

Design and Testing of 3D Textile Materials with Vibro-Insulating Properties, Applicable in the Construction of Vibroisolating Seats for Machine and Device Operators

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Abstract

In this article, the author describes the problem with low frequency vibrations in the range of 0-100 Hz and how exposure to these vibrations could affect human health when working in dangerous environments. For this research, vibrations in the range of 0-30 Hz were studied as this frequency range has the largest impact on human health and such vibrations usually occur when operating excavators, forklifts or Melex vehicles. Workers who are exposed to these vibrations usually work in a seated position for many hours. Over time, exposure to dangerous vibrations in the working environment will cause damage to the human spine, resulting in a great deal of discomfort for the worker. In order to alleviate the pain, the worker will tend to shift their seating position away from the correct position, which further compounds the issue. The author proposes the use of a 3D knitted seat mat in order to reduce the amplitude of any harmful vibrations. This will provide better ergonomic conditions for the user and will reduce the effects of low frequency vibrations.

Keywords

vibroisolation, measurement, spacer materials, OHS, seats.

1. Introduction

Human exposure to harmful vibrations can lead to long term health conditions, such as heart problems [1,2], organ damage, problems with concentration, increase in muscle tone, breathing difficulties and depression [3]. Laborers who are exposed to these vibrations may develop vibration sickness if the employer does not take action to mitigate the issue [4]. Based on data from the Central Statistical Office in the second quarter of 2020, it shows that every third employee was exposed to physical strain on the spine caused by an uncomfortable or painful position, while over 20% of people indicated that they experienced back pain due to work performed in the 12 months before the survey. Data presented for the United States indicate that back pain is the most common cause of accidents and accounts for 40% of employee absenteeism. Table 1 presents a list of diseases caused by exposure to various frequencies of vibrations in individual professional activities.

Scientists are working on new ways to eliminate vibrations as this is a very serious issue. This is not only a matter of respecting working conditions, but

also to apply new preventative methods. Minimization of vibration can be obtained using technical means such as:

- leveling or eliminating collision forces,
- modification of the vibration spectrum,
- changes in the system parameters,
- vibration eliminators: damping covers (pastes, paints), expansion joints, anti-vibration materials (rubber, resilient and other),
- manner of foundation vibration sources,
- adjustment of rigidity of machine structures,
- proper placement of vibration source.

Seats are one of the most important elements in vehicles because people working as drivers or machine operators spend most of their working time in them. Their attitude depends on the design of the chair, the way work is performed and the employee's subjective behavior. People working in such chairs complain about discomfort while working, indicating pain in the lower spine, neck, shoulder, feet, hips, etc. These ailments are symptoms of disorders of the musculoskeletal system, which are the main cause of accidents at work or lead to disability. This research

presents the hypothesis of using distance knitted fabrics for car seats to help limit vibration levels [3]. The author designed and built a seat with distance knitted fabrics with appropriate vibro-insulating properties for a Melex electric trolley vehicle. Distance knitted fabrics have been available on the market for many years. Their unique vibration absorbing properties make them a very attractive proposition for many industries. They have already been used as an innovative replacement for fabrics covered with sponge in automotive seats and mattresses intended for medical purposes. In many industries, distance knitted fabrics have achieved excellent results due to their innovative design [6]. In this work, the author focuses on vibration eliminators. New types of materials have been proposed and tested that could be used as vibration isolators - vibration damping inserts. Different variants of distance knitted fabrics were tested. These knitted fabrics differed in surface area, thickness, bending stiffness and air permeability. These parameters determine vibration absorption and damping properties. In the design of seats for construction machinery operators and drivers of trucks, ergonomics plays a crucial role.

Activity	Disease	Frequency, Hz
All	Labyrinth disorders	5 – 15
Operator of a construction machine	Bone lesions, vascular neurosis	70-200
Driver of an agricultural tractor	Changes along the spine within the intervertebral joints	6 – 12
Operator of a manual mechanical tool, e.g. a hammer drill	Osteoarticular changes	10 – 130
Truck driver	Nerve vascular disease	40 – 260
Operator of a machine for whipping the ground	Abnormalities in the circulatory system	above 30
Operator of an orbital sander	Disorders in the muscular system	50
Operator of a pneumatic hammer	Paroxysmal finger skin whitening	above 30
Helicopter pilot	Weakness of vision, blurred vision	18
Machine operator for excavation and drilling	Angioneurotic problems Raynaud syndrome Keratoses of the skin Sensation problem	40 – 300

Table 1. The type of disease depends on the frequency of vibrations [1]

The goal is to create a seating arrangement that ensures safety, comfort, and work efficiency for the operator. This involves considering various factors such as the placement of vehicle components, human anthropometric measurements, and seat height. From an ergonomics perspective, it is essential to position vehicle components correctly relative to the seating position. This includes the steering wheel, gear lever, pedals, buttons, knobs, switches, and handles. By placing these components within easy reach of the operator, it enhances their comfort and reduces the need for excessive body movements while operating the vehicle. The design of the seating area also takes into account the dimensions of the operator. e.g. leg length is used to establish the correct seat height, maximizing comfort for the operator. In this context, a seat height suitable for the 95th percentile of men is proposed. The 95th percentile pattern means that the seating measurements will accommodate at least 95 percent of men in a comfortable position during their work. This approach promotes a more effective and safer working environment by considering the needs of a diverse range of operators [5]. By incorporating ergonomics principles into seat design, the overall workplace environment can be optimized for safety, comfort, and work efficiency. This not only benefits the operator but also contributes to improved

productivity and reduced risk of work-related injuries [7-9].

