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EXAMINATION AND ASSESSMENT OF SPECIAL PURPOSE VEHICLE CREWS' COMFORT WHILE OPERATING IN OFF-ROAD CONDITIONS

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Abstract:

In the era of the rapid development of motorization one of the most important characteristics of transport vehicles is the safety and comfort of their drivers and passengers. In particular, people driving vehicles professionally are exposed to vibrations, which may adversely affect their bodies, causing discomfort, dysfunctions, and even lesions of disease. The vibration level triggered by the system a road – a vehicle depends on the type and profile of the road surface as well as the driving speed. Vibration levels are assessed by means of characteristics and comfort comparative indexes determined by experimental methods. Attempts at assessing the comfort while driving along paved roads may be found in many publications; however, there is a lack of information on testing vehicles moving in off-road conditions, which is substantial from the point of view of military vehicle crews' comfort. The driving comfort of crews of wheeled vehicles is subjected to examinations at the Military Institute of Armored and Automotive Technology.

Keywords:
driving comfort, effective vibration acceleration, special purpose vehicles

INTRODUCTION

In the era of the rapid development of motorization one of the most important characteristics of transport vehicles is the safety and comfort of their drivers and passengers. In particular, people driving vehicles professionally are exposed to vibrations, which may adversely affect their bodies, causing discomfort, dysfunctions, and even lesions of disease [6,7]. The vibration level triggered by the system a road - a vehicle depends on the type and profile of the road surface as well as the driving speed [5]. Vibration levels are assessed by means of characteristics and comfort comparative indexes determined by experimental methods. Attempts at assessing the comfort while driving along paved roads may be found in many publications; however, there is a lack of information on testing vehicles moving in off-road conditions, which is substantial from the point of view of military vehicle crews' comfort. The driving comfort of crews of wheeled vehicles is subjected to examinations at the Military Institute of Armored and Automotive Technology.

1. THE IMPACT OF VIBRATIONS ON THE HUMAN BODY

Mechanical vibrations can negatively affect individual organs of the human body. It is possible to induce vibration of the whole body, its organs or even cellular structures. Long-term vibration impacts on humans can result in persistent, irreversible lesions and disorders of the vascular, nervous or osteoarticular systems.

Vibrations affecting the entire human body through body parts that come into contact with the vehicle components belong to general vibrations. The first symptom of a negative effect on the human body is driver fatigue and impairment of psychophysical aptitude.

Long-term human body's exposure to vibrations has a negative impact primarily on the skeletal system and internal organs. In the skeletal system, the lesions most often occur in the lumbar spine, sometimes in the cervical spine [6,7]. These are the most common ailments of vehicle drivers causing incapacity for further work. Crews of military vehicles moving in tough terrain belong to a group of people particularly susceptible to vibrations. Road roughness or high-amplitude roadless tracks may translate into high levels of the vibration acceleration. At the same time, when driving in field conditions, irritation of the balance organ can cause severe complaints known as motion sickness. This situation often occurs during the soldiers' transport by a vehicle, which is not equipped with windows allowing observation of the environment. Soldiers feel the stimuli resulting from the acceleration in different directions that arise while driving, but there is a lack of conformity of labyrinth stimuli with visual ones. Such driving deteriorates wellbeing and causes general fatigue leading to dizziness and headaches as well as nausea or vomiting.

Vibration frequencies of most human body organs are typically in the range of 2-18Hz. Higher frequencies cause visual resonance (20-40Hz and 60-90Hz), which is further accompanied by visual distortion, narrowing of the field of vision, and weakening of the ability to distinguish colors [7]. Table 1 summarizes the vibration frequencies of selected organs and parts of the adult human body determined by the experimental method.

2. THE METHOD OF EXAMINATION AND ASSESSMENT OF DRIVING COMFORT

The spectral estimation method for constant driving speed according to PN-91 S-04100 [6, 10, 11] was applied for the analysis of the experimental testing results. This method measures the acceleration in the longitudinal, transverse and vertical directions in the seat of a driver or a passenger. The driving comfort of a vehicle is evaluated by the characteristics of the acceleration of the effective vibration as a function of the frequency of middle third octave bands.

