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Noise Reduction in the Cab of a Special Vehicle

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ABSTRACT

Noise is highly associated with adverse effects on health, the human psyche and performance. Current special vehicles do not possess sufficient technologies to suppress the transmission of noise or vibration, which typically results in loss of control, comfort, driving safety, the performance of tasks, etc. At the same time, noise reduces attention and work efficiency while increasing fatigue, leading to hazards, dangerous situations, and missions that may not be completed. This article briefly presents selected parts of a project which included additional soundproofing of a special armoured mobile vehicle on a TATRA wheeled chassis. Basic theoretical, experimental, and practical information about this project is presented. To reduce noise, a selected damping material was used, which is a combination of recycled PUR foam and black rubber with a rough structure. The damping material was selected based on repeated experimental testing of sound absorption measurements from several damping materials. The material was chosen for suitable damping effects and corresponding technological properties (resistance to high temperatures, non-flammability, etc.). In the engine compartment and the cab of the vehicle, the damping properties were experimentally verified after retrofitting, while the noise was significantly reduced.

Keywords: Noise; Vibration; Anti-noise materials; Sound absorption; Testing; Cab 3D model; Additive manufacturing file

NOMENCLATURE

L_p	Sound pressure level
p_0	Pressure reference value
v	Sound speed
L_I	Sound intensity level
I_0	Sound intensity reference value
η	Internal loss factor
I_q	Vibration intensity converted to heat
W	Sound power
c_t	Speed of sound at temperature t
I_2	Intensity of sound of the absorbed wave
β	Sound reflectance factor
ρ_F	Density of fibrous material (kg/m^3)
I_4	Intensity of sound wave that passed behind the Wall through the holes and pores
I_6	Intensity of sound wave that is conducted to the other parts
h	Porosity of the material
A	Wall area (m^2)
V_T	Total volume of materials (m^3)
p	Sound pressure (dB)
L_v	Sound speed level
v_0	Speed reference value
I	Sound intensity
L_W	Sound power level
f	Frequency (Hz)
I_a	Sound absorption coefficient
W_0	Sound power reference value
a	Sound absorption factor
I_{0A}	Sound power incident on the surface
I_1	Intensity of sound of the reflected wave
I_3	Total intensity of the sound wave on the wall
I_5	Intensity of sound wave emitted by the wall due to oscillations
I_7	Intensity of the sound converted into heat in the wall
ρ_P	Density of porous material (kg/m^3)
V_P	Pore volume (m^3)
V	Volume of space (m^3)

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1. INTRODUCTION

Acoustics is a field of science that deals with sound from its origin to transmission through space to perception by the human senses. Sound is an organized mechanical oscillating motion of particles in a flexible material environment through which sound propagates (through gas and liquid molecules or solid atoms) and is perceived by the human ear and processed in the brain. Sound perception in humans is evoked in the frequency band between 16 Hz and 20 kHz. However, each person has an individual level of audibility; sounds up to 16 Hz or above 20 kHz are not heard but perceived. Sounds with a frequency lower than 16 Hz are called infrasound, and frequencies higher than 20 kHz are called ultrasound. Sound propagates in the wavefronts and has a significant directional effect. The human ear registers sound in the form of acoustic pressure in a relatively wide range. The lower limit of the sound pressure level, the so-called audibility threshold at a frequency of 1000 Hz, is $2 \cdot 10^{-5}$ Pa[1]. This value is used as a reference, and other reference values of acoustic quantities are derived from it. The highest value of sound pressure at which a person feels pain in the auditory organ is about $2 \cdot 10^{2}$ Pa (pain threshold)[2]. The ratio of audibility and pain thresholds is relatively large; acoustic quantities vary geometrically, but the human ear perceives them as an arithmetic series, i.e., multiples of the acoustic signal are perceived by the ear only as increments[3-6]. The logarithm function enables the conversion of a geometric series to an arithmetic function; it is expressed by the levels of acoustic quantities (Weber-Fechner's law) with unit B or dB. The acoustic environment is usually considered to be the air environment. Air is a non-viscous, non-rotating compressible fluid medium with variable pressures throughout the space of this subsystem[3]. Fluid media are described by Euler's equation,