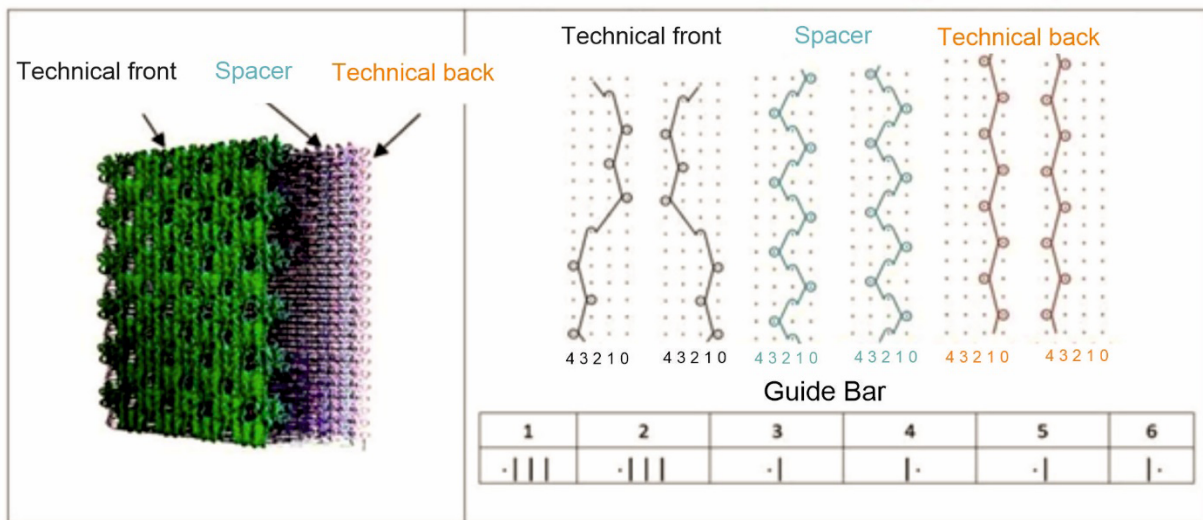
2. Materials and Methods

In the research, spacer knitted fabrics were used as vibro-insulation inserts that could be used in seats. These inserts would be subjected to general vibrations. A spacer knitted fabric is also called 3D or distance knitted fabric of the mesh type. It is a knitted or a double-knit structure with a significant thickness determined by the distance between the outer layers of the knitted fabric. see Fig. 1A. The research materials consist of 7 variants (W1 – W7) of spacer knitted fabrics. During the production of fabrics W1 - W3, a constant distance between the needle combs of $x = 23$ mm was used. The fabrics were made on a HD 6/20-65 EL machine from the Karl Mayer company with gauge number E12. This machine operates in the range of knitted fabric thicknesses from 20 to 65 mm. It is equipped with 6 needle combs and its working width is 138 inches. Knitted fabrics marked with symbols W4 to W7 were created on a Karl Mayer RDPJ 7/EL machine with gauge number E24. The thickness range of these knitted fabrics was 2 – 8 mm, with a working width of 138 inches. The control was electronic. The raw material for the production of these knitted fabrics was polyester monofilaments.

The knitted fabric structure is shown in Figure 1, and the basic physical parameters of the component yarns are given in Table 2 (A).

This type of knitted fabric is modern and ensures high air permeability and minimal absorption of water and moisture. Due to their advantages, distance knitted fabrics are gaining popularity in many applications [10-14]. They are commonly used as a replacement for the sponge inside products such as mattresses, sofas, cushions, car seats etc. [15]. Spacers with a layered structure are being formed in a single knitting process without any additional joining. They consist of two separate outer layers connected by rows of spacers of monofilaments [16,17]. Materials of this type are currently used in the upholstery of seats. The samples of knitted fabrics mentioned are warp knitted. The physical and mechanical parameters of the distance fabrics tested are presented in Table 2. The thickness parameter was measured in accordance with PN-EN ISO 5084: 2008 (Determination of the thickness of textile products) [18]. The test sample was placed between the two reference surfaces, exerting a specific pressure, and the distance between them was measured using an optical thickness gauge. The measurement results were determined in accordance with the standard, with an accuracy of 0.01 mm. The coefficient of variation was calculated as 0.1%. The areal

(A)



(B)

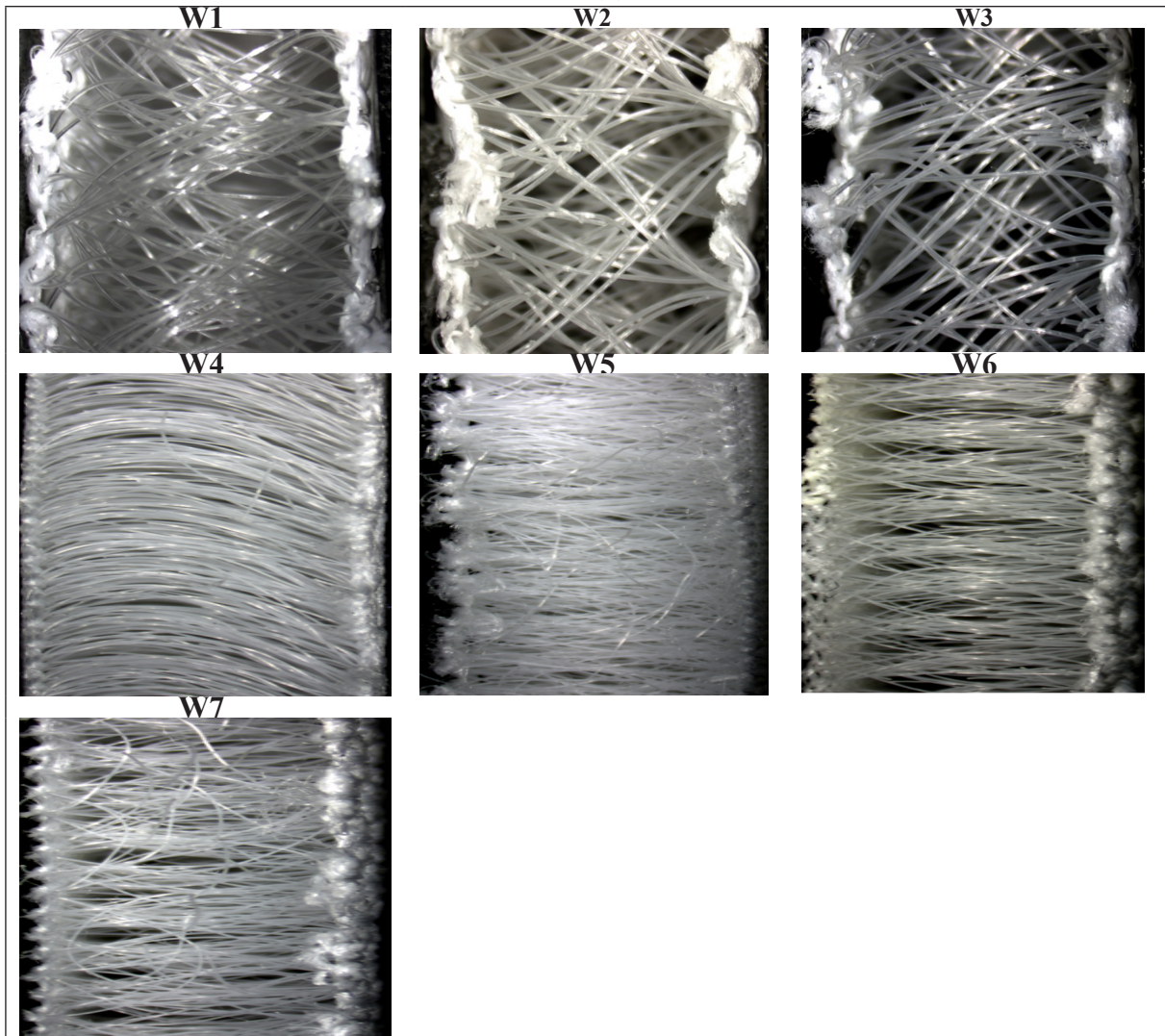


Fig. 1. (A) Example construction of a spacer knit structure; CAD visualization of knitted structure, guide bar of front and back view and spacer. (B) Cross section photographs of all the variants of the tested materials (OPTA-TECH X2000 microscope, magnification range: standard equipment 8-80x (head 1:10); from 8x 330x (optional equipment - head 1:10))

