VEHICLE VIBRATION IN HUMAN HEALTH

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Abstract

Fast development of technology over the last decades has contributed to the adverse effects that may affect human health (both physical and mental). Such negative effects may include noise and vibration. These phenomena are accompanied by most of the technological processes. Need for more efficient and productive processes is causing rising trend in intensifying of these phenomena. It is unavoidable to increase efficiency without increasing the operating speed of machinery and equipment.

The main goal of this paper is to carry out NVH (noise, vibration and harshness) analysis of engines; compression-ignition engine (diesel) and spark-ignition engine (gasoline) equipped in the same type of vehicle. But purpose is laying on presented methodology, not results of researches (but of course it will be presented too) which often (mainly) is made for failure detections.

This paper will also cover influence of the engine mounting on generated acoustic vibrations followed by comparative NVH analysis of states occurring in diesel and gasoline engine. Scope of the work:

a) theoretical introduction,
b) presentation of vibration measurement (using LDV: Laser Doppler Vibrometry),
c) NVH analysis in two types of engines,
d) comparison of results,
e) conclusions.

***Keywords**: Noise and vibration, Laser Doppler Vibrometry, Digital Signal Processing*

1. Introduction

Redundant dynamic interactions will take form of undesirable effects like vibrations or noise [1]. Both vibrations and noise have negative impact on human safety and health. These effects may cause:

a) balance disorder (motion sickness),
b) neck and occiput area pain (connected with stressed back muscles preventing excessive movement of head caused by vibrations), common among professional drivers,

These factors cannot be underestimated, because the consequences have unquestionable impact on human health and safety.

Noise, vibration, and harshness (NVH), also known as noise and vibration (N&V), is the study and modification of the noise and vibration characteristics of vehicles, particularly cars and trucks. While noise and vibration can be readily measured, harshness is a subjective quality, and is measured either via "jury" evaluations, or with analytical tools that provide results reflecting human subjective impressions.

Vibration is a mechanical phenomenon whereby oscillations occur about an equilibrium point. Kinetic energy is transformed to form of potential energy to be transformed once again to kinetic energy. This leads to the loop of cycle until excitation of this phenomenon [1]. The measurement of vibrations is affected by the number degrees of freedom of measured object. Mechanical system such internal combustion engine has a very large number of degrees of freedom.

In order to cope with this problem and avoid the large number of calculations, interpolation functions are used to bring physical system to state in which the number of degrees of freedom is known. Components are divided in regard to mass. Components with lower mass are treated as deformable bonds, and those with larger mass are treated as mass points or rigid bodies.

Vibroacoustic signal is often incorrectly identified with acoustic vibrations. This is caused by fact that the definitions of both vibroacoustic signal and acoustic vibrations are not precisely specified [1]. Therefore, it should be assumed that the acoustic vibrations cover narrower, more specific area of expertise. However, vibroacoustic signal describes the whole issue with use of discrete representation of vibrations which is necessary to characterize vibration. This signal is a "mechanoacoustic" phenomenon occurring in variety of machines and equipment. These phenomena include vibration, noise, air and material sound and 6 pulsations of fluids in machines. Vibroacoustic signal can be generated either by technical and biological objects.

Today the main purpose of vibroacoustic measurement is in diagnostics or prediagnostics of machinery failures. Majority of vibroacoustic detection systems are based on accelerometers. The reason of this state is due to the cost and knowledge (so – cost too). Therefore LDV has more possibilities (e.g. direct measurement of velocity and displacement) but sometimes environment excluded this kind of systems. The influence of vibrations on human (and animals) health is important or even more important. This conclusion could change direction of uses vibroacoustic acquisition process.