Table 1. Overview of the used and related relations

Name	Definition	Note
Sound pressure level L_p	$L_p = 20 \cdot log \dfrac{p}{p_0}$	$p_0 = 2 \cdot 10^{-5}\ Pa$
Sound speed level L_v	$L_v = 20 \cdot log \dfrac{v}{v_0}$	$v_0 = 5 \cdot 10^{-8}\ m \cdot s^{-1}$
Sound intensity level L_I	$L_I = 10 \cdot log \dfrac{I}{I_0}$	$I_0 = 10^{-12}\ W \cdot m^{-2}$
Sound power level L_W	$L_W = 10 \cdot log \dfrac{W}{W_0}$	$W_0 = 10^{-12}\ W$
Speed of sound c_t	$c_t = 331.82 + 0.61 \cdot t$	At temperature t
Sound absorption coefficient α	$\alpha = \dfrac{I_2}{I_{0A}} = 1 - \lvert\beta\rvert^2$	I_{0A} = acoustic power incident on an area of 1 m^2
Porosity of the material h	$h = 1 - \dfrac{\rho_P}{\rho_F} = \dfrac{V_P}{V_T}$	Porosity is usually in the range of 0.6 – 0.95
Sound reflectance factor β	$\beta = \dfrac{I_1}{I_{0A}}$	$\beta = \in 0 - 1$
Sum of reflectance and absorption factors	$\alpha + \beta = 1$	Energy aspect
Sound transmission coefficient τ	$\tau = \dfrac{I_3}{I_0} = \dfrac{I_4 + I_5}{I_0}$	
Heat transfer coefficient	$\varepsilon = \dfrac{I_7}{I_0}$	
Vibration energy	$\beta + \tau + \varepsilon = 1$	It is negligible for insulation material
By comparing Eqn. (9) and Eqn. (12), it holds	$\alpha = \varepsilon + \tau$	
Internal loss factor η	$\eta = \dfrac{I_q}{I_a}$	
Sound absorption coefficient α	$\alpha = \dfrac{8\pi f V}{c_t A}\eta$	

Note:
Sound levels indicate them either as band levels that correspond to a particular frequency band or as total levels for an audible frequency band.

and the continuity equation, the relationship between pressure and density. The basis for the calculation of acoustic quantity levels is the effective values of the signal, but the levels are primarily a hygienic quantity. These are, for example, sound pressure level L_p, Eqn. (1), sound speed level L_v, Eqn. (2), sound intensity level L_I, Eqn. (3), and sound power level L_W, Eqn. (4). Table 1 lists selected relationships used in this article. An important characteristic of the environment in terms of sound propagation is its speed, which ranges from $5 \cdot 10^{-8}\ m \cdot s^{-1}$ (audibility threshold) to $1.6 \cdot 10^{-1}\ m \cdot s^{-1}$ (pain threshold). The speed of sound in air depends on the density and composition of the air (impurities, humidity), temperature, barometric pressure, etc.[4 – 5]. For air with temperature t in degrees Celsius, sound velocity is specified in an Eqn. (5). Noise is any unwanted, annoying and disturbing sound. Noise can be divided according to its origin into two categories: mechanical and aerodynamic[3].

The cause of mechanical noise is the oscillating surface of the body, which causes acoustic disturbance of the gaseous environment and transfers its energy to this environment. Acoustic energy then propagates through sound waves into the entire acoustic environment and is related to the dimensions of the oscillating body, its shape, the morphology of its surface and the characteristics of its oscillations (deflection, velocity, acceleration, frequency)[6 - 7]. The source of mechanical noise in special military ground vehicles is all sounds, except for the air flowing outside the vehicle. The main source of noise is the engine (pressure changes in the combustion chamber, aerodynamic forces during intake and exhaust, pressure waves during expansion, tilting of the piston in the cylinder when changing the direction of normal force, backlash in bearings, external wall vibrations, distribution system noise, etc.). Other sources include transmissions, wheel arches, shock absorbers and tires. The standard element for reducing mechanical noise, e.g., of the engine, is the length and construction of the exhaust pipe. Noise from the road surface or terrain depends on the morphology and shape of the road (terrain), tire pattern, speed of movement, etc.[5 – 8, 12].

