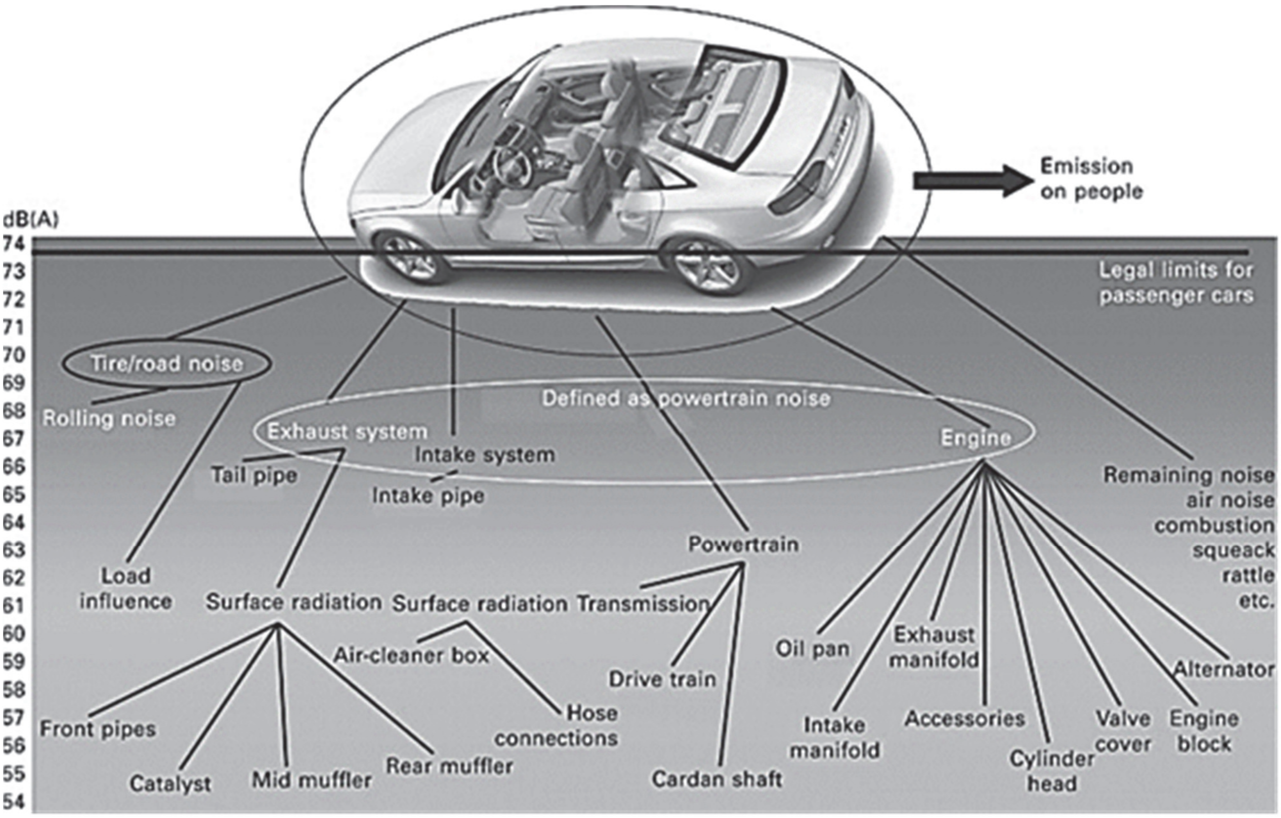


Fig. 1. Vehicle main noise sources (Bein et al., 2012)

Table 2. Noise level for vehicle component (Harrison, 2004)

	Passenger car	***Light truck***	***Heavy truck***
	Target level at 7.5 m, acceleration test (dBA)		
Engine	69	72	77
Exhaust	69	70	70
Intake	63	63	65
Tires	68	69	75
Transmission	60	63	66
Other	60	72	65
Combined level	74.2	77.3	80.1

Table 3. Human response in comfort to various vehicle vibrations (Campbell, 2009)

Frequency-weighted vibration magnitude [m/s²]	***Human reaction onboard of the vehicle***
< 0.315	A
0.315 - 0.63	B
0.5 - 1	C
0.8 - 1.6	D
1.25 - 2.5	E
> 2	F