2. NVH influence on health

The basic factors of danger may occur in the working environment. Assuming that the main sources of noise occurring at the workplace are machinery, equipment or technological processes. It can be mentioned to basic groups [2]:

a) machinery which constitute the source of energy, for example internal combustion engines (maximum sound levels to 125 dB), compressors (up to 113 dB),
b) tools and pneumatic engines, pneumatic tools as hammers, chipping hammers, Sanders (134 dB),
c) machinery for grain, crushing, screening, treatment, for example mills ball (up to 120 dB), vibrating sieve (up to 119 dB), crusher (up to 119 dB), Grill shock (up to 115 dB),
d) machines for forming, for example picks (122 dB), press (up to 115 dB),
e) machine cutting tools for metal, for example turning and milling machines, (up to 104 dB),
f) machine cutting tools for wood, for example slotter (up to 108 dB), planer (up to 101 dB) miller (up to 101 dB), sawing machine (up to 99 dB),
g) rotating device, for example valves (up to 120 dB), fans (up to 114 dB),
h) transport equipment inside a share for example gantry crane, dumping, conveyors, feeders (up to 112 dB).

Excessive noise affecting the human body has an influence on human's health, the functions of the organs and systems, in particular the ear. Noise impacts not only the ear, but also other organs by the central nervous system. Influence of noise has an important role on psychological and mental efficiency, and also quality of the work, and of course driving. Noise impact on human organism was performed 54 years ago (showed on Fig. 1) [3].

Harmfulness, nuisance and annoyance of noise depend on its physical characteristics and factors that characterize these features in time, such as spectral characteristics, values of noise levels, time length of the noise impact, the nature of the impact (continuous, intermittent, impulsive). The frequency of vibration of human organs oscillates within the limits are given in the Tab. 1.

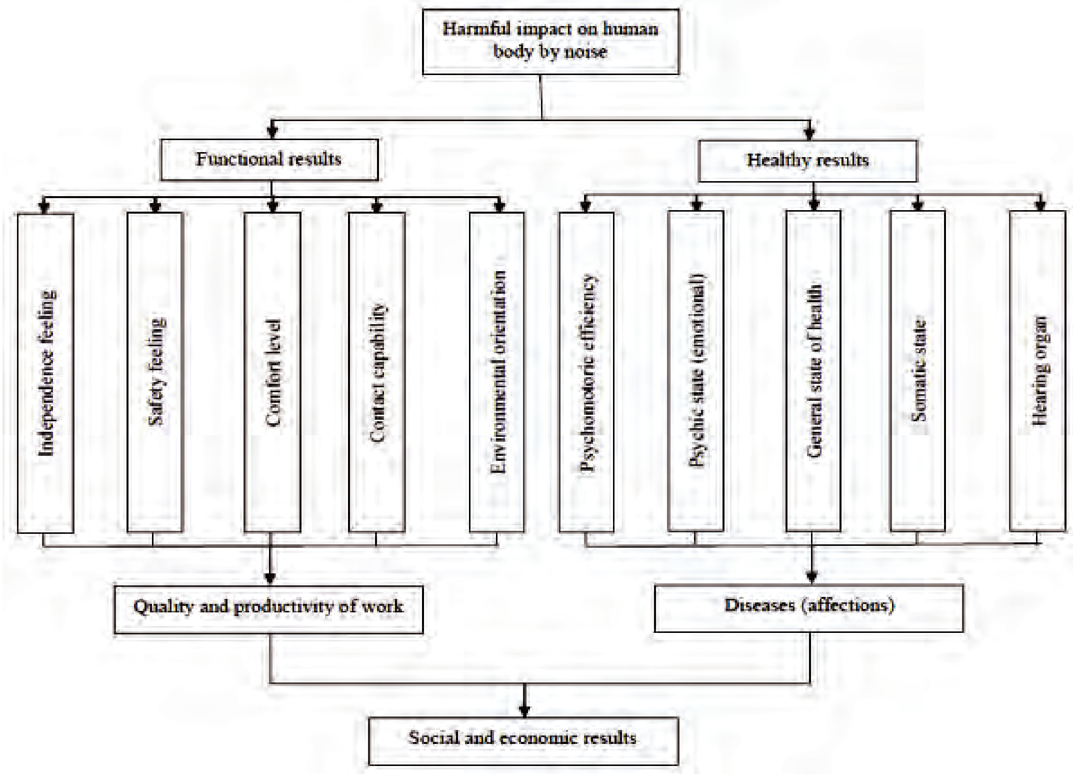

Fig. 1. Table of noise impact on human [3]