Aerodynamic noise can be characterized as the sound caused by the action of an airstream on the surrounding environment. The cause of aerodynamic noise is the movement of air where a sharp change in pressure and direction occurs during turbulent flow, e.g., around solid obstacles. This pressure excitation is the cause of pressure, i.e., sound waves in a certain frequency spectrum. Aerodynamic noise is created by a stream of air impinging on a moving vehicle. Manufacturers are trying to design vehicles to be as aerodynamically clean as possible. The reason is, for example, lower fuel consumption, but also a reduction in the internal noise of a vehicle[9 – 11]. Aerodynamic noise of a vehicle is usually caused by protruding parts (sensor systems, antennas, weapon systems, armour, etc.), uncovered chassis and wheel parts, sealing of doors and windows, shape, and the size and inclination of the vehicle windshield, etc.

In this paper, the authors describe the solution of additional soundproofing of the engine compartment and cabin of a special mobile device. For this purpose, the results obtained during experimental research of sound absorption of porous materials based on polyester fibres, polyurethane and melamine foams, textiles and others were used. A total of 30 damping materials and their various combinations were experimentally tested. Damping materials have been tested depending on the prevailing frequencies that cause maximum sound pressure in this vehicle. Based on repeated absorption measurements using the transfer function method and the Kundt impedance tube, a material consisting of a combination of recycled PUR foam, black rubber with a rough structure and an air gap was selected. An important part of the project was the practical implementation of soundproofing using 3D printing of a soundproofing frame made of PETG filament material (containing 20 % carbon fibres). The damping material was attached to the individual parts of the skeleton (a total of 43 parts) by gluing.

2. LEGISLATION AND POSSIBILITIES OF NOISE REDUCTION OF SPECIAL VEHICLES

In this section, the authors briefly present the current legislation and general noise reduction options, focusing on possible applications in vehicles. The current legal noise limits for special off-road vehicles of category M_2G with engine power $P > 250$ kW are based on UN/ECE Regulation No. 51, which considers three successive phases of reducing external noise limits (Table 2).

Table 2. Sound pressure limits *P*

Category M_2G	Phase 1 (valid)	Phase 2 (6/2022)	Phase 3 (6/2024)
$P > 250$ kW	80 dB	78 dB	77 dB

In general, it can be stated that noise can be reduced passively or actively. Passive methods include isolating sources of vibration and noise and preventing transmission to or from the environment[12-15]. Noise can be passively reduced, e.g., by porous materials that absorb noise, resonant absorbers that work on the Helmholtz resonator principle, vibration insulations (e.g., rubber, felt, cork, crushed rubber with textiles, etc.), large-area absorbers, flexible elements, and couplings in the body (flexible metal elements, airbags, rubber blocks, etc.), soundproof plates, silencers in pipes, anti-vibration coatings, etc. Sound-absorbing materials convert acoustic energy into another form of energy, mostly thermal energy. Energy transformations are based on mechanisms of friction, fluctuations in sound pressure, inelastic deformations of bodies (hysteresis), etc. The methods of active noise cancellation (ANC) are based on wave interference, i.e., noise suppression by generating sound waves with the same amplitude but with a reversed phase. The air, which is usually the sound carrier, will only be minimally rippled because the sound pressure we want to filter out is suppressed by the counter-wave coming out of the speakers. The generated counter-wave has a minimum standing wave motion, and the sum of the two amplitudes is zero[3 – 4]. Active noise cancellation technology has been known since the late 1980s, but it is not used as a standard in the field of special vehicles. ANC technology has its origins in military aviation, currently is used in aviation, expensive cars but also offices (special headphones), etc. In civil engineering, ASAC methods (Active Structural Acoustic Control) that reduce the amount of radiated energy are used. Known noise reduction technologies are generally relatively complex, operationally demanding, and expensive. The ANC system consists of microphones located in individual areas (driver, commander, shooter, crew) of the mobile device and speakers inside the cabin, which filter out noise, and is controlled by advanced software.