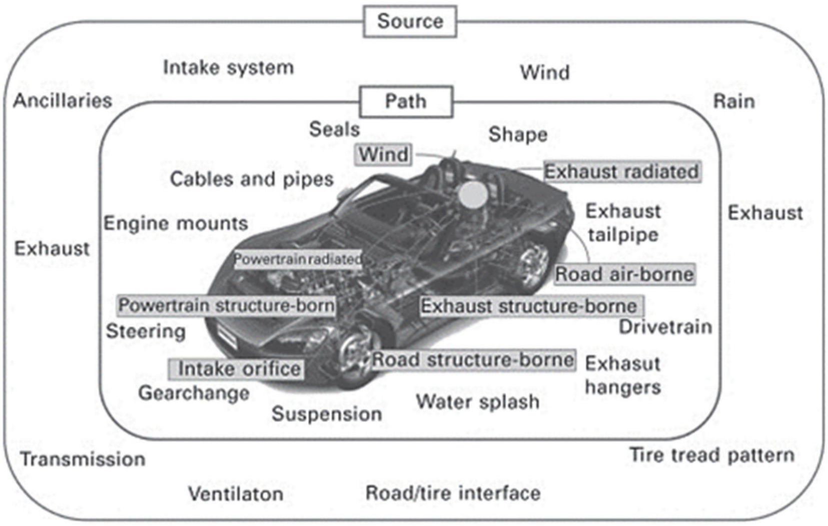


Fig. 2. Vehicle NVH sources combined with the transfer paths (Bein et al., 2012)

2.2. Selection of detection sensor for vibroacoustic monitoring of the vehicle components

The process of selecting the proper detection sensor for vehicle vibroacoustic diagnostic must take into account certain criteria, which can have different ranking depending to cases:

a. target signal:
- vibration, default sensor can be accelerometer - which are specific for structure borne transmission, with accepted limit of 300-500 Hz (Young, 2014);
- noise, default sensor can be microphone - which is representative for air borne transmission of the signal of the main components of the vehicle specific, which should be able to measure at maximum 20 kHz or above (Murphy, 2020).

b. transmission path:
- air borne;
- structure borne.

c. target fault:
- mechanical;
- hydraulic;
- pneumatic/vacuum;
- electrical.

d. propulsion type:
- internal combustion engine;
- hybrid vehicle;
- battery electric vehicle.

e. vehicle class:
- passenger car;
- commercial vehicle.

f. target vehicle component with corroborated natural frequency range, as it is represented in Fig. 2:
- engine;
- exhaust;
- accessories;
- gear box and drive train;
- steering and suspension;

- wheels with wheels hubs as unsuspended mass.

As can be seen in Fig. 2, certain perturbator factor can affect the signal detection, as for example:

- environment background noise and vibration,
- wind noise,
- road noise.

2.3. Open/Closed vibroacoustic type of engine compartment – main characteristics

According to the noise and vibration generating sources, Table 4 is explaining the proportion of each of them from the global vibroacoustic fingerprint of the vehicle.

Table 4. Contribution of NVH sources in the vehicle vibroacoustic fingerprint (Deulgaonkar, 2020)

Sr. no.	***Source***	***Contribution %***
1.	Engine	22 - 30
2.	Exhaust system	25 - 35
3.	Intake system	05 - 15
4.	Fan and cooling system	07 - 15
5.	Transmission	12 - 15
6.	Tyres	09 - 15

As could be observed from Table 4, the biggest proportion of noise and vibration sources are coming from engine compartment, that means this area is the main source and should be perceived as focus area in the vibroacoustic study of the vehicle. According to this, one of the main objectives is to establish the correct proportion of accelerometers and microphones from sensors matrix for experimental vibroacoustic monitoring of the vehicles.

During the study of vibroacoustic behaviour of the vehicles we observed that the matrix of sensors needs different proportion of accelerometers and microphones according to the studied vehicle category. From deeper analysis we determined two main categories of the engine compartment. We classified them, starting from noise and vibration characteristics. Those two categories we named closed and open vibroacoustic volumes, relative to the radiation of the noise and vibration from the outside, and according to the influence of disturbing vibracoustic environmental factors on the measurements. Table 5 shows both open and close vibroacoustic volume type of engine compartment.

Our goal in this study is to demonstrate, through experimental measurement, the influence of the two categories of volume in the engine compartment on the design of the array of sensors used to monitor vehicle noise and vibrations.