Table. 1. Exemplary frequencies of natural vibrations of the organs and parts of the human body determined by experimental means

Name of organ	Frequency [Hz]	Possible disease symptoms observed
Head Head with neck Barges and head Jaw Eyeballs	4÷5, 17÷25 20÷30 6÷8 60÷90 i 40÷90	Pains, dizziness, imbalances, larynx pressure, nausea, forced rotation movement of the head, speech impediment, general psychophysical fatigue
Abdominal organs: liver stomach urinary bladder kidneys	4,5÷10 3÷4 2÷3 10÷18 6÷8	Sensation of internal organs vibration, pain, nausea, feeling of fullness, urinary and bowel urgency, weakness and fatigue, reluctance to performing work
Chest	5÷7 4÷11	Respiratory distress, pressure sensation, shallow breathing, burning chest pains
Chest organs: lungs heart trachea, bronchi	5÷9 4÷11 4÷6 12÷16	Respiratory distress, dyspnea, tachypnea, sensation of restlessness, pulse acceleration, blood pressure changes, heart beat, speech disorders, general malaise
Upper torso: Barges and head	4÷5 20÷30	Joint and muscle pains, cervical spine pains, increased muscle tension, fatigue
Lower torso: pelvis spine sacral spine lumbar spine	4÷6 5÷9 10÷12 8÷12 8÷12	Joint and muscle pains, lumbar and cervical spine pain, increased muscle tension, fatigue
Lower limbs: hips calves feet	5 5 20 -	Joint and muscle pains, increased muscle tension, numbness and tingling of muscles
Upper limbs: arm forearm	4÷5 16÷30 4÷6	Joint pains, increased muscle tension, muscle pains, involuntary muscular contractions resulting in additional hand movements, difficulty

Source: [7]

The first step in processing the measurement results is to transfer the recorded acceleration time courses from the time to frequency domain using the Fast Fourier Transform (FFT). The next step is the calculation of the effective vibration acceleration a_f for individual frequencies of the middle third octave bands using the expression [10]:

$$a_f = \sqrt{\frac{1}{n}\sum_{i=1}^{n} a_i^2} \text{ [m/s}^2\text{]} \quad (1)$$

where:

a_i – the value of the vibration acceleration measured in the i^{th} frequency interval [m/s²];

n – the number of readings at equal frequency intervals .

The characteristics obtained allow us to determine in which of the third octave bands of frequency the highest accelerations occur and whether their values exceed the limits of comfort, nuisance or harmfulness (Fig. 2.1, 2.2.).

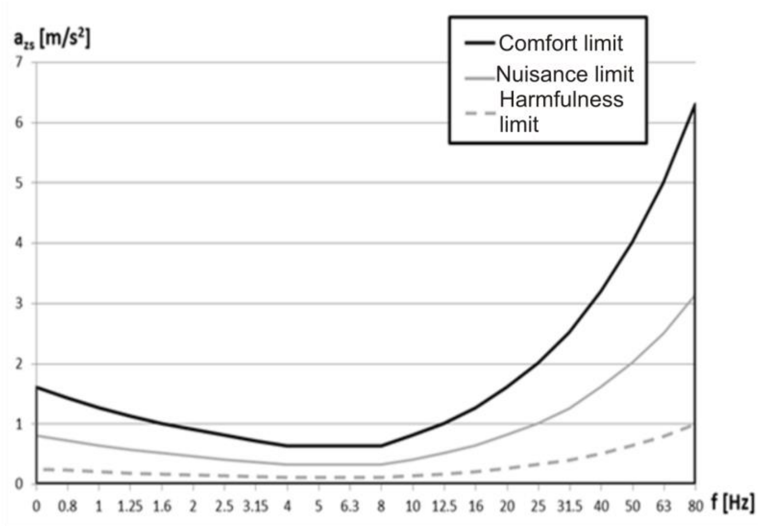


Fig. 1. Limits of comfort, nuisance I harmfulness in the vertical direction, where: azs –the effective acceleration towards Z.

Source: [10]