The first implemented application for active elimination of noise from the engine and chassis in the car RANC (Road Active Noise Control) came from the HMG Company. ANC technology is controlled by sophisticated software. This technology is limited by the possibilities of measuring, analysing, and processing noise. Engine and chassis noise (including resonances and booming sounds) enter the cab in about 0.009 seconds and DSP (Digital Signal Processor) processing takes just 0.002 seconds, a response that can be considered a real-time response. Existing measurements confirm a 3 – 5 dB reduction in cabin noise. The great advantage of this active noise reduction technology is the reduction of weight and the elimination of acoustic waves of very low frequencies (on the border between audible sound and infrasound).

The primary acoustic property of classical anti-noise materials is the conversion of acoustic energy into heat, which depends on the absorption coefficient α, Eqn. (6), which expresses the ability of the material to absorb noise. Porous materials are among the materials that significantly dampen ambient noise. They are produced in various shapes, e.g., mats, carpets, covers, boards, cartons, mouldings, etc., from mineral or organic materials.

Polyurethane foam cell materials are often used; they have pores up to 1 mm in size, which is less than the amplitude of a sound wave flowing across the material. When a sound wave strikes fibrous materials, air molecules move and oscillate in the slits and gaps of these materials with the frequency of a propagating sound wave. These oscillations cause the movement of air molecules and particles that touch the fibres of the material and thus reduce their kinetic energy[8]. Due to the irregularities of the pores, there is a change in the direction of propagation, shrinkage and expansion of the wave flow occur, which reduces the momentum of air molecules in the direction of the wave motion. The basic physical characteristics of porous materials include porosity, fibre diameter, density, structure factor and flow resistance[8], defined by Eqn. (7).

Note:

The density of fibrous material, e.g., for glass fibres and mineral wool is $\rho_F = 2450\,kg/m^3$*; the porosity is usually in the range of 0.6 - 0.95.*

The damping properties of materials are often described using the coefficient of internal losses η, Eqn. (14), or the sound absorption coefficient α, Eqn. (15). Conventional construction materials show relatively low values of material damping. Vibration and noise attenuation of these materials is often increased by combination with other materials with high internal damping-so-called multi-layer materials, often in the form of anti-vibration coatings. Anti-vibration materials are made of various plastics. Their high coefficient of internal damping significantly reduces amplitudes and thus the emission of acoustic energy[4 – 6]. In vehicles, anti-vibration coatings are used for soundproofing the wheel arches, to reduce tire noise, the noise of stones hitting the vehicle wheel arch, which is transferred to the cab, etc. Anti-vibration coatings provide high noise attenuation at frequencies up to 200 Hz[8]. Noise caused by vibrations can be significantly reduced by separating the sources of vibrations across the flexible bearing - vibration isolation. In practice, vibration isolation of a particular vibration source or the location closest to the vibration source is preferred. Vibration isolation prevents the formation of other forces transmitted from one structure to another. For special vehicles, vibration isolation is used to attach the drive unit to the frame (chassis, body) and prevent the transmission of vibration to the surrounding structure, so-called silent blocks. Passive vibration isolation is the protection of sensitive equipment from vibrations transmitted by the surrounding structure. When operating a special vehicle, the internal combustion engine is the main source of natural oscillations of a certain frequency. Due to uneven terrain, the tires vibrate the axle suspension and chassis with forced oscillations. Both natural and forced oscillations are composed, and there is a so-called interference and amplification of vibrations and noise; in the extreme case, there may even be a resonance when the amplitudes of the oscillations increase dangerously.

