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EQUIPMENT REQUIREMENTS FOR THE INVESTIGATION OF SOUND INSULATION PROPERTIES OF 3D PRINTED POLYMERIC MATERIALS

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Abstract: *Among the properties of interest of 3D printed polymeric materials is their ability to ensure the reduction of sound wave transmission where certain activities require it. To identify a constructive equipment solution capable of providing conditions for evaluating the sound insulation capacity of small polymeric panels, functional requirements were used following axiomatic design principles. Some solutions to ensure the fulfillment of the functional requirements have been identified. Thus, it has become possible to gradually define the equipment that allows the evaluation of the sound insulation capacity of small panels made of polymeric materials by 3D printing.*

Key words: *sound insulation, small dimensions panels, polymeric materials, 3D printing, axiomatic design, functional requirements, design parameters, designed equipment.*

1. INTRODUCTION

The mechanical vibrations can be part of the category of *infrasound* (for frequencies f<20 Hz), *sounds* (for frequencies f=20 Hz – 20 kHz), *ultrasound* (for frequencies f=20 kHz – 106 kHz), and *microwaves*, respectively (f>106 kHz). According to this classification, the acoustic domain corresponds to the frequency range f=20 Hz – 20 kHz, sound being a mechanical vibration with a frequency in the mentioned range. The frequencies corresponding to the sounds were established, taking into account the possibilities of the human ear to sense them.

About the energy source used to generate vibrations in the field of sounds, mechanical, electrical, hydraulic, and pneumatic sources can be mentioned.

The existence of sounds is important to human society, which preferentially uses them to transmit information. To be considered harmless by the human being, the intensity of the sounds must not exceed certain limits.

There are situations where it is necessary to protect the human being from the action of sounds characterized by too high an intensity. In such situations, if the intensity of the vibrations generated by the sound source cannot be reduced, the problem arises of using sound insulation solutions, thus reducing the intensity of the sound vibrations in certain spaces. In other circumstances, vibrations of too high intensity are not acceptable for various reasons, as they are considered a stress factor.

On the other hand, the last decades have highlighted a significant expansion of *additive manufacturing technologies,* and one group of these technologies is based on *3D printing processes*. Through such technologies, a very wide range of parts is made, among which sound insulation panels can be found. Since the values of some input factors in the 3D printing process can be changed relatively easily by the user of the process, it has become of interest to develop research on how some factors specific to the 3D printing process can affect the sound insulation properties of parts manufactured by 3D printing processes.

Thus, without actually resorting to 3D printing processes, Chevillotte and Perrot [1] and, respectively, Perrot et al. proposed a better knowledge of the factors that allow the modeling of the acoustic properties of some foam-type materials [2]. Let's emphasize that, at present, there is the possibility of manufacturing by 3D printing some foams from plastic materials used for sound insulation [3].

There are national and international regulations on determining the sound absorption coefficient [4].

The paper presents the results of research that sought to outline a solution for equipment that can be used for the experimental study of the sound insulation capacity of small panels made of polymeric materials through 3D printing processes.

The identification of the essential components of the equipment was carried out using principles from axiomatic design.

2. INITIAL CONSIDERATIONS

Sound propagation takes place at speeds that depend on the nature of the medium traversed, as each type of medium absorbs part of the energy of the mechanical vibrations that make up the sounds.

Thus, it is accepted that the speed of sound in different media can be determined using a relationship of the form:

- in the case of fluids:

$$c_f = \sqrt{\frac{K}{\rho}}; \quad (1)$$

- in the case of solids:

$$c_s = \sqrt{\frac{E}{\rho}}, \quad (2)$$

where K is the adiabatic volume modulus of the fluid, ρ – the density of the fluid or solid medium, and E – the Young's modulus.