Tab. 1. Examples of the frequency of vibration of human organs [4]

Human Organ	Frequency of resonance [Hz]
Head	4-5
Jaw	6-8
Eyes	60-90
Chest organs	5-9
Upper limb	3
Stomach organs	4.5-10
Bladder	10-18
Pelvis	5-9
Muscles	13-20
Liver	3-4

3. Laser Doppler Vibrometry

Sound changes its frequency and phase when source of them is in move against destination (or both in move). This is set when the source is moving relative to the observer and the observer is moving relative to the source. In the case of light the same phenomenon is observed. Laser Doppler vibrometry allows for direct measurement of vibration velocity and displacement.

LDV system is showed on Fig. 2. Laser head is a transceiver device. Inside it there is the source of laser, interferometer and the layout of the lens. In the head, light uncouples into two components. The first one is the reference beam, which going by Bragg cell moves the beam of frequency of (about and generally) 40 MHz. It is driven on the photo detector. This process allows for the measurement of the constant component and the direction of movement of object. The second component of the light is set on object, it is car body in our case. After reflection from our element beam measuring returns to the head of the vibrometer and on the photo detector. This way, we can achieve an accurate measurement of the displacement and the velocity of transverse test object [1, 5].

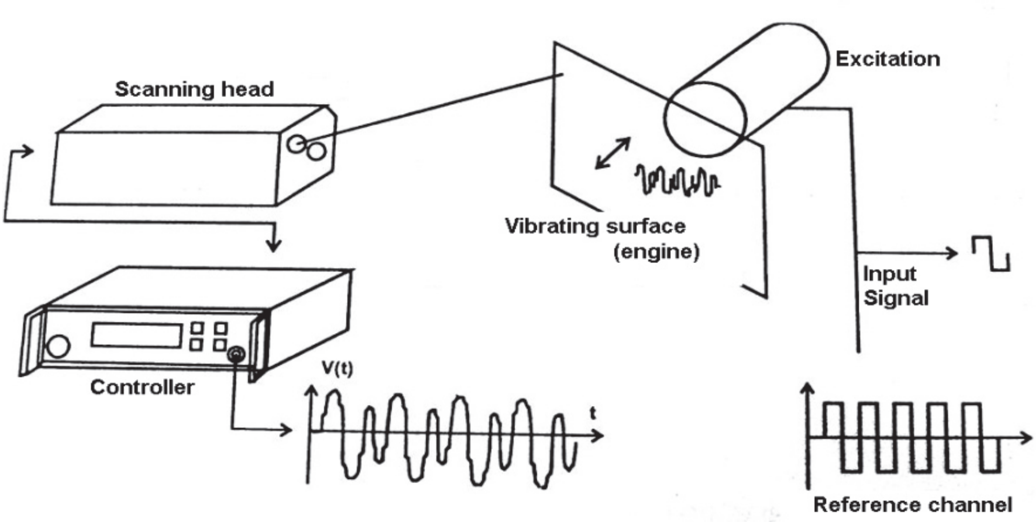

Fig. 2. LDV system

Used equipment gathered vibroacoustic signal from single point via (normal) mirror. Measurement parameters was standard for LDV (presented in Tab. 2).

Tab. 2. Vibration measurement parameters

Parameter	Value
Kind of measurement	Speed vector
Averaging	Off
Number of samples	4096
Sampling frequency	2048 Hz
Measurement duration	2 s
Filter	No
Directivity	+Z
Barrier frequency	20 kHz
Vibration range	640 /m

4. Digital Signal Processing for LDV

Without proper signal processing direct measurements sometimes do not yield explicit results. In addition, the proposed method requires multidimensional measurements, i.e. of a series of vibrations in the torque (of motor engine) domain.

The aim of all the signal digital processing operations performed during the investigations was to change the shape of the signal spectrum in a replicable way using standard methods. The first operation is signal windowing. In this case, windowing in the time domain since it is limited to the multiplication of the discrete vibration signal and the discrete window spectrum. Naturally, one could use a window in the frequency domain, but this would require the convolution of the two discrete signals.