3. Vibroacoustic monitoring system. Results and discussion

3.1. Design of the experimental system for vibroacoustic monitoring of vehicles

In our test, designed to prove the hypothesis of the closed and opened vibroacoustic volume engine type, we create a monitoring system based on the following components:

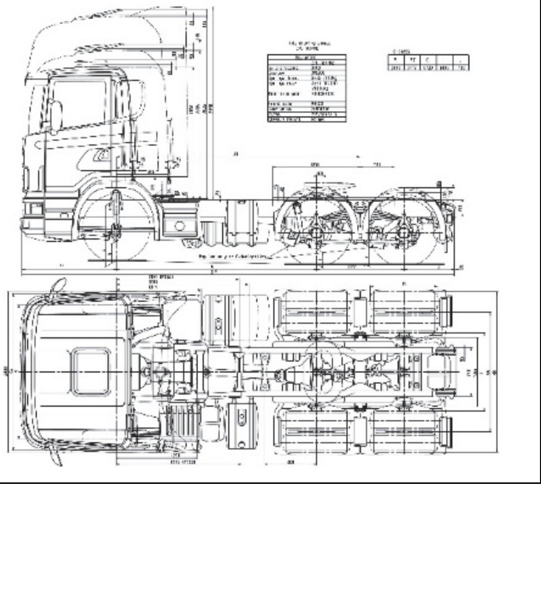
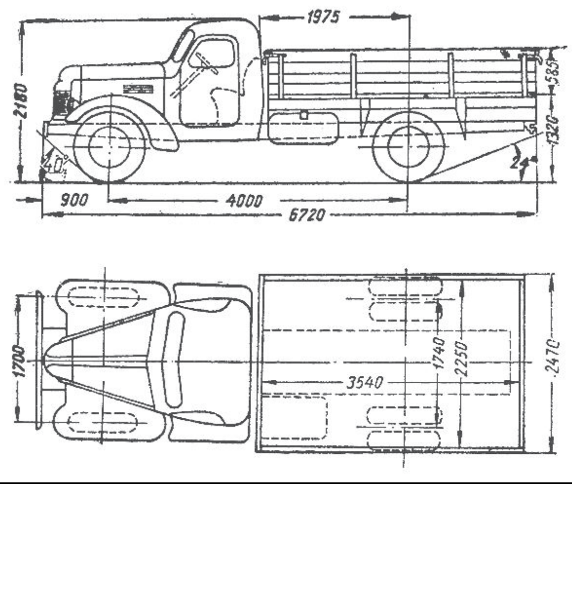
1.ADXL345 accelerometer, capacitive type with three axes measurement, frequency range from ±2g to ±16g and I2C communication;

2. MPU6050 accelerometer, capacitive type with three axes measurement, frequency range from ±2g to ±16g and I2C communication;

3. STEVAL-MIC007V1 microphone, capacitive type with scale of max 130 dBSPL, sensitivity of -38dBV and analogic communication;

4. Arduino UNO R3 and Arduino DUE data acquisition boards.

Table 5. Engine compartment categories from vibroacoustic perspective

Open volume	***Closed volume***
	

As a solver solution we chose MatLab software for signal acquisition and processing with mathematical models like Fast Fourier Transform for frequency analysis, as it is represented in (Eq. 1) (Patil and Patil, 2018):

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-i\omega t}\, dt \quad (1)$$

Where:

- $F(\omega)$ is the frequency spectrum of the signal;
- ω is the frequency, measured in radians per second;
- $e^{-i\omega t}$ is a complex exponential function.

Even if the specialized literature is mentioning mostly the measurement with sample rate of 100 Hz (Butt et al., 2020) we preferred to develop a software routine which was able to measure with sample rate of 4 Hz and 200 Hz. Measurement with 4 Hz, using an Arduino UNO R3 data acquisition board, have the goal to study the raw values of the acceleration vectors for every axis of cartesian system and the resultant acceleration vector, and the sound power signal from microphones. The 200 Hz measurement was done using an Arduino DUE data acquisition board aiming to study precisely the FFT processed signals for acceleration of every axle and the resultant one.

For ease of analyzing and study of measurement results we preferred to make a graphical representation of the raw and processed signals recorded with accelerometers and microphones using MatLab PLOT function. In addition, we used the resulting values of the processed signals of the accelerometers and microphones for further analysis.