To evaluate the ability to absorb sound energy by a certain medium, the absorption coefficient determined with the help of the relationship [5] is used:

$$\alpha = \frac{E_i - E_r}{E_i} \quad (3)$$

or:

$$\alpha = \frac{E_a}{E_i}, \quad (4)$$

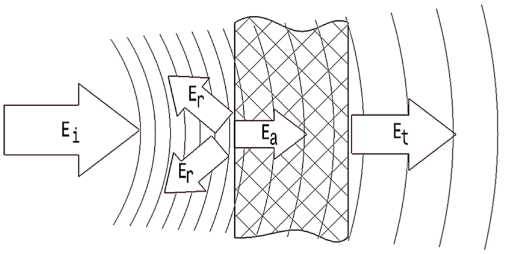

Fig. 1. The passage of sound waves through a small panel made of polymer materials: E_i– the incident energy; E_a – energy entering the small panel; E_r – energy reflected by the surface of the small panel; E_t – a fraction of the incident energy that passed through the small panel.

where E_i is the incident energy, E_r – the reflected energy, E_a – the absorbed energy.

In the schematic representation in figure 1, it can be observed that the sound energy reaching a wall made of solid material (incident energy E_i) breaks down into two components. The wall surface reflects part (Er) of the incident energy Ei.

Another part E_a of the incident energy E_i penetrates the material of the wall, passes through this wall and can exit to the outside environment through the surface of the wall opposite to the entrance surface. This E_t energy that passes through the wall will be found in the form of sound waves whose characteristics can be evaluated with the help of a specialized device.

The characteristics of the sounds that pass through the wall can be significantly influenced by the thickness and structure of the wall material, the nature of this material, etc.

The following main factors and groups of factors can influence the sound insulation capacity of the wall material:

- the type of wall material;
- wall thickness;
- characteristics of the surface through which the sounds penetrate the wall and, respectively, those of the surface through which the sounds that have passed through the wall exit to the outside environment;
- characteristics of the wall structure (disposition of the material in the wall, density of the wall material, etc.).

The experimental study of how sounds propagate through different media can be carried out with the help of so-called Kundt tubes [5-8].

3. FUNCTIONAL REQUIREMENTS IN THE CASE OF EQUIPMENT FOR INVESTIGATING THE MATERIALS CAPACITY OF SOUND INSULATION

Axiomatic design is a way of approaching design problems based on the use of two axioms, namely:

- *Axiom of independence of functional requirements*;
- *The axiom of the minimum of information*.

According to the second axiom, among several available solutions, the selection of that solution characterized by the highest probability of successful application will be preferred.

The American professor Nam Pyo Suh formulated axiomatic design principles at the end of the 70s of the previous century. At that time, professor Nam Pyo Suh was considering optimizing manufacturing processes. Later, it was found that axiomatic design principles could be applied to solve a much wider range of problems, such as, for example, the problems related to the design of road traffic, planning of surgical operations, educational processes, etc. [9, 10].

Next, some stages specific to axiomatic design will be briefly covered, with a more pronounced highlighting of certain aspects. Let us note that two basic axiomatic design concepts are *functional requirements* and *design parameters*, respectively.

Suppose the functional requirements refer to those requirements the tracked equipment or some components must fulfill. The design parameters consider the solutions to solve those functional requirements.

The first step in applying axiomatic design is clarifying the *client's needs*. We will consider, in this sense, the need to design and produce equipment that allows for investigating the sound insulation capacity of small panels manufactured by 3D printing.

Under these conditions, *the zero-order functional requirement* can be formulated:

*FR*0: Ensure equipment design to investigate the sound insulation capacity of small panels manufactured by 3D printing. As a design parameter related to the zero-order functional requirement, we will have *the zero-order design parameter*:

*DP*0: Equipment for investigating the sound insulation capacity of small panels manufactured by 3D printing.