Fig. 3. LDV acquisition in progress: 1- laser probe, 2- mirror, 3- place of laser beam reflection

A rectangular spectrum would have an ideal windowing sequence for damping uncharacteristic (from the investigation point of view) parts of the spectrum and simultaneously amplifying its characteristic parts. The ideal window would not distort the signal and prevent spectral leakage (an effect in which a part of the signal component, not situated by the frequencies for which the analysis is made, appears in all the output discrete signal values after transformation to the frequency domain [6, 7]).

Since it is impossible to obtain a rectangular frequency characteristic a compromise is necessary. The compromise consists in the use of the best (from the investigation point of view) windowing sequence.

It has been experimentally found that a flap-top window is a good solution. This window is characterized by a low resolution at high dynamics [1, 6]. Also its amplitude rendering accuracy is quite high.

After windowing the signal is transformed to the frequency domain, using the fast Fourier transform with a base of 2. Thanks to the algorithm the calculations can be significantly speeded up and a modern PC (or even DSP) does the job in part of second (of course it depends on number of samples).

One of the features of the discrete signal after the Fourier transformation, i.e. the time domain shift theorem, was used in the investigations. It follows from the definition of the Fourier transformation that a shift of the signal in the time domain by the value x is equivalent to multiplying the signal spectrum by the complex number $e^{-j\omega x}$ [1, 6]. The multiplication result has no effect on the shift of the spectrum in the frequency domain.

Since the spectral module is insensitive to the shift a decision was made to use the finite pulse response (FPR) filter design method. It is a very popular method of designing filters (except phase filters). The digital filter samples prepared (by extended Remez alghoritm also called the Parks-McClellan method) in this way are multiplied in the time domain by the samples of the frequency spectrum of the vibrations generated by the engine.

5. Experiment results

The results are presented in the form of diagrams in which the measured vibration velocities generated by the cars are compared. The waveforms were registered during 0.5 s long tests being part of the measurement lasting 2 s and involving 2048 samples in each case. Figures below (Fig. 4, 5) are presented results for idle run. Line which represented frontier for health danger is presented on frequency spectrum (Fig. 5).