3.2. Experimental proof of the vibroacoustic volume type of the vehicle's engine compartment for the sensor matrix design

As a study vehicle, we selected the variant of the open vibroacoustic volume type of engine compartment, represented by a truck with cab over the engine. This option gives us the opportunity to work in difficult conditions compared to those of close volume type, because here the noise and vibration are approximatively easy to radiate outside of the engine compartment. The received signals by sensors are affected by interferences with working noise and vibration. For example, they may interfere with other noises/vibrations coming from the cooling unit of the frigorific trailer or semi-trailer which is working using diesel engine for driving the refrigerating compressor. From the engine operating modes, we decided to measure noise and vibration at idle speed, but in two different stages: first one is representative for idle in normal operating conditions and the second one is representative for artificial fault created using dedicated diagnosis tester. In the Fig. 3 is presented An example of the fault induced with a dedicated tester by shutting off the injection of individual cylinders.is shown in Fig. 3. In the same manner, Fig. 4 presents the details of an induced fault with dedicated tester by actuating the engine decompression brake.

From the point of view of the engine operating modes according to the measurement steps, the comparative analysis of the results confirms the correctness use of accelerometer as well as the work routine in MatLab for the processing of the acquired signals.

Thus, Table 6 presents raw signal recorded when idling, for case I in normal operating conditions, and for case II, in faulty operating conditions induced by diagnosis dedicated tester. The accelerometer located on the rear right cover of the gearbox acquires these signals.

Practically from the evolution curve for the resultant vector of acceleration, the reproduction of the induced defect can be observed from the point of view of the repetition interval of the trigger at approximately 30 seconds for artificial created fault, as well as the amplitude of the signal peaks. The resultant vector of acceleration is calculated in MatLab with (Eq. 2) (Ware et al., 2016):

$$a_r = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (2)$$

where:

a_r = the value of the resultant acceleration recorded by an accelerometer

a_x = the actual value recorded by the accelerometer on the X axis

a_y = the actual value recorded by the accelerometer on the Y axis

a_z = the actual value recorded by the accelerometer on the Z axis

$a_{x/y/z}$ = the actual values, which means that they have already had the calibration values removed from them through a routine integrated into the software routine in MatLab that runs before the actual data acquisition

All the measurement of acceleration and sound pressure level were done after initial calibration of recorded value of sensors. The measurement was done with engine off just to identify values of environmental perturbations in normal conditions. MatLab work software routine was designed to remove automatically the influence of these factors.

The use of the microphones, from the point of view of the comparative analysis, highlights the influence of the open type volume of the engine compartment on the fidelity of the measurements. This aspect is presented in Table 7 through the evolution of the voltage/sound pressure variable over time, for the acoustic signals recorded by a microphone placed directly on the chassis in the immediate vicinity of the accelerometer mentioned in Table 6.

Case I corresponds to the idle speed in normal operating conditions and case II in faulty operating conditions created by diagnosis dedicated tester. It is clearly observed for case I that the peaks of the variable voltage/sound pressure are different both in maximum values and in distribution compared to case II, but not as clear as for raw acceleration signals as in Table 6 where trigger of 30 seconds is retrieved in case II. This fact denotes that the signal recorded by the microphone is strongly and significantly affected by the influence of the volume open type of the engine compartment. Practically for the vibroacoustic study of a vehicle with an open-volume engine compartment, the accelerometer is the easier solution to place compared to the microphone, which for an effective acquisition of acoustic data requires the identification of areas of optimal acoustic radiation.

In Fig. 5 it is presented the front view of studied truck with accelerometer and sensor placed in positions corresponding to signal measurement according to Table 6 and Table 7. Another aspect which should be mentioned is that both Table 6 and Table 7 are presenting raw result corresponding to measurement at 4 Hz. As it was mentioned at the beginning, we did the measurement with two sensors at the same sample rate of 200 Hz. Table 8 is presenting the Fast Fourier Transform (FFT) processed signal recorded by two different accelerometers located in different areas of drivetrain compartment. From this we observe that they measure the same main frequency of 25 Hz corresponding to engine running at idle speed.

From the point of view of the sample rate, in Table 8 we could observe that using accelerometer for vibroacoustic study of the vehicle, allows us to develop the work routine in MatLab according to one of the objectives for our analysis method, namely to make it possible to identify the dominant frequencies that appear when vibroacoustic anomalies are present.

To be able to achieve this process, it was necessary to connect in parallel an Arduino UNO board with a single ADXL 345 sensor with sample rate of 4 Hz and respectively an Arduino DUE board with ADXL 345 and MPU6050 sensors with sample rate of 200.