2.1 Sound Absorption

Sound propagates in an acoustic environment by the waves of its particles. In addition to a decrease in intensity, sound waves in the atmosphere are affected. For example, sound waves are affected by the temperature and velocity gradient of the environment; when the direction of the waves changes, turbulence is created, which deforms the acoustic field and the viscosity of the environment causes part of acoustic energy to be absorbed. The absorption of sound in air varies with frequency, humidity and temperature. When a sound wave strikes an obstacle, part of the wave bounces off, part is absorbed, and part passes into the space behind the obstacle[7 – 9]. The intensity I_0 of the sound, i.e., the sound power that impacts $1m^2$ of the area, is divided into components, Fig. 1. I_0 až I_7. Based on the energy balance of the sound wave impact, individual sound factors can be defined[10 – 12]. The body's ability to absorb sound is characterized by the sound absorption coefficient α, Eqn. (6), which is given by the ratio of energy absorbed I_2 by a certain area to energy incident I_0 and the sound reflectance coefficient β, Eqn. (8) is the ratio of sound intensity of a wave reflected from a wall to sound intensity of a wave impacting this wall. The sound reflectance coefficient β lies in the interval $\langle 0,1 \rangle$. The wall that perfectly reflects acoustic energy has $\beta = 1$, and the wall that absorbs all incident acoustic energy has $\beta = 0$. The energy aspect is expressed by Eqn. (9). It follows from the above information on absorption and reflectivity that part of the absorbed energy passes behind the obstacle, part is converted into thermal energy and part is transferred to the structure by vibration[10 – 17]. This allows the introduction of the sound transmittance coefficient, Eqn. (10), and the heat transfer coefficient ε, Eqn. (11). The energy propagating in the form of vibrations I_6 into the structure has a negligible level in sound-insulating materials. Measurements of the sound absorption factor are legislatively regulated by standards[26 – 29] expressing the standing wave ratio, the reverberation chamber method and the transmission function of the given structure.

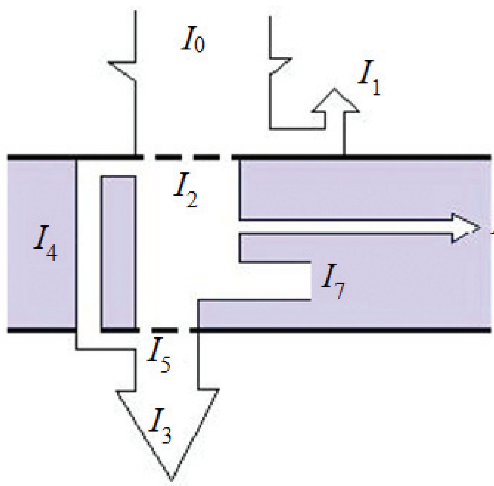

Figure 1. Energy balance when a sound wave impacts the surface.

Note:

A relatively new method of fault diagnosis using sound analysis is used, for example, by the VW Group (e.g., in SKODA AUTO JSC) in selected branded services. The principle is to record the sound of the vehicle in the specified modes and compare it with already available acoustic standards. If discrepancies occur, the application uses an intelligent algorithm to determine what could cause these discrepancies and how they can be corrected. The application is based on artificial intelligence, which relatively reliably, unambiguously and quickly assesses the state of wear of parts and draws attention to the necessary service interventions. A smartphone or tablet helps the technician to diagnose the issue. Just record the sound of the engine, and the fault will be detected by the application. If the sound of the test vehicle differs from the correct sound according to the defined models, it will indicate the need for maintenance or repair. At present, sound recordings are intensively created for the databases (big data) of individual vehicles for the software learning process. At the time of writing this paper, it is possible to recognize about 15 faults with 90 per cent reliability (e.g., air conditioning compressor, dual-clutch gearbox, etc.).

2.2 Selected Anti-Noise Materials and Sound Absorption Measurement

Anti-noise materials must meet a number of requirements, namely legislative, user, production, specific, etc. These are requirements for flammability, waterproofing properties (resistance to weather conditions), emissions of pollutants like formaldehyde and carbon, or phthalates, hygienic safety, noise insulation, absorption, thermal conductivity, specific weight, ductility, compressive and tensile strength, chemical resistance, etc.[26 – 29]. For noise absorption, we can generally use various felt materials (polyester fibres), polyurethane (PUR) foams (foams with hydrophobic treatment, e.g., ANS – foam with carbon fibre), melamine foams (with an open cell structure covered with hydrophobic fabric), nonwovens, mineral and glass wool, sandwich materials, etc. Experimental measurement of the sound absorption factor was performed on selected anti-noise materials by means of the transfer function method according to[27] using[18 – 24]. Samples of materials and their combinations without and with an air gap were gradually inserted into the impedance tube[15 – 17]. The result of the measurement is the frequency dependences of the sound absorption factor in the frequency band $f = \langle 0{,}1600 \rangle Hz$ [18]. Various types of acoustic materials were used for the measurement: glass wool, rubber, polyurethane foam and its recycled materials whose physical and chemical properties are suitable for use in special vehicles (non-flammability, resistance to higher temperatures, etc.). Experimental measurement of the sound absorption factor was performed on selected anti-noise materials and was performed by the method of the transfer function according to[26–29] using[18 – 24]. The diagram of the measuring chain is shown in Fig. 2 and the Kundot impedance tube for determining the acoustic properties of materials is shown in Fig. 3.