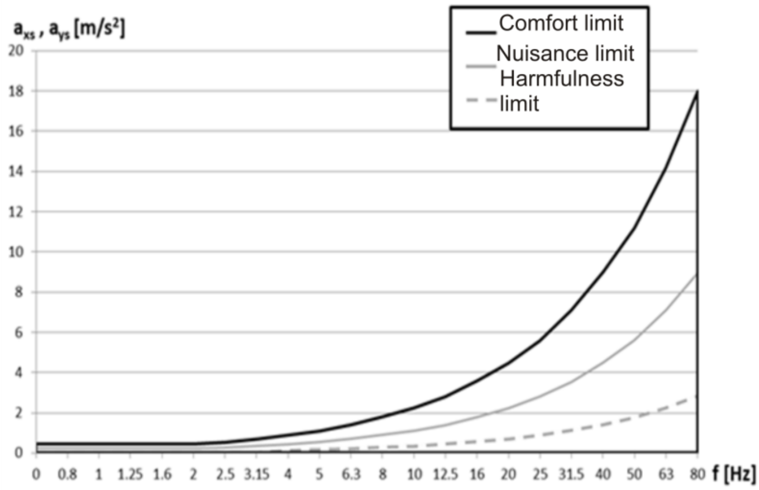


Fig. 2. Limits of comfort, nuisance I harmfulness in the horizontal direction, where: axs – the effective acceleration towards X, ays – the effective acceleration towards Y.

Source: [10]

Further computations are made in accordance with the principles for the assessment of the value of the adjusted acceleration and the assessment of the spectral acceleration.

The following numerical indicators are calculated using the principles for the assessment of the adjusted acceleration value:

- the equivalent adjusted value of the vibration acceleration aw(v);
- the allowable duration of the impact of vibrations tvdop on a driver.

The principle for the assessment of the spectral acceleration is used for the calculation of the following numerical indicators:

- the coefficient of multiplicity of exceeding the limit of nuisance (KGU);
- the allowable duration of the impact of vibrations t_{vdop} on a driver.

2.1. The principle for the assessment of the adjusted acceleration value

According to the principle for the assessment of the value of the adjusted acceleration [6,11], the equivalent adjusted value of the vibration acceleration aw(v) is determined using the formula:

$$a_{w(v)} = \sqrt{\sum_{i=1}^{n} a_f^2 \cdot W_f^2} \ [\mathrm{m/s^2}] \tag{2}$$

where:

a_f – the effective value of the vibration acceleration for the mid-frequency third octave band f obtained by the spectral analysis [m/s^2];

W_f – the correction coefficient for mid frequencies of third octave bands (Table 2.3.);

n – the number of the realized third octave bands.

Table 2. The values of the correction coefficient W_f

Middle frequencies of third octave bands [Hz]	Values of the correction coefficient Wf for		Middle frequencies of third octave bands [Hz]	Values of the correction coefficient Wf for	
	Z	Y,X		Z	Y,X
0,8	0,45	1	10	0,8	0,2
1	0,5	1	12,5	0,63	0,16
1,25	0,56	1	16	0,5	0,125
1,6	0,63	1	20	0,4	0,1
2	0,71	1	25	0,315	0,08
2,5	0,6	0,6	31,5	0,25	0,063
3,15	0,9	0,63	40	0,2	0,05
4	1	0,5	50	0,16	0,04
5	1	0,4	63	0,125	0,0315
6,3	1	0,315	80	0,1	0,025
8	1	0,25			

Source: [11]

The obtained adjusted values of the vibration acceleration $a_{w(v)}$ are compared to the allowable adjusted values of the vibration acceleration a480 for the nuisance limits from Table 2. If the equivalent value of the adjusted vibration acceleration $a_{w(v)}$ exceeds the allowable values (Table 2), the allowable duration of the vibration impact t_{vdop} is computated (5), otherwise t_{vdop} is 480 minutes.

2.2. The principle for the assessment of spectral acceleration

According to the principle for the assessment of the spectral acceleration, the multiplicity coefficient of the exceedance of the nuisance limits KGU is calculated according to the formula below:

$$KGU = \frac{a_{v(f)}}{a_{f480}} \text{ [-]} \tag{3}$$

where:

- $a_{v(f)}$ – the value of the effective vibration acceleration for the third octave band of frequency [m/s^2];
- a_{f480} – the allowable value of the vibration acceleration for the third octave band of frequency [m/s^2].

When the values of the multiplicity of the exceedance of the limit of nuisance KGU is less than 1, the allowable duration of the vibration impact is t_{vdop}=480 min. Otherwise, the allowable duration of the vibration impact t_{vdop} is calculated according to the formula:

$$t_{vdop} = \left(\frac{a_{f480}}{a_f}\right)^2 \cdot 480 \text{ [min]} \tag{4}$$

where:

- af_{480} – the allowable effective value of the acceleration of the third octave band of frequency f for the nuisance limits [m/s^2], (Fig. 2.2, 2.3);
- a_f – the value of the acceleration of the third octave band of frequency f in which the exceedance of the limit of nuisance was observed [m/s^2].