First-order functional requirements still need to be formulated, and they could be:

*FR*1: Generate sound signals;

*FR*2: Receive and analyze the sound signal;

*FR*3: Provide test samples of the materials whose sound insulation capacity is to be investigated;

*FR*4: Provide locating and clamping of the test samples;

*FR*5: Provide locating and clamping of the sound signal-generating source;

*FR*6: Provide locating and clamping of the sound signal receiver;

*FR*7: Provide an enclosure in which the sample, the generator, and the receiver of the sound signal can be inserted;

*FR*8: Provide minimum possibilities for sound insulation of the equipment to the outside environment and respectively to avoid the reception of reflected sound signals by the receiver.

To solve each first-order functional requirement, it is necessary to identify some constructive solutions that contribute to their materialization, thus identifying *the first-order design parameters*. These first-order design parameters could be:

*DP*1: Audio minibox to which a digital signal corresponding to an audio signal with preset characteristics can be transmitted via WiFi;

*DP*2: Receiver corresponding to a sound signal capture and analysis equipment, with possible connection possibilities to a computer;

*DP*3: Test samples in the form of small panels manufactured by 3D printing with different values of the input factors in the 3D printing process;

*DP*4: Subsystem with levers and elastic elements to allow the operative replacement of a sample with another sample;

*DP*5: Subsystem for locating and clamping the audio minibox;

*DP*6: Subsystem for locating and clamping the sound signal receiver;

*DP*7: Enclosure in the form of a box in which the test sample, the generator, and the receiver of the sound signal can be inserted;

*DP*8: Wood for constructing the box-type enclosure and soundproofing material placed on the inner surfaces of the walls that could contribute to a reflection of sound waves.

A more detailed application of axiomatic design principles might necessitate formulating functional requirements and second-order design parameters.

For example, in the case of first-order functional requirement *FR*1, the following *second-order functional requirements* could be identified:

*FR*1.1: Provide a subsystem that can be used to generate a digital signal corresponding to a sound signal with certain characteristics;

*FR*1.2: Provide the change of the values of some parameters of the digital signal that will later be transformed into a sound signal;

*FR*1.3: Provide transmitting the digital signal to the digital signal receiver;

*FR*1.4: Provide a subsystem that receives the digital signal and transforms this signal into an audio signal with certain characteristics.

Correspondingly, the design parameters capable of ensuring the fulfillment of the aforementioned functional requirements can be identified:

*DP*1.1: Computing subsystem of a digital computer or smartphone type;

DP1.2: Specialized software for generating a digital signal corresponding to a sound signal with different characteristics;

*DP*1.3: Components for sending and receiving a WiFi signal;

DP1.4: Audio minibox.

Sometimes it may also be necessary to identify the other functional requirements corresponding to some of the components of the tracked equipment or even all the first-order functional requirements, thus obtaining the sets of the second-order functional requirements and, subsequently, the second-order design parameters. For reasons of limiting the volume of this paper, we will resort to considering only the functional requirements of the second order in the case of the functional requirement of the first order *FR*1.

The set of functional requirements specific to the tracked equipment can be highlighted suggestively and systematically through the content of table 1.

Let's also note that the correlations between the functional requirements *FR*s and the design parameters *DP*s can also be highlighted with the help of a mathematical relationship, in which one of the components is the so-called *design matrix*. In its most general form, the equation mentioned above has the form:

$$\{FR\}=[A]\,\{DP\}, \tag{5}$$

where $[A]$ is the design matrix corresponding to the transfer function between *the functional requirements matrix* $\{FR\}$ and *the design parameters matrix* $\{DP\}$, respectively.

Analysis of the content of the design matrix can highlight the extent to which we are dealing with an ideal design of the equipment. It is thus considered that if the "*X*" symbols are placed along a descending diagonal, we will be dealing with a decoupled design, which would mean an ideal design.

In practice, however, situations can also be encountered where "X" symbols are located outside the descending diagonal of the design matrix. It is thus appreciated that if there are "*X*" symbols all placed either above the descending diagonal or below it, we are dealing with an acceptable triangular matrix.

In situations where the "*X*" symbols are distributed in the design matrix both above and below the descending diagonal, it is considered that the design is not ideal and that there are possibilities for its improvement.