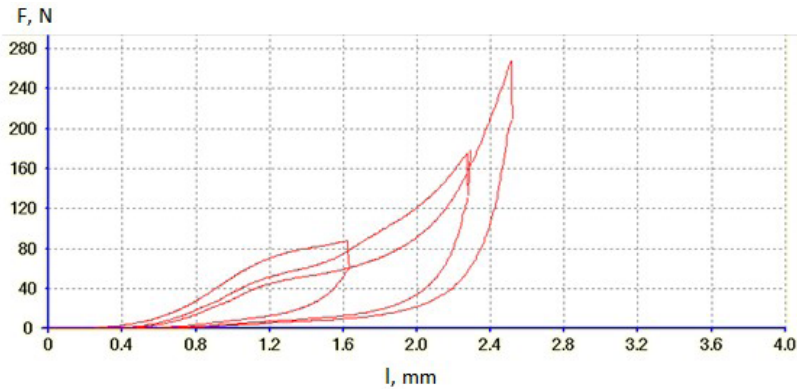


Fig. 2. Hysteresis loops for compression forces $F_{25\%}$, $F_{50\%}$ and $F_{75\%}$ for sample W5

	Thickness, mm	Areal density, g/m ²	Stiffness compression module, kPa	Material
W1	16.94	642	31.54	polyester
W2	15.22	786	56.37	polyester
W3	14.43	661	41.57	polyester
W4	7.98	743	111.34	polyester
W5	8.18	489	29.46	polyester
W6	6.30	446	83.42	polyester
W7	5.30	400	117.82	polyester

Table 2. Physical and mechanical parameters of distance knitted fabrics

Code of yarn	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Yarn 6
linear density of mass	tex	tex	tex	tex	tex	tex
W1	167	167	434	434	167	167
W2	167	167	677	677	167	167
W3	167	167	677	677	167	167
W4	111	111	50	50	111	111
W5	111	111	50	50	111	111
W6	111	111	50	50	111	111
W7	111	111	50	50	111	111

Table 3. Linear density of component yarns of spacer knitted fabrics

density was determined based on Standard PN-P-04613:1997 (Textiles: Knitted and yarn - Determination of linear and areal density) [19]. Ten samples were tested for each variant of the knitted fabric. The measurement was made on the scale with an accuracy of 0.01 g. The compression stiffness was measured using the Chinese standard FZ/T01051.2-1998 [20]. The tests were carried out on an Haunsfield H50K-S testing machine. The diameter of the tested samples was 106 mm. The compression process was carried out at the head speed $v=10$ mm/min. Compression

was carried out in three consecutive hysteresis loops for 25%, 50% and 75% of the maximum forces. An example of hysteresis is presented in Figure 2.

The linear density of component yarns of spacer knitted fabrics are presented in Table 3.

2.1. Concept of seat

The seat area was chosen as the focal point for the study because it is the

most effective area in a vehicle to limit vibrations. Studies have shown a threefold reduction in vertical shocks at a speed of about 40 km/h. This reduction in vibrations is beneficial for the operators of high-performance machinery who may be exposed to unhealthy levels of vibrations. [21] However, as the speed increases to 90 km/h, the effectiveness of the seat in reducing vibrations decreases. This decrease in effectiveness may be due to the higher levels of vibrations generated at higher speeds. Vertical vibrations are typically generated when the vehicle travels over uneven surfaces, such as cobblestones, rubble, and speed bumps.

The design of the prototype seat structure was carried out in accordance with the basics of ergonomics - adapting the machine to the person. It must be ensured that the driver's seat is ergonomically designed to provide proper support and comfort. The driver's seat should be positioned in a way that ensures good visibility of the road and surroundings. This is achieved by appropriate body and vehicle dimensions and posture behind the wheel. Figure 3 and Table 4 show the dimensions of the test vehicle.

To ensure the correct seat design, which was vital to the success of the experiment, the author of this research undertook a study of human (driver) body measurements. According to the data of the European Community countries, for 2010, the anthropometric dimensions of the lower body of a man for the 95th percentile according to the standard PN-EN 547-3+A1:2010 (PN -Polish Norms) (Safety of machinery - Human body dimensions - Part 3: Anthropometric data) [22] and from calculations based on them, the lengths are classified as follows, table 5.

2.2. Methods

When seated, vibrations are transmitted centrally to the spine at the first point of contact, which are the sciatic bones.

Figure 4 (A) shows a schematic distribution of the pressure applied by the human body on individual parts of the chair.

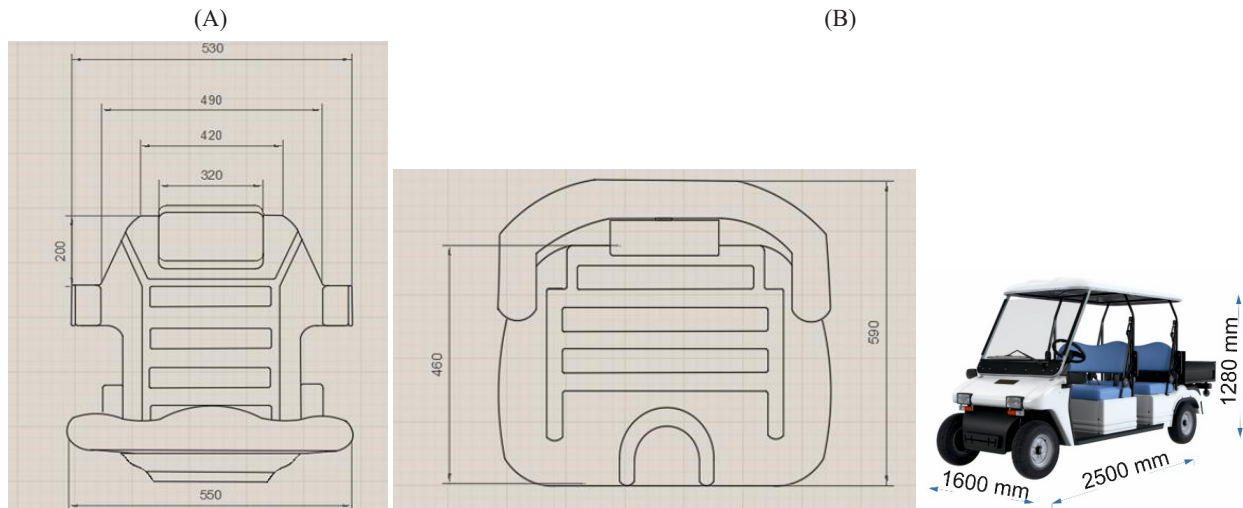


Fig. 3. Main dimensions of the seat of the melex test vehicle: (A) front view and top view ; (B) Melex dimensions