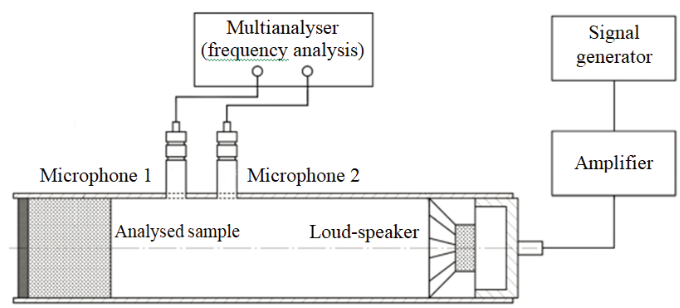

Figure 2. Measuring chain for measuring absorption by the transfer function method.

Figure 3. Kundt impedance tube.

Examples of selected acoustic materials: PUR foam and fine pores (sample No. 1 – corrugated surface), recycled PUR foam (sample No. 2 – flat surface), technical glass wool (sample No. 3) and black coarse-structure rubber (sample No. 4), Fig. 4. In total, various variants of acoustic materials and their combinations were measured (PUR foam with fine pores, recycled PUR foam, glass wool, black rubber, PUR straight, PUR corrugated, numerous rubber with a rough structure, composite of black rubber and recycled PUR foam) was realized for different thicknesses of materials (1 – 5 cm) and different thicknesses of the air gap (0 – 5 cm), for 34 variants. Based on the results, a variant of PUR composite and black rubber was selected. A comparison of the sound absorption of the optimal combination of PUR composite and black rubber used for additional engine and cab sound insulation (blue curve) with the original sound insulation (red curve) is shown in Fig. 5.

Sample No. 1 Sample No. 2

Sample No. 3 Sample No. 4

Figure 4. Sample No.1 PUR foam, corrugated, 5 cm and sample No.2 PUR foam, flat, 1, 3, 5 cm, sample No. 3 glass wool 5 cm and sample No. 4 black rubber 2 cm.

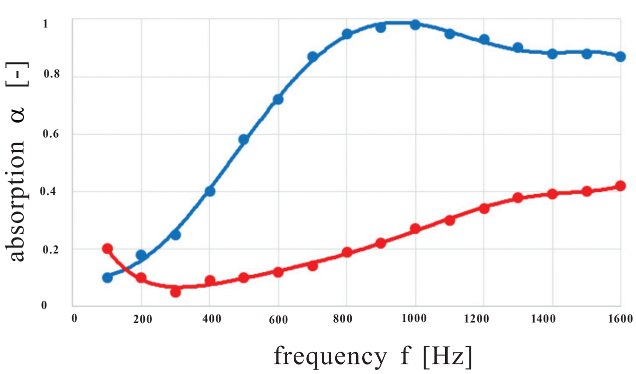

Figure 5. Absorption of PUR composite and black rubber for engine soundproofing (blue curve) and original material 3 cm thick glass wool without air gap (red curve).

3. SOUNDPROOFING OF THE CAB OF A SPECIAL VEHICLE

The project of additional soundproofing of a special vehicle was modelled on an armoured container carrier TATRAPAN 8 x 8 of the Slovak product of the VYVOJ Martin joint stock company on the chassis of the Czech company TATRA TRUCKS with the engine T3-930-55, Fig. 6.