In the specific case of the equipment for investigating the sound insulation capacity of some test samples manufactured by 3D printing (Table 1), it is found that essentially, except for one element, all "*X*" symbols are placed above the descending diagonal, which is a situation very close to that of a triangular matrix, considered acceptable from the point of view of the first axiom. The existence of an "*X*" symbol under the descending diagonal suggests the existence of some possibilities for improving the equipment solution so that the specific requirement of the first axiom is better fulfilled.

Table 1

The matrix containing *FRi* functional requirements and *DPi* design parameters in the case of equipment for investigating the sound insulation capacity of small panels made of polymeric materials by 3D printing.

1	**Design parameters** **Functional requirements**		DP0: Equipment for investigating the sound insulation capacity of small panels made of polymeric materials by 3D printing.							
2			*DP*1: Audio minibox	*DP2*: Receiver	*DP3*: Test samples in the form of small panels	*DP*4: Subsystem with levers and elastic elements	*DP*5: Subsystem for locating and clamping audio minibox	*DP*6: Subsystem for locating and clamping the sound signal	*DP7*: Enclosure in the form of a box	*DP*8: Wood
3 Co-lumn no. 1	**2**	**3**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
4	**Zero order functional require-ment**	**1st order *FR* functional requirements**	**Highlighting the *DPi* design parameters corresponding to each *FRi* functional requirement**							
5	*FR*0: equipment that allows the evaluation of the sound insulation capacity of small panels made of polymeric materials by 3D printing	***FR1:*** Provide a source generating sound signals with different characteristics	X						X	
6		*FR*2: Provide a receiver of the sound signal, which also allows the determination of values and the analysis of some characteristics of the sound signal		X					X	
7		*F*R3: Provide test samples of the materials whose sound insulation capacity is to be investigated			X				X	
8		*FR*4: Provide the locating and clamping of the test samples				X			X	
9		*FR*5: Provide the locating and clamping of the sound signal-generating source					X		X	
10		*FR*6: Provide the locating and fixing of the audio signal receiver						X	X	
11		*FR*7: Provide an enclosure in which the test tube, generator, and receiver of the sound signal can be inserted							X	
12		*FR*8: Provide sound insulation of the equipment to the external environment and respectively to avoid the capture by the receiver of some reflected sound signals							X	X

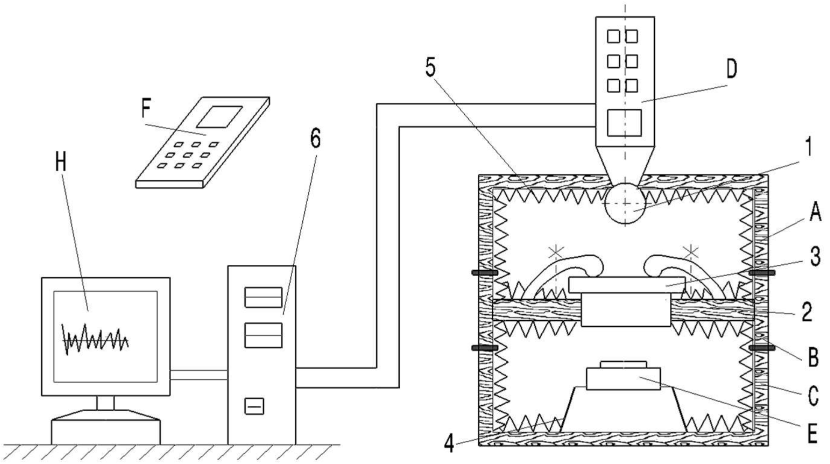

Fig. 2. Schematic representation of the proposed equipment for evaluating the sound insulation capacity of some panels made of polymeric materials made by additive manufacturing processes.