MELEX vehicle dimensions	Parameter	Dimension in, 10^{-3}m
	Length of melex	2500
	Width of melex	1600
	Height of melex	1280
	Length of seat	1100 –for 2 people; 530 –for 1 person
	Distance from floor to the seat (seat height)	360
Seat dimensions	Distance from seat to the inside back of seat	250
	Width of seat	530
	Length of inside back of seat	490
	Width of inside back of seat	460

Table 4. List of detailed dimensions of the Melex test vehicle

Nr.	BodyMeasurements	Measurement, 10^{-3}m
1	Hip Circumference	346
2	Thigh length from rise to knee level	472
3	Sciatic bone length finishing at buttock level	134.3
4	Length from the middle of knee to the end of the buttock	606.3
5	Length from the knee level to the end of the buttock	646
6	Length from the middle of the knee to the end of the knee	39.7
7	Length from the floor to hip level (hip height)	99.4
8	Length from the floor to knee level (knee height)	52,2
9	Knee height; middle of knee height	108; 54
10	Tibia length from ankle to knee level	429
11	Length from the floor to the knee bentat 95°	466

Table 5. Anthropometric measurements of the human body

This necessitates the selection of a material with appropriate damping properties.

Analyzing the diagram, it can be concluded that the greatest pressure is on the ischial bones in the center of the buttocks and amounts to as much

as 0.70 N/cm^2 . The forces with which the human body pushes against the chair decrease with the distance from the first point of contact, i.e. the ischial bones. Thus, it can be concluded that the material used to eliminate low-frequency vibrations must cover the area in which the pressure is greatest. As the forces

decrease in places remote from the sciatic bone, materials with a lower damping coefficient can be used to maintain an even distribution of forces and greater material hardness due to the lower damping coefficient. This will translate into the stabilization of the operator's position.

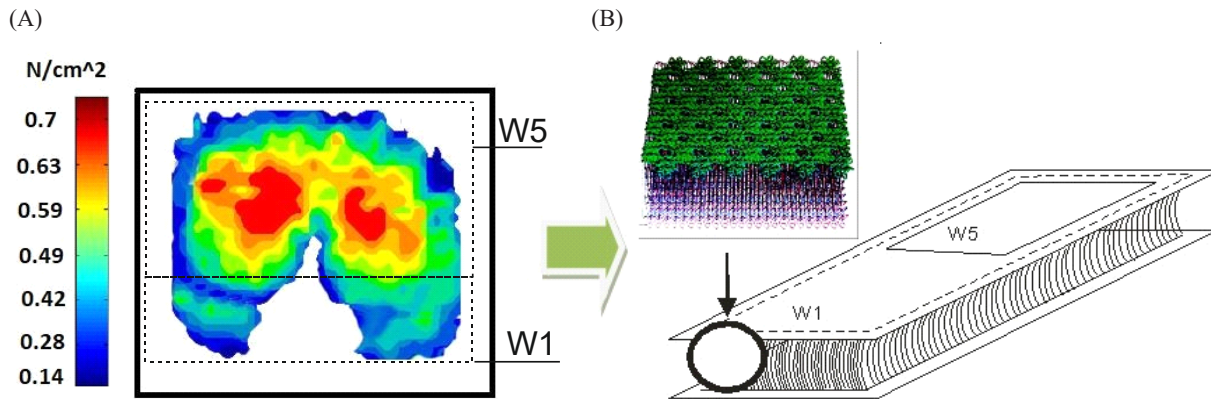


Fig. 4. (A) Distribution of pressure forces on the seat through the lower body part for a typical man; (B) Scheme of the distribution of knitted layers in the prototype seat – consisting of two segments of material, W5 and W1

The next stage of the research was focused on the following:

- Testing and comparing the research material samples (distance knitted fabrics) in terms of their vibroinsulation properties in the low frequency range (1-100 Hz) with the use of a dimensionless SEAT coefficient.
- Selection of the most optimal distance knitted fabric, in relation to the best damping characteristics for selected frequencies.

A stand designed to excite general vibrations in the low frequency range under laboratory conditions was constructed for testing and is presented in Figure 5. The stand consists of a 20 MHz function generator with a 50 W power output JC5620P (3), an electromagnetic actuator (exciter) (2) placed on an aluminum rail. In addition, the stand includes a mechanical vibration meter type SV 106 (1) with a SVANTEK type SV150 vibration transducer from SVANTEK (1A). On the rail there is also an aluminum barrier with adjustable distance to the work piece, used to attach the samples (4).

Vibration waveforms were also recorded using a computerized recording set consisting of an oscilloscope, USB Pico 3406D MSO PP936 and PC computer with dedicated software (5).

In order to determine the value of vibration acceleration with the use of a sensor (1A), three repetitions were made,