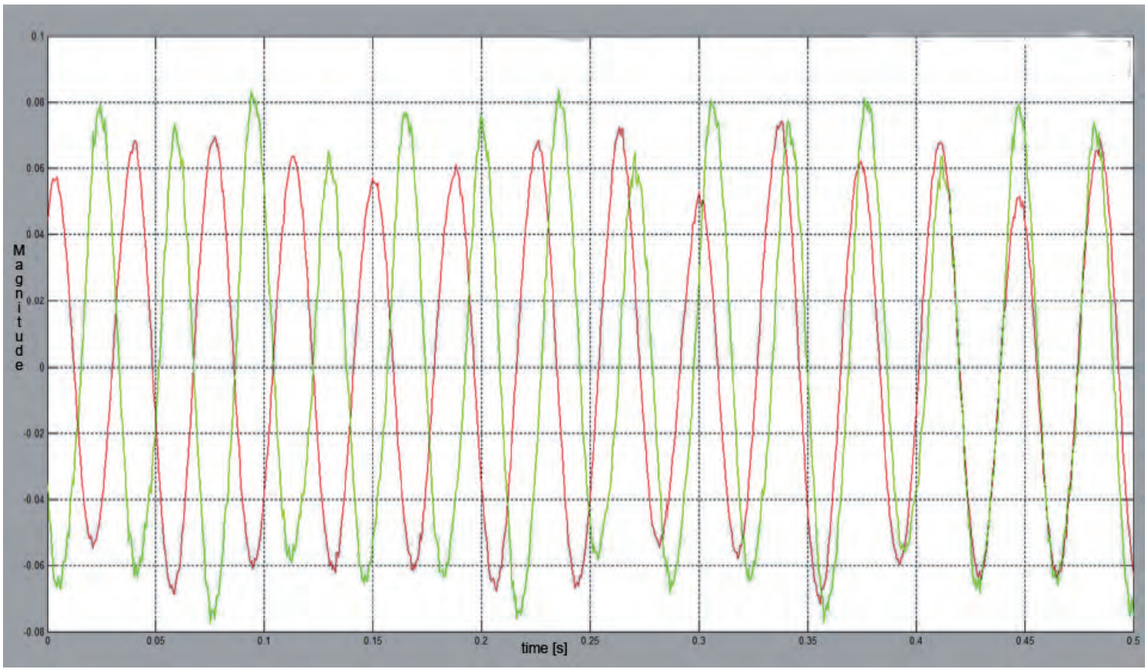

Fig. 4. Waveform of vibration velocity in engines, idle run, red line represents spark-ignition engine; green line represents compression-ignition engine

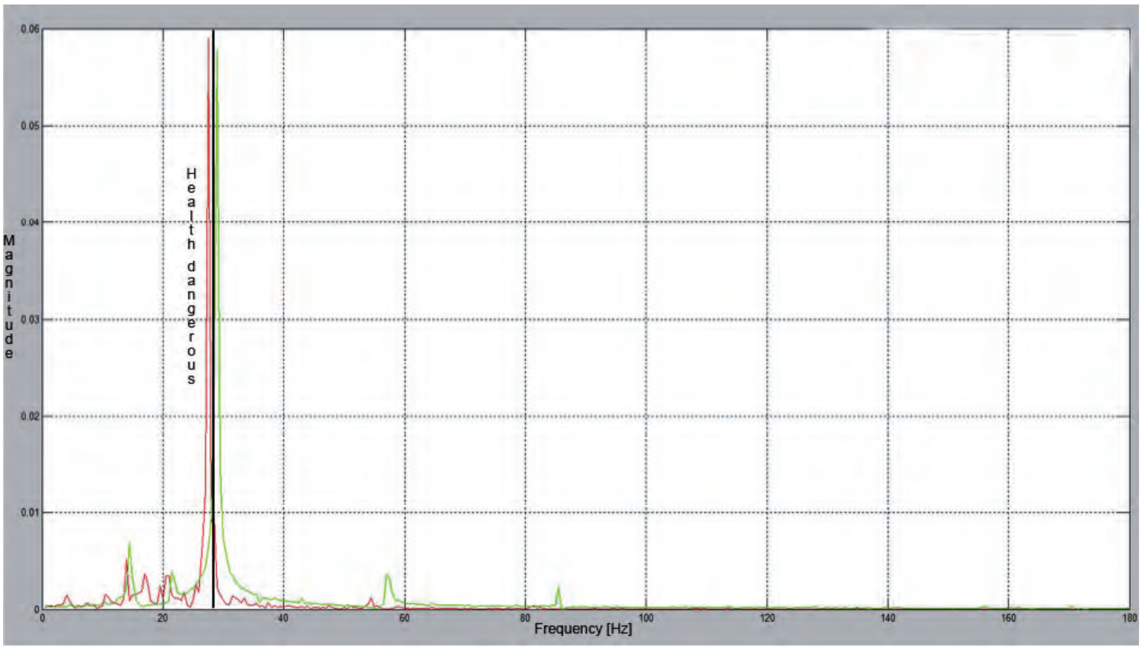

Fig. 5. Frequency spectrum of vibration velocity in engines, idle run, red line represents spark-ignition engine; green line represents compression-ignition engine, red – without compression

In Fig. 5 it can be seen as higher harmonics, in particular in case of an engine intercooler (58 and 84 Hz). The basic harmonic, whose values are close to the limit of the human health hazard (in both cases) is slightly less for the vehicle with an intercooler.. It can therefore be concluded that the charge has a “positive impact” on harm in infrasound, simultaneously with a negative effect on engine power (keep turning of the compressor blades for small velocity of crankshaft).

Next two Fig. 6, 7 presented results idle run but with forced 2000 rpm. In this part of researchers spark – ignition and compression – ignition engines were compared too.