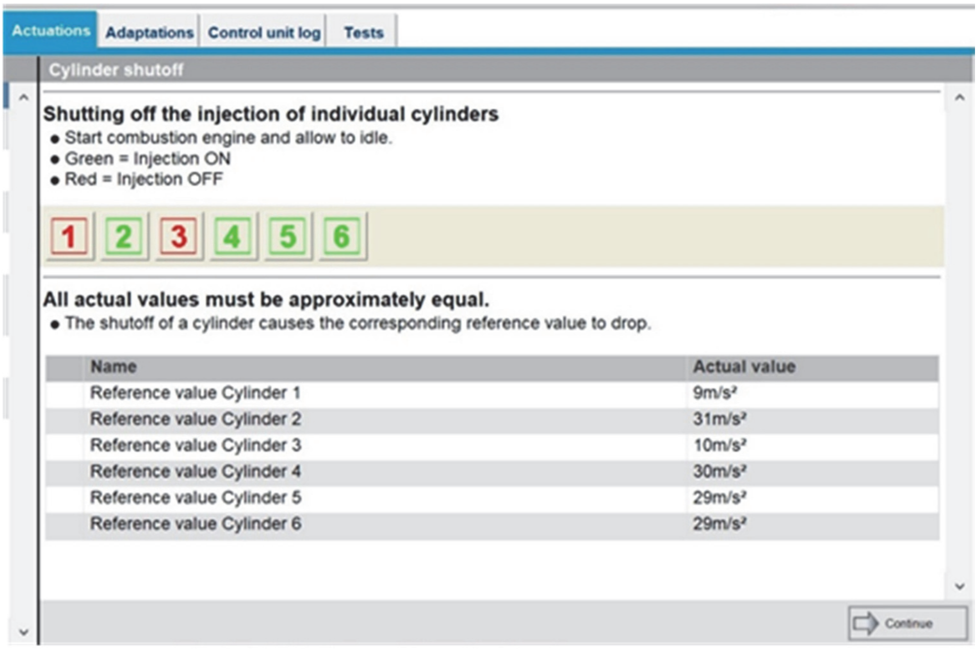


Fig. 3. Example of inducted fault by shutting off the cylinders injection

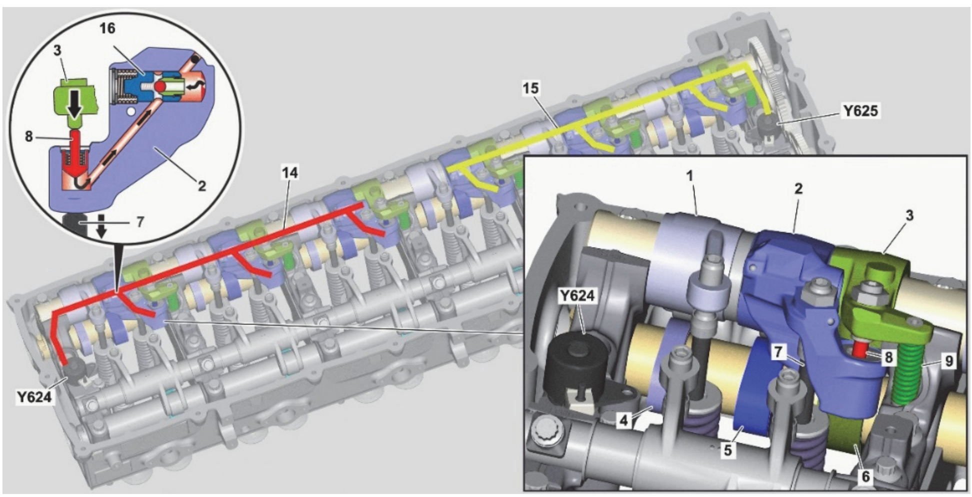


Fig. 4. Example of inducted fault by engine decompression brake valve

Table 6. Example of engine vibration recording for normal and faulty operating status