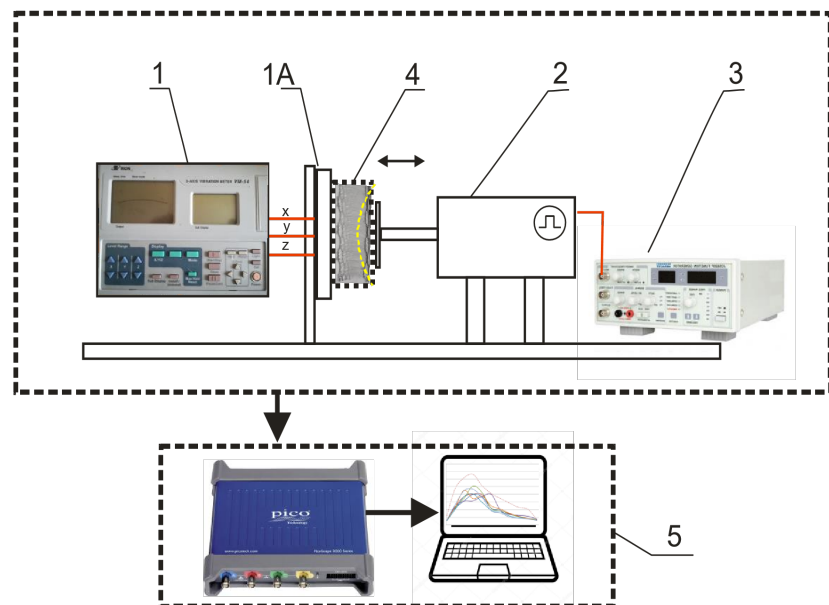


Fig. 5. Laboratory scheme used to measure the overall vibration excitation in the low frequency range

with each test lasting 30 minutes for each sample. The tests were carried out in the low frequency range, i.e. from 1 to 100 Hz, with 10 Hz steps. The test results were automatically recorded with the use of a meter (1) and measuring set (5).

The second stage of the research was focused on testing the prototype seat in real conditions. The prototype seat structure was placed on the Melex sofa, and two tests were conducted. The first test was to measure the vibration acceleration without the prototype seat. The second test was to measure the vibration acceleration with the prototype seat with spacer material. These tests

were carried out in accordance with the standards, which involved placing the PV - 62 RION CO.LTD sensor in a manner consistent with the standard, i.e. directing the X axis towards the legs, and aligning the Z axis with the vertical axis of the human spine. Axis directions are shown in Fig. 6 B. In both tests, the PV - 62 RION CO.LTD (three-axis accelerometer) sensor, which is used for measuring acceleration, was placed under the ischial bone of the test candidate. The measurement started during the driving of the Melex at point H towards point A, and was also completed at point H. The route points are shown in Figure 6 A. The total length of the test route was

3.8 km. The entire route is shown on satellite photos with registration using a GPS mobile device. The results of acceleration on the seat were read from the 3-axis vibration meter VM-54 RION, together with the measuring head (three-axis accelerometer PV-62 RION), which was placed on the seat (Fig. 6B). The test was performed in accordance with the standard presented in Table 6. Fig. 6B shows the measurement method and the components of the measuring system for specific tests.

3. Results

For evaluation of the quality of the damping spacer knitted materials, the method of total assessment (effective weighted value of vibration acceleration in a certain time interval) for steady-state vibrations was applied. Seat Effective Amplitude Transmissibility (SEAT) was calculated using formula (1) [25-28].

$$SEAT = ARMS / ARMS,D \quad (1)$$

where: SEAT-effectiveness of protection indicator, $ARMS$ -the effective value of weighted vibration acceleration without the suppression (damping inserts) Ref line in figure 3, $ARMS,D$ - the effective value of weighted vibration acceleration with the suppressing (damping inserts) characteristic W1-W7.

A protection efficiency index equal to one ($SEAT = 1$) would mean that the protection does not limit vibration transmission in general, so there is no impact. A protection efficiency index less than one ($SEAT < 1$) would mean that the protection of vibrations applied strengthens the transmission. Whereas a protection index greater than one ($SEAT > 1$) indicates that the applied protection (spacer fabrics) limits the transmission of vibrations and therefore reduces them. Thus, it is desirable that the value of the SEAT coefficient is as high as possible. The effective value of calculated SEAT coefficients is presented in figure 7.

As shown in Figure 7, all materials were characterized by vibro-insulation

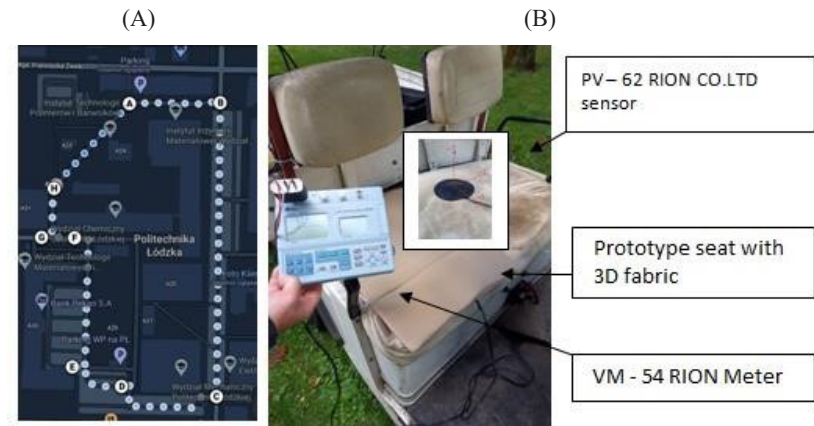


Fig. 6.(A) Dotted line shows the route taken for the two tests. (B) Components of the measuring system; prototype seat with 3D knitted fabric and the measuring system: meter VM - 54 RION and sensor PV - 62 RION CO.LTD.

Norm	Norm name
ISO 2631 - 1:1997	Mechanical vibrations and shocks - assessment of human exposure to whole body vibration - part 1: General requirements
ISO 8041 - 2005	Human reaction to vibrations - measuring instrumentation

Table 6. List of standards for testing vibrations transmitted by the chair onto the human body in real conditions [23,24]

properties in the low frequency range up to 100Hz. The worst vibro-insulating properties among the knitted fabrics was seen in the sample marked W4 where SEAT was equal to 1 at 50 Hz frequency. The analysis of the characteristics in Figure 7 showed that all materials provided adequate protection in this frequency range. The best vibro-insulating properties within the specified frequency range (0–20 Hz) was seen in the W5 marked sample. The SEAT coefficient for W5 was equal to 2.37 at a 10 Hz frequency; therefore, this trial material was selected for the construction of the prototype seat.

The tests of the prototype seat consisted of measuring the value of instantaneous accelerations and the average RMS values for test runs in a Melex vehicle. As a result of the tests, the acceleration values in the x, y, and z directions were measured. The RMS values for the two tests were read, are collected in Table 7, and presented in the graphs in Figure 8-10. The instantaneous acceleration values for individual waveforms are also presented in charts 8-10.

Analyzing the results presented in Table 7, it was observed that the acceleration values for the Y axis from the proper test were lower than those from the "0" test. Another factor in this result was that the spacer connectors were placed in the direction of the Y axis during the driving, without ensuring vibration damping in that direction. The force vector was applied diagonally, and the tests were carried out in motion.

Figures 8-10 show the RMS acceleration values during the travel tests. They were compared with the results of the RMS acceleration values over time for test "0" - measurement without the prototype seat. Graphs for 3 components of accelerations x, y, z are shown in Figures 8-10.