3. TOOLS FOR DETERMINING THE CHARACTERISTICS AND COMPARATIVE INDICATORS FOR THE ASSESSMENT OF VEHICLE DRIVING COMFORT

It is necessary to use numerical tools to identify the characteristics and comparative indexes [1, 4]. The calculation of indices and the generation of characteristics require complex computational procedures, which are facilitated by computer programs such as MS Excel (including Visual Basic) or MATLAB. The individual steps of the computational algorithm are shown in Figure 3.

This way a set of characteristics and comparative indexes for assessing driving comfort is obtained:

- the acceleration time courses;
- the power spectral density (PSD);
- the diagrams of the effective vibration acceleration as a function of the frequency of third octave bands;
- the equivalent adjusted value of the vibration acceleration $a_{w(v)}$;

- the multiplicity coefficient of exceeding the nuisance limits KGU;
- the allowable duration of the vibration impact t_{vdop} on a driver.

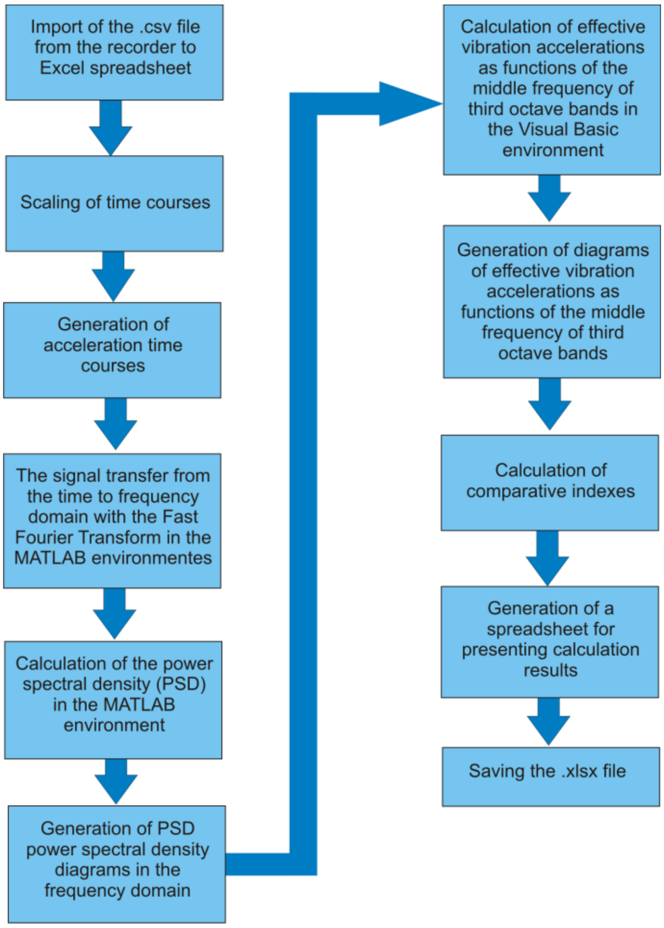


Fig. 3. The block diagram of the algorithm operation for determining the characteristics and comparative indicators of vehicle driving comfort

Source: own elaboration

4. EXPERIMENTAL STUDIES

The experimental studies were carried out to evaluate the driving comfort of the special purpose vehicle crew in off-road conditions. The truck was field-tested. The research was carried out on military training field roads. The measured physical quantities included momentary acceleration of vibrations on the driver's seat.

4.1. The object studied

The studies used the high mobility off-road truck Star 1466 (Figure 4). The air pressure in its wheels was the same as that recommended by the manufacturer

Fig. 4. View of the Star 1466 vehicle during the road test in the military training ground roads (tank road No. 2)

Source: own elaboration

The vehicle was fitted with 6 Continental HCS 14.00R20 tires with the average tread block height (Figures 5 and 6) of approximately 20mm.

a) **b)**

Fig. 5. Continental HCS tire a)Side view, b) Front view

Source: own elaboration

4.2. Testing conditions

The experimental studies were conducted along several road sections in the military training area. The sections differed in the type of surface and shape of the road profile. The following road sections were selected:

– roadless tracks (B) - a circle-shaped section characterized by the deformable substrate of small but irregular unevenness (Table 4a);
– tank road No. 2 (DC) – a wide rectilinear section characterized by the deformable substrate of medium sized and large unevenness (Table 4b);
– tank road No. 3 (TC) – a rectilinear section characterized by the deformable substrate of large sinus-shaped unevenness (Table 4c);
– gravel road (DS) - a rectilinear section characterized by the hardened substrate, covered with stones and gravel (Table 4d);
– destroyed concrete road (ZB) - a rectilinear section characterized by the hardened substrate of cracked concrete slabs with protruding edges (Table b 4e).