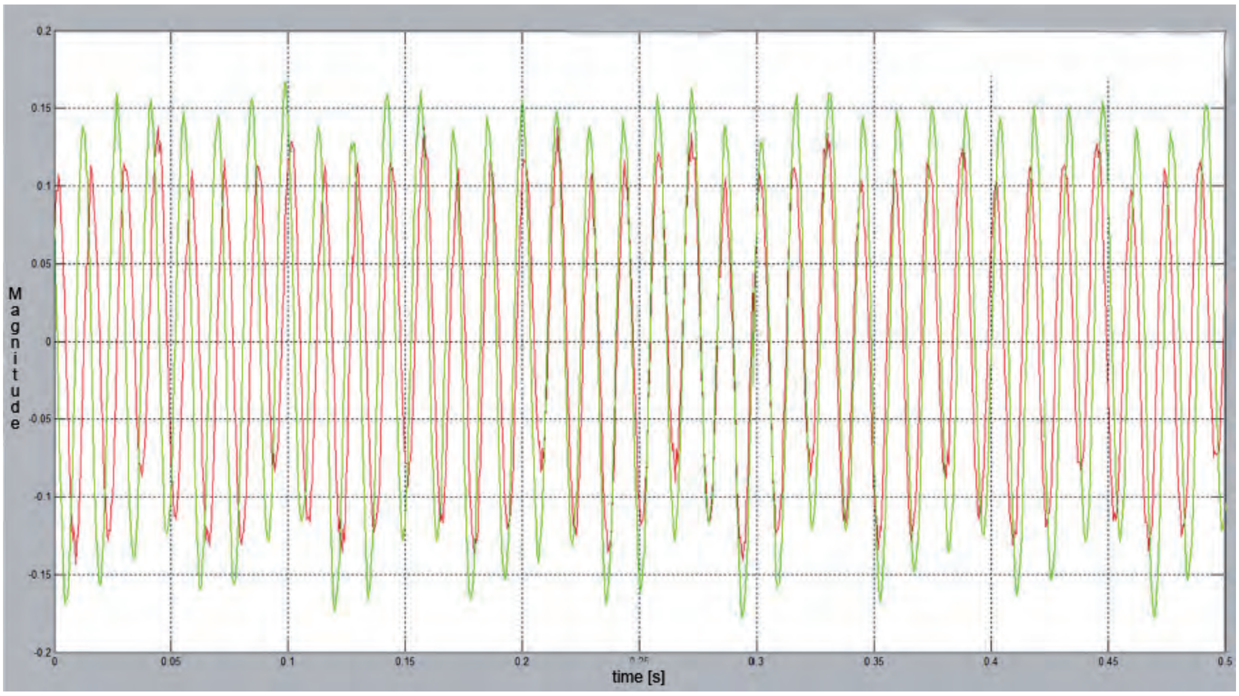

Fig. 6. Waveform of vibration velocity in engines, idle run with forced 2000 rpm, red line represents spark-ignition engine, green line represents compression-ignition engine