For a detailed analysis, the instantaneous values for each test variant and for each component of the x, y, z sensor were compared. The sections from each run were selected in the first 10-second interval. Figures 11-13 show representative peak acceleration slices for the x, y, and z axes.

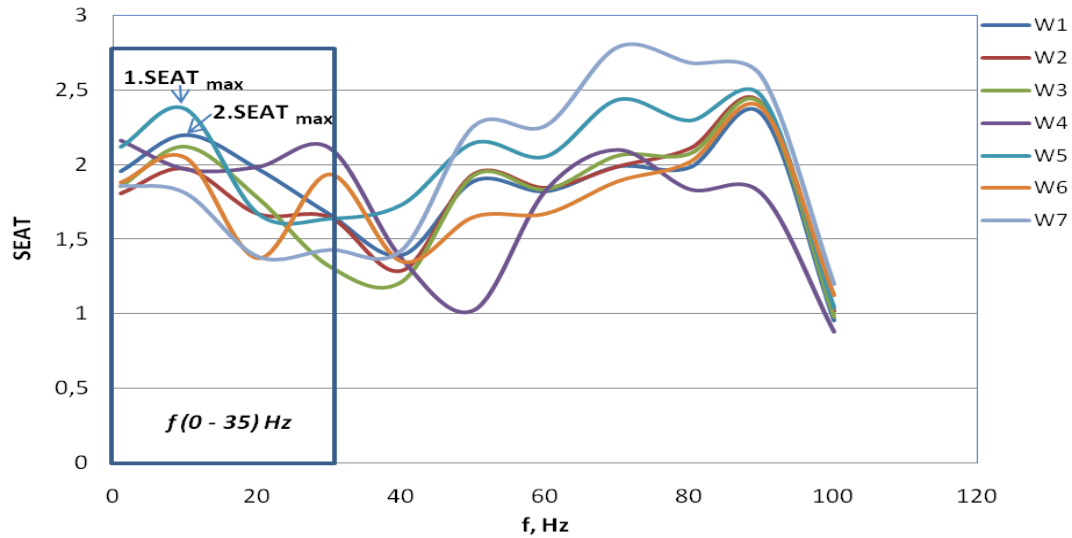


Fig. 7. Characteristics of the SEAT damping protection effectiveness coefficient for the materials tested

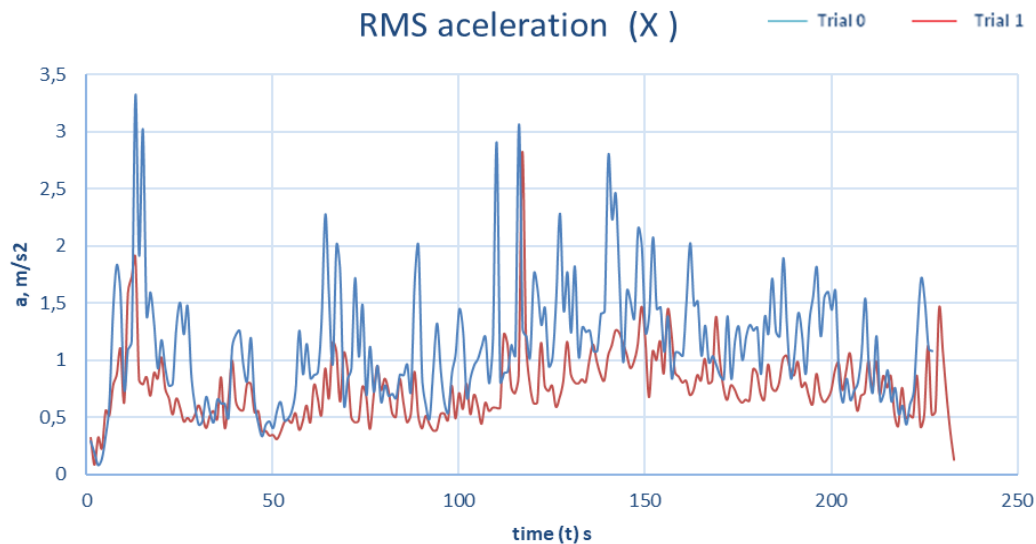


Fig. 8. Graph showing RMS acceleration (a , m/s^2) values over time for the X axis

	Average value RMS (X)	Average value RMS (Y)	Average value RMS (Z)
Sample Zero - Mean	1.146 m/s^2	0.625 m/s^2	2.130 m/s^2
Medium sample	0.765 m/s^2	0.626 m/s^2	2.053 m/s^2
SEAT coefficient for the prototype seat	1.499	1.000	1.000

Table 7. Average RMS values and the calculated SEAT damping coefficient for individual components X, Y, Z

In order to numerically present the prototype seat attenuation, the SEAT coefficient is shown in Table 8 for the selected images shown in Figs. 11-13.

4. Discussion and conclusions

The development of the automotive industry has brought with it some

enormous benefits, but also many disadvantages. As a result of the operation of machines, vibrations arise, which not only have a negative impact on the human body, but also have negative effects on the operation of the machine itself. These effects include, but are not limited to, disturbances in the normal operation of the machine, a negative impact on the individual elements of

the machine, reduced durability and reliability, and hence reduced quality of work. Vibrations are also accompanied by noise, which has a negative effect on a person's work environment.

One of the key elements of vibration reduction in mechanical constructions is in the ability to produce specialized damping materials. The use of spatial