The vehicle speeds were chosen according to the type of track section in question. The highest speed for a given section was such a steady speed at which the vehicle wheels did not detach from the ground. The speeds were of 12, 18 and 24km/h where possible.

Table. 4. Graphic overview of examples of the test track sections

a) view of the test track section classified as a roadless track

b) view of the test track section classified as the tank road No. 2

c) view of the test track section classified as the tank road No. 3

d) view of the test track section classified as a gravel road

e) view of the test track section classified as a destroyed concrete road

Source: own elaboration

4.3. Physical sizes measured during testing

The physical values used to evaluate the driver's overall body vibration were accelerations measured in three directions (x, y, z) under his buttocks (Fig. 7).

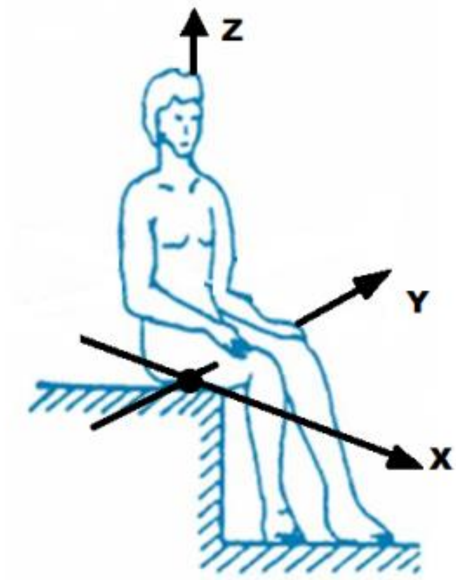


Fig. 7. Diagram of the accepted reference system for the measured acceleration components

Source: [9]

4.4. Measurement equipment

Experimental studies were carried out by means of the following measurement equipment:

- Brüel & Kjær triaxial vibration transmitter with a measuring range of up to 50g (Figure 8) mounted on the driver's seat under his buttocks (Figure 9) (directions of the sensor axis corresponds to the arrangement shown in Figure 7);
- Brüel & Kjær load enhancer;

– HIOKI digital recorder.

Fig. 8. View of the triaxial acceleration sensor

Source: [13]

Fig. 9. View of the measuring disc (cushion) with a mounted triaxial acceleration sensor installed on the driver's seat

Source: [13]

4.5. Exemplary test results

Exemplary results of the acceleration time courses obtained on the surface of tank road No. 2 for the speeds of 12 and 18 km/h (DC12, DC18) are shown in Figure 10.

In this case it is clear that, for example, for X direction, at the 50% growth in speed, the maximum vibration accelerations increase by up to 200%, from 6m/s2 to over 10m/s2. This proves that even a small change in speed can bring with it high increase in the obtained acceleration values. The results obtained in the presented system were processed, which consisted in the determination of the spectrum and other comparative indexes according to the test methodology used (Figure 11).