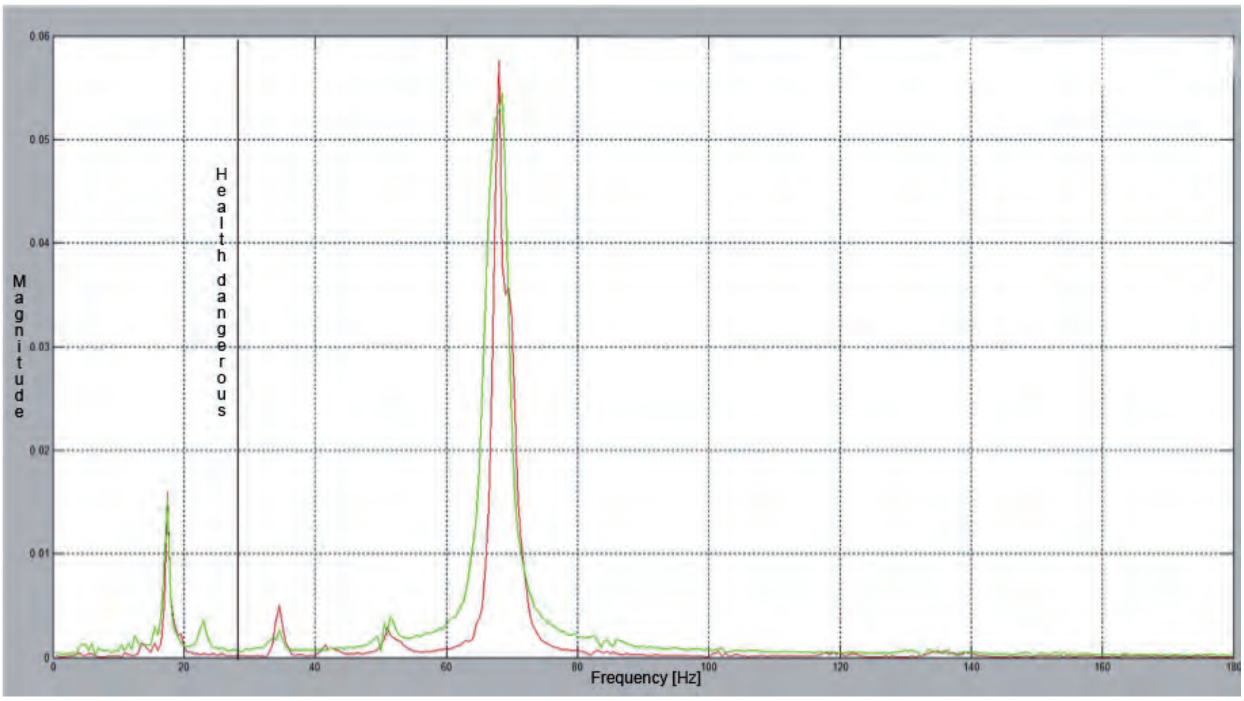

Fig. 7. Frequency spectrum of vibration velocity in engines, idle run with forced 2000 rpm, red line represents spark-ignition engine, green line represents compression-ignition engine

In Fig. 7 it can be seen dominant harmonic of 70 Hz. It is a harmonic, which directly indicates on crankshaft speed, as demonstrated in previous studies, which result was patented [8]. In this case, an electronically controlled compressor does not generate significant higher harmonics, and the harmonic potentially endangering human health is low.

Tab. 3. Averages and maximum value of velocity vibration (0 -100Hz)

No.	Description	Compression-ignition engine		Spark-ignition engine	
		V_{max} [m/s]	V_{AV} [m/s]	V_{max} [m/s]	V_{AV} [m/s]
1.	Idle running engine without forcing	0.084	-0.00023	0.086	0.000084
2.	Idle running engine with forced 2000 rpm	0.170	-0.00025	0.138	-0.000083

6. Conclusions

1. As it was shown, frequency may have an implications for the health and comfort of vehicle travellers.
2. The maximum vibration velocities are higher in case of the vehicle equipped with diesel engine. But dominant frequency is bigger (and not so dangerous for human health).
3. The engine mounting system is highly effective in damping the vibrations transmitted to the rest of the car. But standards for frequency value (rotation speed of crankshaft) must be established.
4. The gasoline engine in almost all measurement series (one exception) generated lower velocities of vibrations compared to compression-ignition engine.
5. It is necessary to make cheaper and cheaper LDV systems for "in – drive" researchers (accelerometers in this case achieve worse results regarding sensitivity for low frequency).
6. Previous studies, which are based on international standards (e.g. European standard ISO5128:1980 [9]) are based on the microphone measurement noise, which is the result of vibrations generated by the engine. In this case the measurement of the lower harmonic is limited, or even impossible in the case of piezoelectric sensors. A new way of measuring, using LDV, removes blemishes previously used methods and may be base for a new researchers and standards.
7. Minimizing the potentially dangerous effects of vibration is possible not only by getting a better vehicle suspension and the separation of the driver, but also by the use of the compressor, which increases the frequency of the dominant harmonic outside the hazardous area. However, it is now rarely used method because it has negative impact on an electronic control of engine supply at low engine speeds (and it is more expensive).

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