Figure 6. Special vehicle TATRAPAN 8x8

The sound insulation of the cabin and engine compartment was solved with regard to the specific space of the cabin and the physical possibilities of placement of insulation so that the placement of relatively spacious parts does not hinder any function (view, control, access to the engine compartment during maintenance and repairs, etc.). The issue of the 3D model is much more complex, and the authors present only basic information; their specific procedures are unfortunately outside the topic and scope of this paper. The model was used only to specify the shapes and dimensions in 3D printing of skeletons to which damping materials were glued.

3.1 Model of a Special Vehicle Cab

The 3D model of the cab of a special vehicle was created using a digital camera and photogrammetric software. The model was checked twice according to the available drawings and also by direct measurement of the dimensions of the cabin. The tolerance for dimensional differences was ± 5 mm. The 3D model was converted to STL (Standard Triangle Language) binary format using CATIA software for CAD (Computer-Aided Design). The actual printing was carried out using the FFF (Fused Filament Fabrication) method and a PET-G string with carbon admixture was used as the material[25].

3.2 Engine Compartment Sound Insulation

A combination of recycled PUR foam and coarse-structure black rubber with an air gap of 1 cm was used for soundproofing the engine compartment. The composite material is without aluminium foil, because the temperature around the cylinder head is about 105 °C and the rubber withstands temperatures up to 300 °C. The engine compartment sound insulation consists of two parts, i. e. soundproofing under the cab and soundproofing

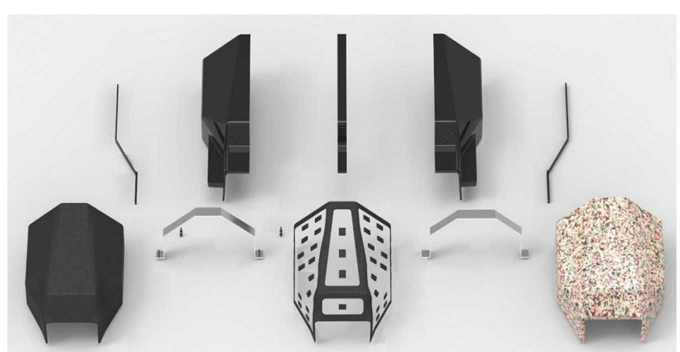

Figure 7. Soundproofing components for the engine compartment under the cab.

behind the cab. The soundproofing components of the engine compartment under the cab are in Fig. 7.

3.3 Cab Soundproofing

A combination of recycled PUR foam and coarse-structure black rubber with an air gap of 5 cm was used to soundproof the cabin. The complete soundproofing of the cabin in the disassembled state is in Fig. 8.

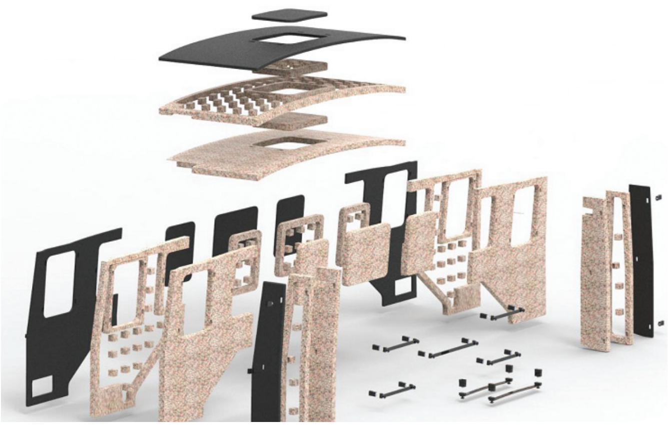

Figure 8. Complete sound insulation of the cab in the disassembled state.

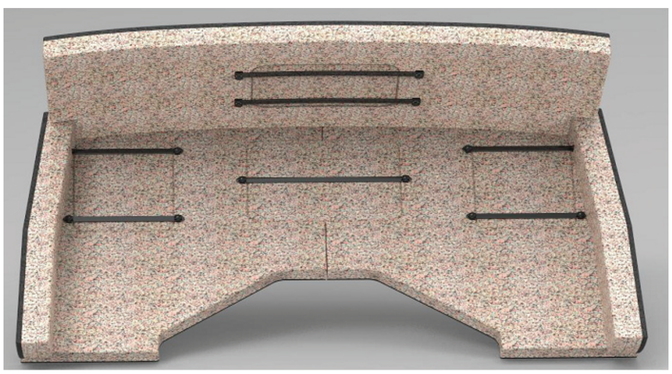

Figure 9. Cab soundproofing when assembled without side section.