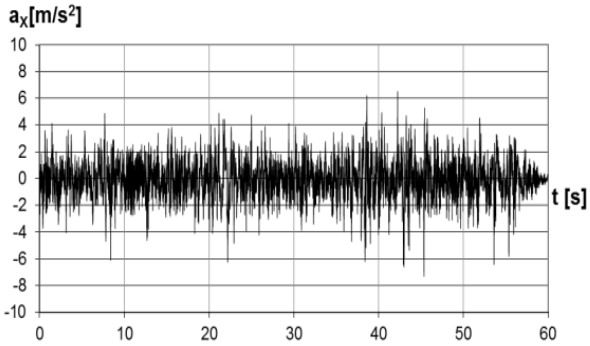
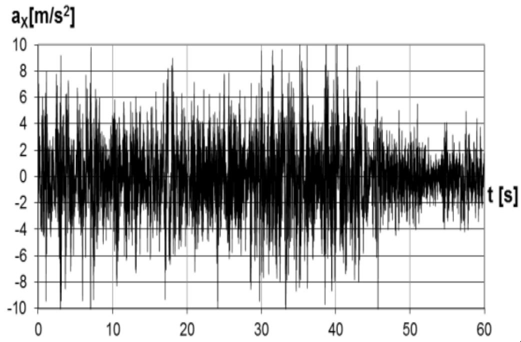
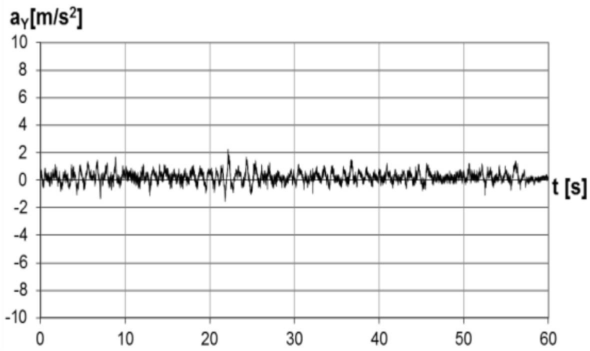
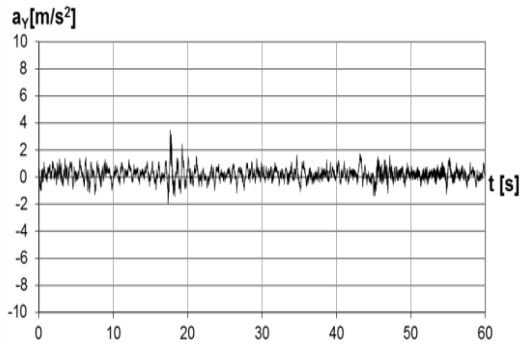
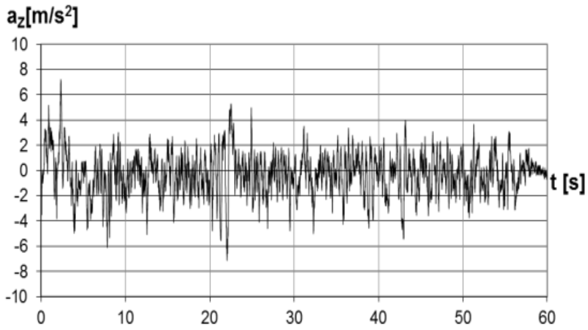
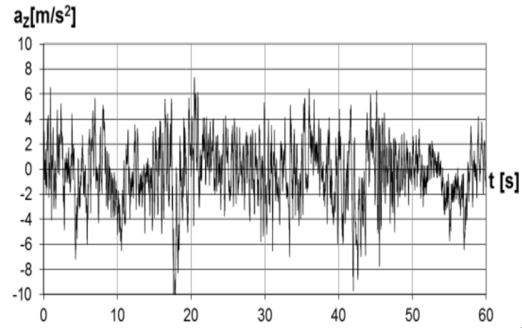
a) Acceleration time courses for the section: tank road No. 2 at the speed of 12 km/h (DC12)	**b)** Acceleration time courses for the section: tank road No. 2 at the speed of 18 km/h (DC18)
- X direction	- X direction
	
- Y direction	- Y direction
	
- Z direction	- Z direction
	

Fig. 10. View of the exemplary results of the acceleration time courses for two different speeds on the same substrate