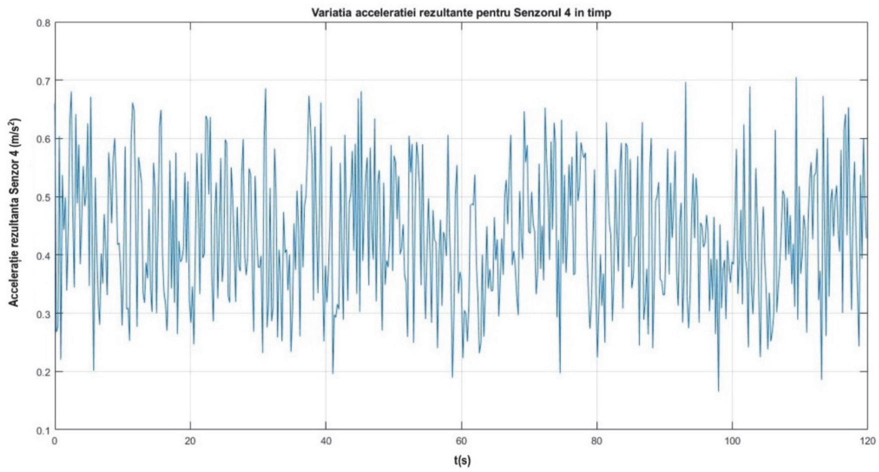
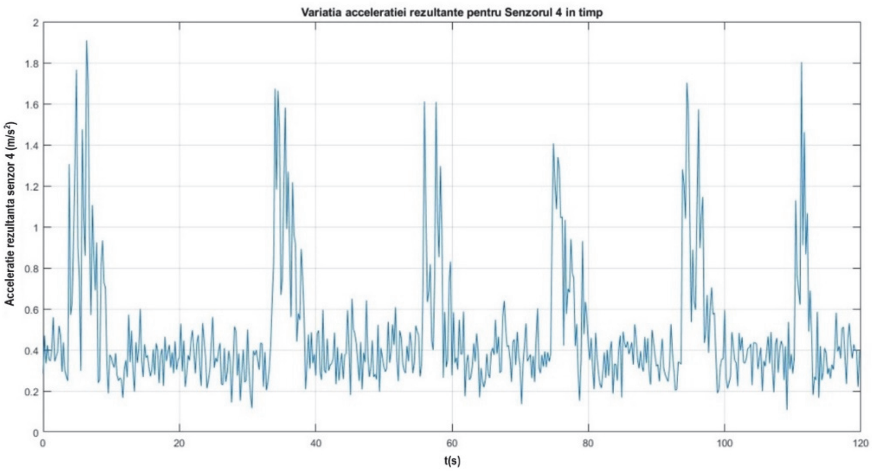
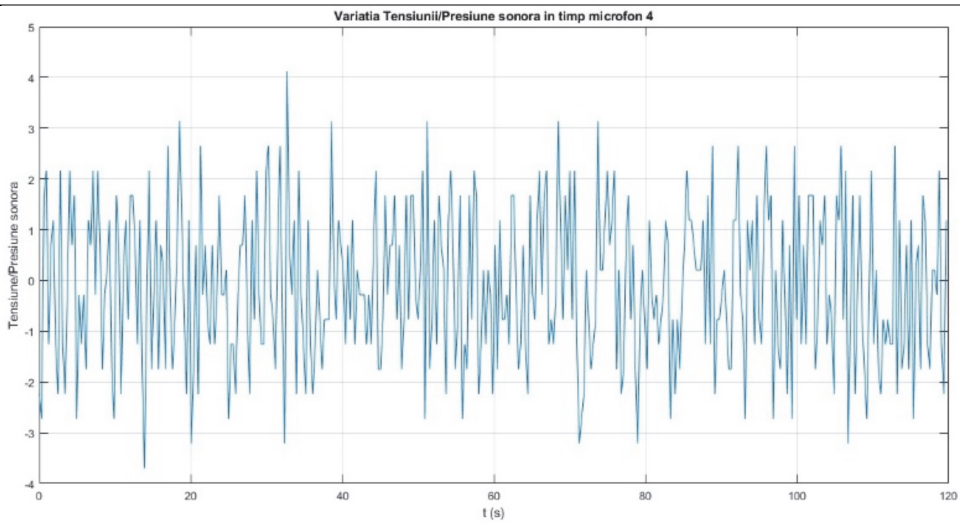
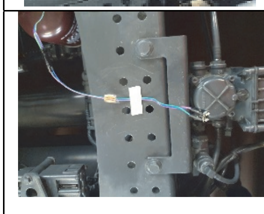
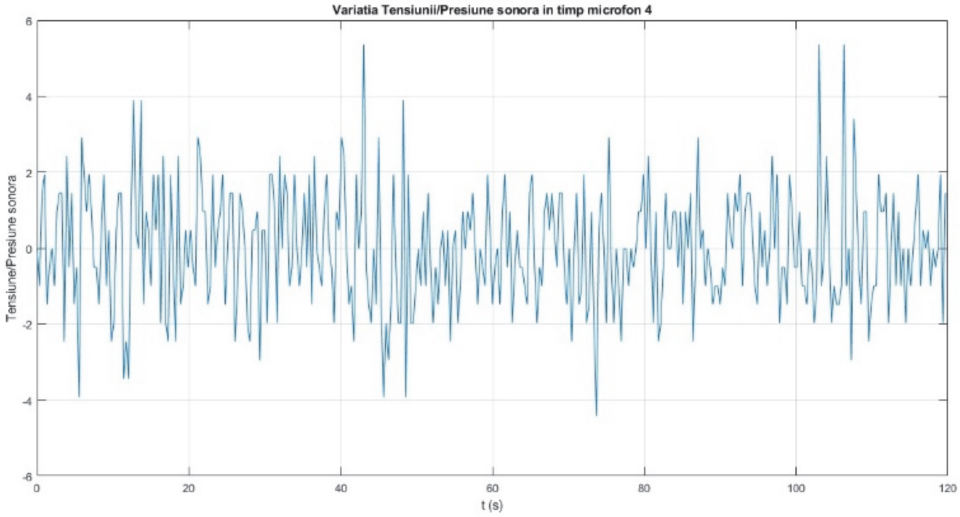
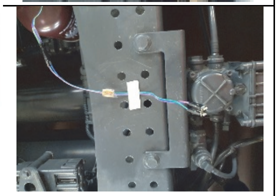
I. ***MPU6050 accelerometer mounted on the rear right cover of the gearbox, data acquisition at idle speed in normal operating status***	
	 