Figure 10. View of the cabin space after soundproofing installation.

The following values were obtained by measuring the sound pressure level after soundproofing:

- In the place of the driver's head, Table 3 and
- At a point 15 cm above the cabin floor, Table 4.

Table 3. Sound pressure level in the place of the driver's head

(a) with additional soundproofing

f [Hz]	99	188	297	410	478	591	680	779
L_p [dB]	69	68	66	70	71	70	71	68
f [Hz]	908	990	1101	1190	1291	1380	1490	1550
L_p [dB]	71	74	75	68	75	70	71	70

(b) original design

f [Hz]	99	188	297	410	478	591	680	779
L_p [dB]	71	72	68	71	74	74	75	69
f [Hz]	908	990	1101	1190	1291	1380	1490	1550
L_p [dB]	79	81	80	70	81	84	86	83

Table 4. Sound pressure at a point 15 cm above the floor of the driver's cab

(a) s with additional soundproofing

f [Hz]	99	188	297	410	478	591	680	779
L_p [dB]	69	71	75	69	75	77	76	73
f [Hz]	908	990	1101	1190	1291	1380	1490	1550
L_p [dB]	68	73	79	75	77	78	77	75

(b) original design

f [Hz]	99	188	297	410	478	591	680	779
L_p [dB]	81	84	79	83	88	82	85	83
f [Hz]	908	990	1101	1190	1291	1380	1490	1550
L_p [dB]	79	80	80	84	90	81	84	82

4. CONCLUSION

The submitted solution of the soundproofing of the engine system and cabin of a special vehicle presents only selected basic information forming the theory of noise reduction, relatively detailed issues of experimental tests of selected damping materials and the solution to the main goal, which was practical elimination of excessive noise using damping materials in a special vehicle. By measuring the noise, it was possible to obtain the data necessary for experimental measurements of the sound absorption of damping materials. The frequencies that cause the maximum sound pressure in the vehicle were selected from the measurements, and then a suitable material was searched for to massively reduce the sound pressure level. The experiment was aimed at sound absorption, because not absorbing noise would lead to a reduction in internal noise, but also to its radiation (reflection) to the surroundings and an increase in external noise. Experimentally tested damping materials were flat and corrugated polyurethane foam, coarse-structure black rubber, glass wool and recycled PUR foam. These materials have good noise absorption. Finally, a combination of recycled PUR foam and coarse-structure black rubber was chosen. The reason for choosing this combination of damping materials is optimal absorption and suitable technological properties (resistance to high temperatures, non-flammability, chemical resistance, use of recycled material, etc.). However, the first experiment was an approximate measurement of the noise load in the cabin of a special vehicle. This load was evaluated as unsatisfactory because when measuring the non-soundproof cabin, the sound pressure level reached values of 77–95 dB. After additional soundproofing, the sound pressure level was reduced to 68–79 dB. The basic statistical characteristics of noise measurement after soundproofing and the original design are given in Table 5.

Table 5. Basic statistical characteristics of noise measurement

Soundproof version			Original version		
Arithmetic mean	μ	72.3	Arithmetic mean	μ	79.5
Dispersion	σ^2	11.9	Dispersion	σ^2	31.6
Standard deviation	σ	3.44	Standard deviation	σ	5.61
Median	$\tilde{x}$	71	Median	$\tilde{x}$	81

The actual design and technology of practical soundproofing are relatively simple, allowing for easy implementation and the performed tests verified the expected reduction of noise in the vehicle cabin. The noise barrier thickness is 12 cm, which reduced the cab space, but in addition to the massive noise insulation, an impact zone was also created in the area of the driver's head, which reduces the possible consequences of injuries in the event of an accident or increases resistance to small arms fire, etc. The soundproofing of the engine also reduced vibrations penetrating the cab, from transmission and suspension frame, which, in addition to decreasing external noise, also increased the life of these components.

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