Source: own elaboration

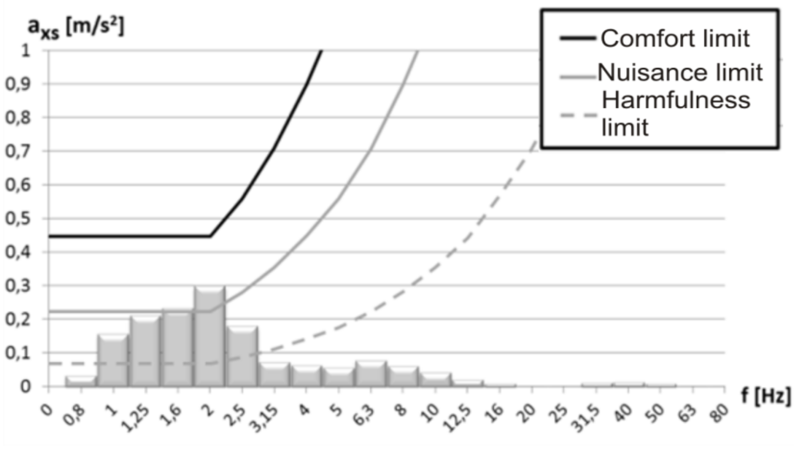
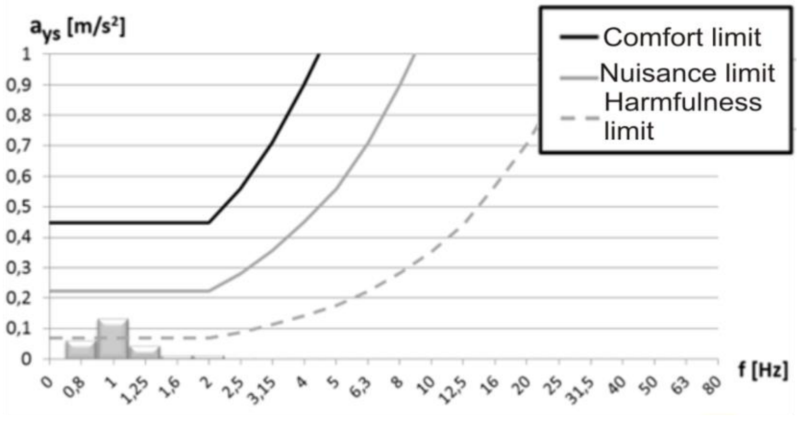
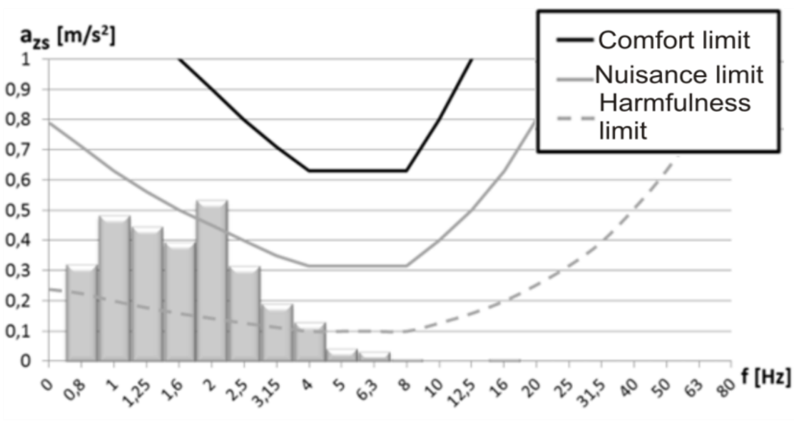
<table>
<tr><th>RMS as a function of the middle frequency of third octave bands</th><th colspan="2">Comparative index [unit]</th></tr>
<tr><td colspan="3">- X direction</td></tr>
<tr><td rowspan="4">
</td><td>$a_{w(v)}$ [m/s²]</td><td>0,48</td></tr>
<tr><td>KGU [-]</td><td>1,33</td></tr>
<tr><td>t_{vdop} wg ZOWP [min]</td><td>273</td></tr>
<tr><td>t_{vdop} wg ZOWPS [min]</td><td>339</td></tr>
<tr><td colspan="3">- Y direction</td></tr>
<tr><td rowspan="4">
</td><td>$a_{w(v)}$ [m/s²]</td><td>0,15</td></tr>
<tr><td>KGU [-]</td><td>0,59</td></tr>
<tr><td>t_{vdop} wg ZOWP [min]</td><td>1367</td></tr>
<tr><td>t_{vdop} wg ZOWPS [min]</td><td>3350</td></tr>
<tr><td colspan="3">- Z direction</td></tr>
<tr><td rowspan="4">
</td><td>$a_{w(v)}$ [m/s²]</td><td>0,65</td></tr>
<tr><td>KGU [-]</td><td>1,18</td></tr>
<tr><td>t_{vdop} wg ZOWP [min]</td><td>344</td></tr>
<tr><td>t_{vdop} wg ZOWPS [min]</td><td>341</td></tr>
</table>

Fig. 11. Summary of experimental testing results and calculations obtained on the section of tank road No. 2 when driving at the speed of 12 km/h (DC12)

Source: own elaboration

where:

- aw(v) - the equivalent corrected value of the vibration acceleration;
- KGU - the multiplicity coefficient of exceeding of the nuisance limit;
- tv dop - the allowable duration of the vibration impact;
- ZOWP - the principle for the acceleration spectrum assessment;
- ZOWPS - the principle for the assessment of the adjusted acceleration value.

The diagrams of effective accelerations of RMS vibrations as a function of the middle frequency third octave bands show the distribution of the effctive accelerations based on the vibration frequency.

In this way, the result can be classified according to the comfort, nuisance and harmfulness criteria under the given traffic conditions. Having the acceleration measured in three directions, the shortest of the times received t_{vdop} is the final result taken into account. On the section of tank road No. 2, at the vehicle speed of 12 km/h (DC12), the minimum allowable vibration duration t_{vdop} was 273min for X direction.