II. ***MPU6050 accelerometer mounted on the rear right cover of the gearbox, data acquisition at idle speed in faulty operating status created with dedicated diagnosis tester***	
	 

Table 7. Example of engine noise recording for normal and faulty operating status

I. ***STEVAL microphone located on the central cross member after the gearbox, data acquisition at idle speed in normal operating status***	
	 

II. ***STEVAL microphone located on the central cross member after the gearbox, data acquisition at idle speed in faulty operating status created with dedicated diagnosis tester***	
	 

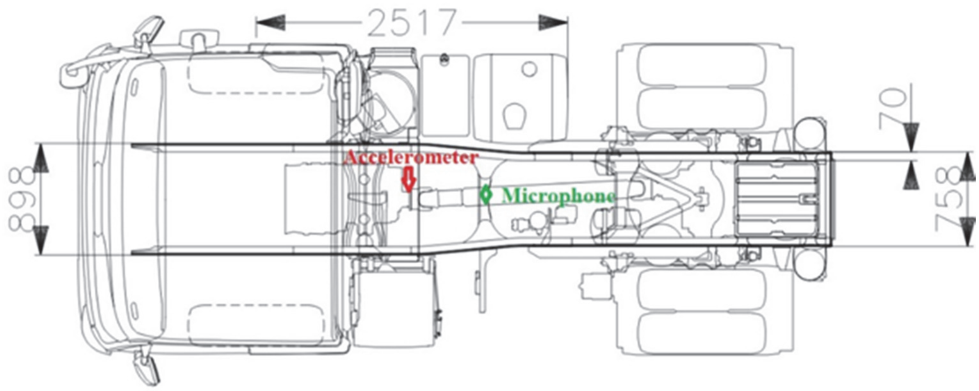
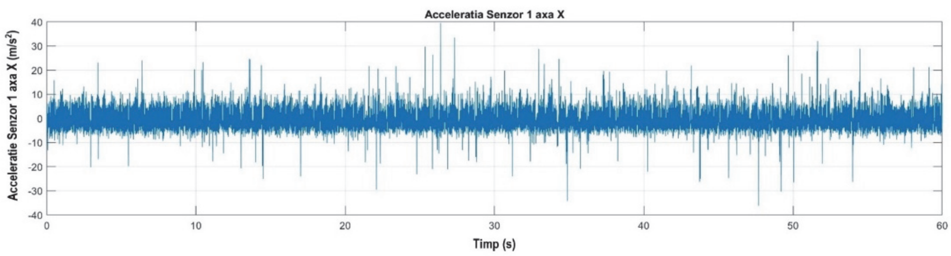
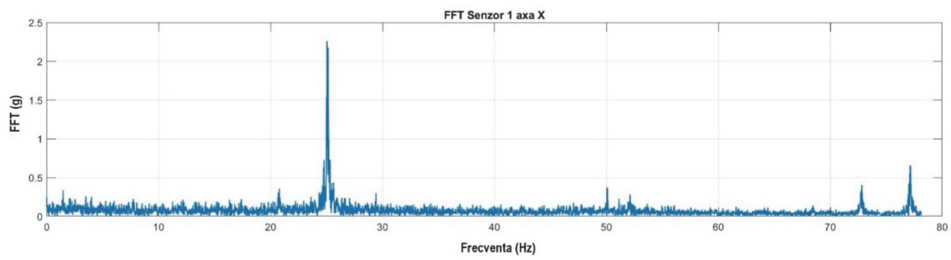
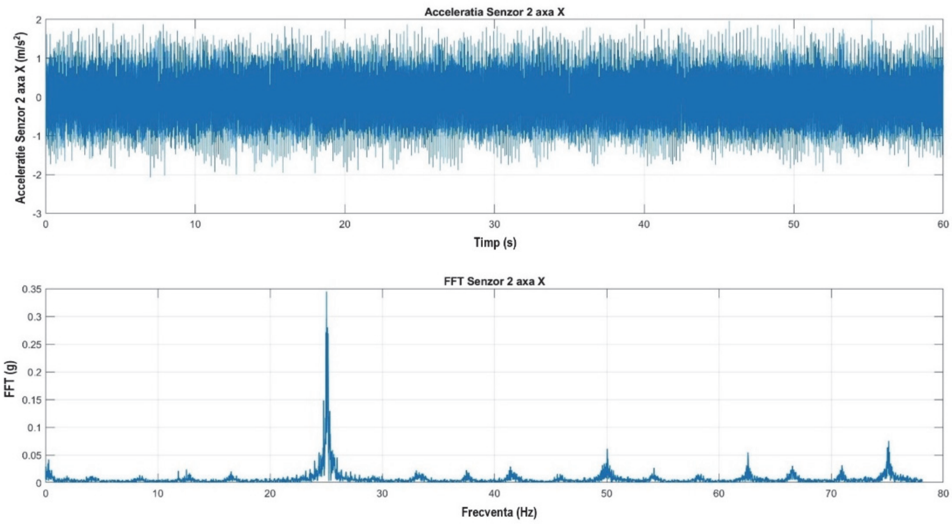


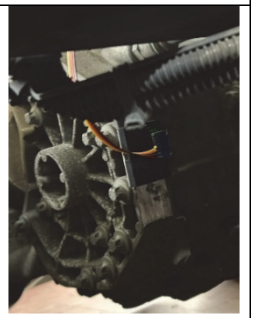
Fig. 5. Placement positions for accelerometer and microphone

Table 8. Evolution of the Fourier-processed X-axis acceleration signal, recorded simultaneously by two accelerometers but at different sample rates

I. ***ADXL345 accelerometer mounted on the rear side of the cylinder head, data acquisition at idle – with sample rate of 200 Hz***	
 	

II. ***MPU6050 accelerometer mounted on the rear side of the gear box, data acquisition at idle – with sample rate of 200 Hz***





4. Conclusions

The vibroacoustic diagnosis of vehicles is an effective way of preventing acoustic pollution, which is felt especially in urban agglomerations. Diagnostic methods and techniques based on noise and vibrations, which can lead to pollution reduction, are subject to continuous refinement, and our study meets this requirement.

The experimental side of the study on the influence of the type of vibroacoustic volume of the engine compartment on the analysis and diagnosis of vehicle noises and vibrations, led to the confirmation of the idea of establishing a matrix of sensors. They must be optimally placed on the vehicle and must be adapted to the volume of the closed or respectively open type, from the vibroacoustic point of view, of the engine compartment.

Thus, in vehicles with an open engine compartment, accelerometers must be placed on the predominant use in the sensor array, while the use of microphones can be viewed from the perspective of closed engine compartment volume.

In addition to the mentioned above, it should also be highlighted that performing measurements at a rate of 4 Hz allows highlighting the peaks of the acceleration vectors on the three axes as well as the resulting one, while the measurements performed at a rate of 200 Hz allow a Fourier processing that ensures the identification dominant frequencies characteristic of the state of vibroacoustic disturbance (or more precisely of the defect induced in the study).

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