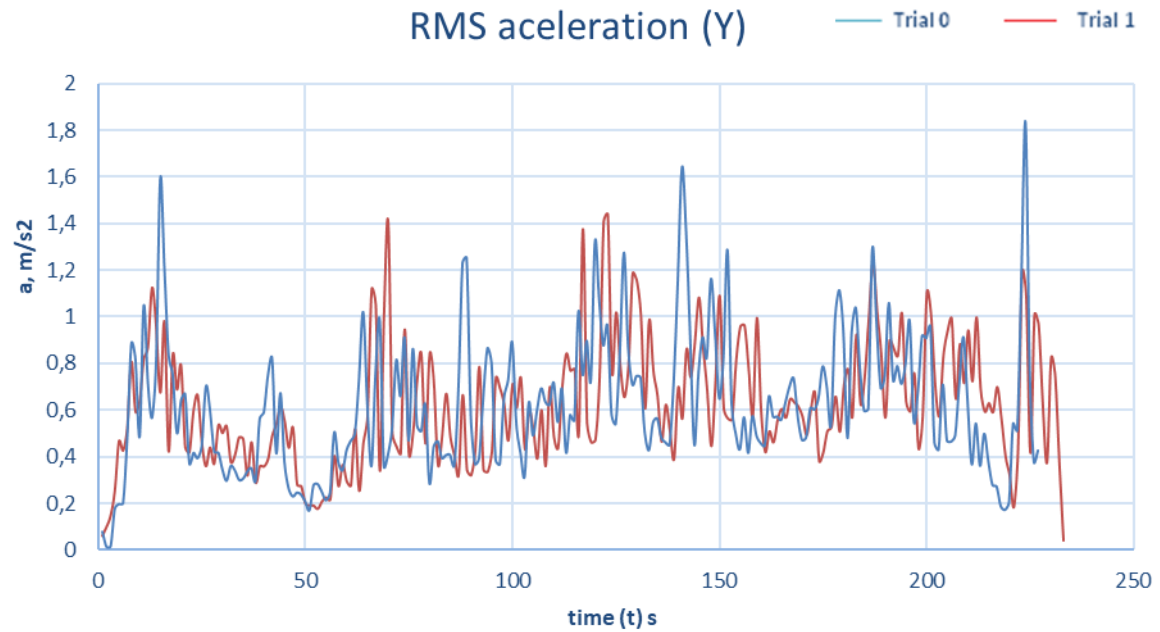


Fig. 9. Graph showing RMS acceleration (a , m/s^2) values over time for the Y axis

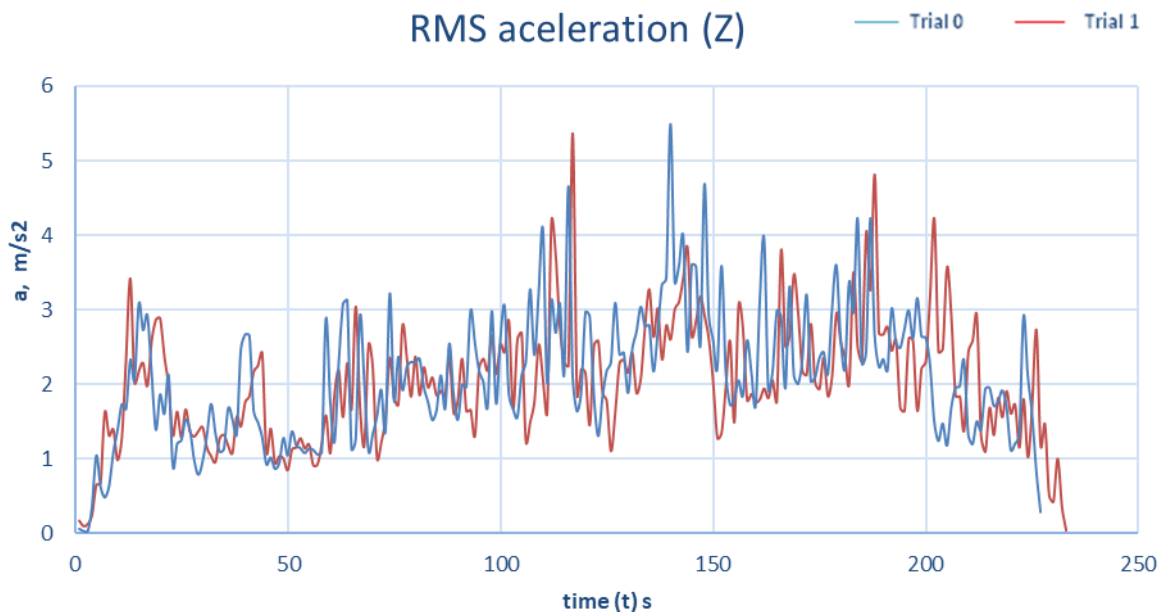


Fig. 10. Graph showing RMS acceleration (a , m/s^2) values over time for the Z axis

textile materials in the form of distance knitted fabrics with vibration damping properties seems very attractive. This type of knitted fabric can now be mass produced and products of this type are increasingly being used in agriculture, medicine and in the space sector.

The technology used to produce distance knitted fabrics is very advanced, and therefore it is now possible to design and manufacture these materials

with appropriate repeatable physical properties (surface weight, thickness, weave, elasticity, type of raw material, etc.).

In the first phase of the experiment, tests were carried out to select the best material, and then a prototype of the seat was made and tested in real test conditions on a mechanical Melex type vehicle. The criterion for selecting the 3D knitted material was the proposed dimensionless

SEAT damping coefficient. The tests were carried out in the low frequency range from 0-100 Hz. SEAT coefficients for each sample were compared in the frequency range of 0-35 Hz due to the specificity of the mechanical device operation.

In this way, in the first phase of the work, the research hypothesis on the use of distance knitted fabrics to minimize vibrations in car seats was proven to be

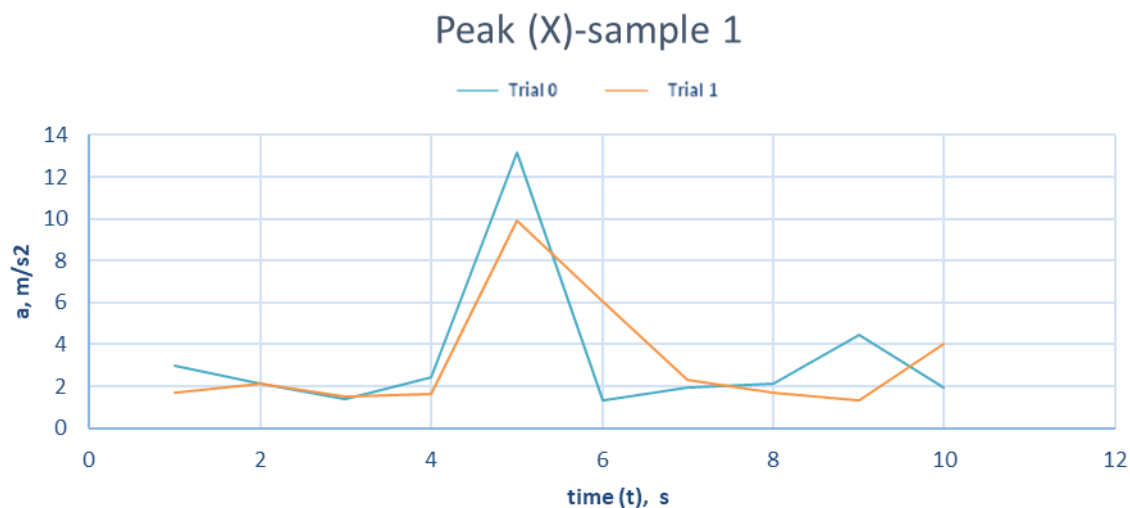


Fig. 11. Graph showing the values of the instantaneous peak accelerations for the X axis – sample 1