The examinations revealed that the driving speed had the greatest influence on the results obtained. The allowable time of the impact of vibrations on a driver decreases as the speed increases (Figure 12).

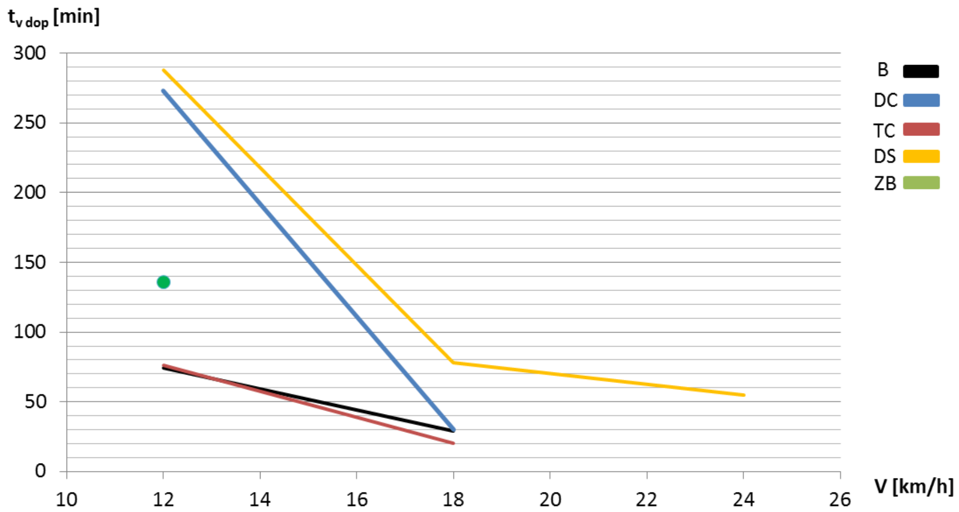


Fig. 12. Influence of the driving speed on the value of the allowable duration of the vibration impact for the substrates under testing

Source: own elaboration

Thus, the right selection of the driving speed makes it possible to control the level of indicators characterizing the driving comfort of special vehicles crews.

CONCLUSIONS

The examinations in subject required the preparation of the testing methodology and necessary equipment. The review of the available standards and literature for the study resulted in choosing the spectral evaluation method in order to analyse the accelerations obtained over a wide frequency range. It is therefore possible to compare the level of driving comfort depending on the comfort, nuisance and harmfulness criteria, and to assess the effect of vibrations with specific component frequencies on the bodies of the vehicle crew.

The experiments conducted enabled to obtain the measurement results that were subsequently processed. The data collected was treated using automatic programs created in MATLAB and Visual Basic environments. The result of the work was to determine the characteristics and comparative indexes of the vehicle driving comfort.

Testing on different substrates is justified because not every substrate that has the largest profile changes generates the highest vibration acceleration. It is crucial to choose the vehicle speed appropriately to the selected section of the test track. Even a small increase in the driving speed may shorten the allowable operating time of a driver up to several times. The level of the driving comfort of different vehicles or seats of the same vehicle can be compared by performing the measurement on one selected section at the same speed.

The prepared measuring equipment and computational procedures allow assessing the working comfort of crews of special-purpose vehicles when driving in off-road conditions. Such studies may be an important element in evaluating vehicle characteristics in the qualification process. At the same time, the results of the tests carried out on individual types of vehicles can provide an important source of data on permissible operating times of military vehicle crews for purposes of planning processes of transport operation.

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BIOGRAPHICAL NOTES

Włodzimierz KUPICZ – Dsc. Eng., Head of the Department of Wheeled Vehicles at the Military Institute of Armored and Automative Technology. He deals with determining static parameters and dynamic characteristics, environmental tests as well as measuring the performance.

Witold LUTY – Dsc. Eng., Head of the Armored Combat Vehicles Testing Laboratory at the Military Institute of Armored and Automative Technology. He deals with the vehicle dynamics, vehicle testing, vehicle tire testing and modeling, military vehicles and special purpose vehicles. The number of his publications - 51, patents -1, monographs - 1, participation in monographs -7, scientific edition of monograph - 2.

Marcin ZWIERZYŃSKI – MSc., graduate of the Faculty of Automotive and Construction Machinery Engineering and Transport at the Warsaw University of Technology. Since 2014 he has been working at the Military Institute of Armored and Automative Technology as a technical engineer specialist.

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