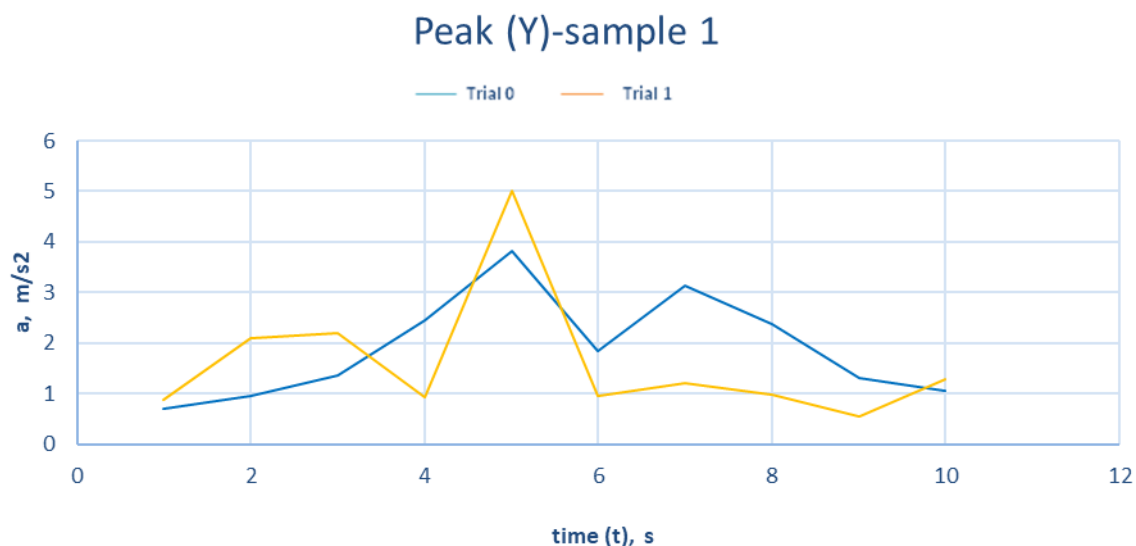


Fig. 12. Graph showing the values of the instantaneous peak accelerations for the Y axis – sample 1

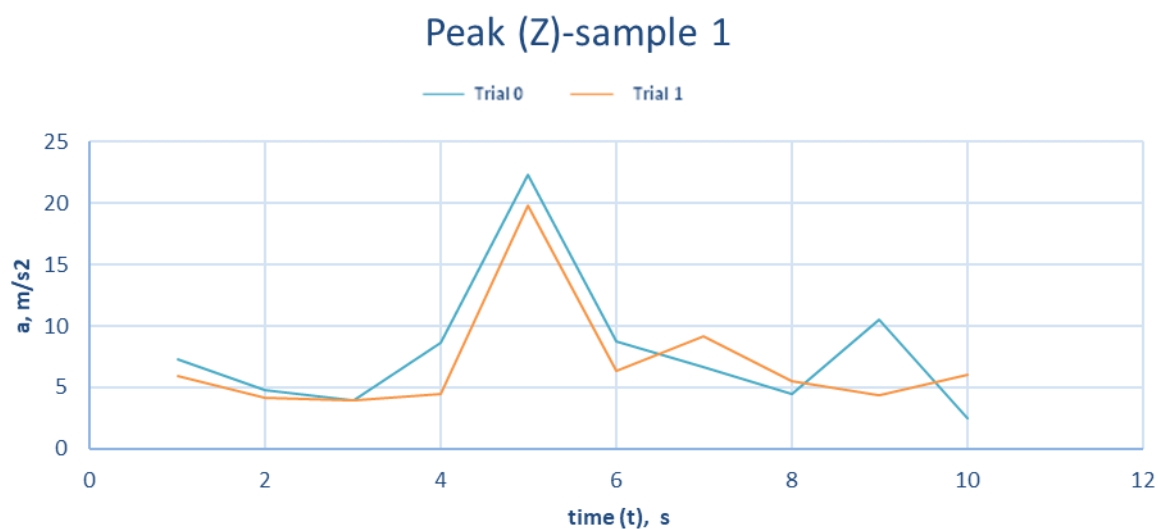


Fig. 13. Graph showing the values of instantaneous peak accelerations for the z axis – sample 1

	Segment number	X Axis	Y Axis	Z Axis
SEAT factor (10 second segment)	Segment 1	1,5	1,0	1,2
	Segment 2	1,1	1,2	1,1
SEAT ratio at the highest point	Segment 1	1,6	1,0	1,1
	Segment 2	1,3	0,8	1,3

Table 8. SEAT coefficient for instantaneous peak accelerations on selected segments for individual axes at 10-second segments and at the highest point

correct, enabling the damping of low-frequency vibrations in the range of 0-35 Hz. Based on the tests of attenuation, 2 types of distance knitted fabrics, called “spacers”, with very good vibroisolating properties, were selected. The damping properties were characterized using the SEAT dimensionless coefficient and were 2.1 for W5 and 1.6 for W1. These tests were carried out on stationary samples in a laboratory.

Field tests of the prototype seat (tests in conditions similar to real ones) were carried out in accordance with the standards, by analyzing the measurement of acceleration in 3 axes X, Y, Z in the field, on a test route with the use of a melex electric vehicle. The acceleration values were read using measuring equipment consisting of a VM-RION

54 meter (measuring accelerations in the X, Y, Z axes) and PV-62 RION CO.LTD sensor. The study analyzed the vibrations caused by uneven ground on which the Melex test vehicle traveled. Due to the electric drive of the vehicle, the vibrations generated by the electric motor were minimal. This allowed for a clear reading of one type of vibration. The diversification of the route made it possible to read the instantaneous peak acceleration and to isolate individual peaks in order to analyze the prototype seat’s vibration damping for rapid acceleration jumps.

The average value of the dimensionless SEAT damping coefficient from all test runs conducted in real conditions was 1.499 for the X component and 1 for both the Y and Z components, shown table

7. This is a satisfactory value from the point of view of operational safety, in terms of mechanical vibration damping. A more detailed analysis was performed for selected vibration segments, shown in Figures 11-13.

The method shown can be used to design a seat for an employee in a mechanical vehicle, taking into account gender differences, and will contribute to better working conditions and may increase the involvement of women in industry.

5. Patents

Number 242086 Textronic diagnostic system to monitor the level of vibration in the seat with increased exposure to vibrations

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