Examining the information in table 1 highlights the existence of a coupled design, as *X* symbols have been placed above and below the descending diagonal. Different solutions can be subjected to additional analysis to arrive at a decoupled design closer to an ideal design. Thus, it can be found, for example, that functional requirements *FR*7 and *FR*8 can be combined into a single new functional requirement *FR*7, namely:

*FR*7: Provide an enclosure in which the test sample, the generator, and the receiver of the sound signal can be inserted and which, at the same time, contribute to an isolation of the equipment from the external environment and respectively reduce the probability of reception of some signals reflected by the receiver.

In this case, the *DP*7 design parameter capable of the fulfillment of the *FR*7 functional requirement would have the form:

*DP*7: Wooden enclosure, lined on the inside with soundproofing material.

By taking into account the new variants for the functional requirement *FR*7 and the design parameter *DP*7, the content of Table 1 will change, and the equation valid for the new situation will have the form:

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \\ FR6 \\ FR7 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & X \\ 0 & X & 0 & 0 & 0 & 0 & X \\ 0 & 0 & X & 0 & 0 & 0 & X \\ 0 & 0 & 0 & X & 0 & 0 & X \\ 0 & 0 & 0 & 0 & X & 0 & X \\ 0 & 0 & 0 & 0 & 0 & X & X \\ 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ DP5 \\ DP6 \\ DP7 \end{Bmatrix} \qquad (6)$$

where the symbols "*X*" means the fulfillment of a functional requirement *FR* by a design parameter *DP*.

It is found that the new variant of the design matrix no longer corresponds to a coupled design but to a decoupled design

By developing an analysis of different materialization alternatives of the various components of the equipment for investigating the sound insulation capacity of small panels manufactured by 3D printing from polymeric materials, the solution presented schematically in figure 2 was gradually outlined. The three distinct components in the structure of the equipment, namely *A*, *B,* and *C*. These components must be made of a material with a good sound insulation capacity, as is, for example, wood. The pairs of components *A* and *B* and, respectively, B and C are assembled together by hinges. In a cap-type hole provided in component *A*, the tube-shaped end of apparatus *D,* usable for measuring some characteristics of sounds, can be placed. Later, on the tube-shaped end, sphere 1, made of porous material, is inserted, through which the sounds whose characteristics must be analyzed will pass. In component *B* there is a wooden plate 2, solidarized with the walls of component *B*. In plate 2 there is a square-shaped hole, closed by panel 3, made of the material whose sound insulation characteristics must be evaluated. Panel 3 is fixed to plate 2 with clamps and screws.

In the lower part of component 3, also in the form of a lid, a sound source is placed in the form of a small audio minibox *E*. Audio minibox *E* is

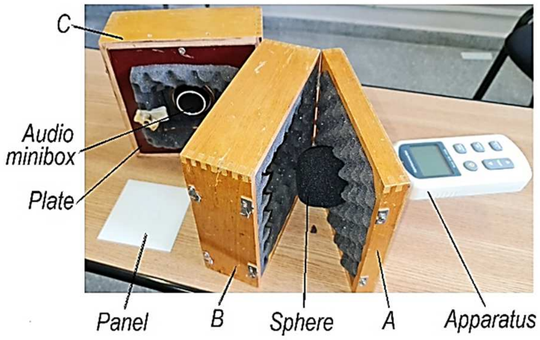

Fig. 3. Equipment for studying the sound insulation capacity of small panels made of polymeric materials.

located and clamped in component *C* with the help of part 4, which has the shape of a conical glass.

A computer program that can generate sounds with different frequency and intensity characteristics can be installed, for example, on a mobile phone *F*. This phone *F* could send a signal via Bluetooth that will force the audio minibox *E* to generate sounds of predetermined characteristics.

The sounds will pass through the hole in wooden plate 2 and then through panel 3, reaching sphere 2 and from there to the sensor of apparatus *D* intended for evaluating the characteristics of the received sounds. The signal captured by the device *D* can be directed to a computer *G*, where a specialized program could contribute to a more detailed analysis of the received sounds after passing through panel 3.

The results obtained can be compared with those in the case of the non-existence of panel 3, thus making it possible to highlight the sound insulation characteristics of the material in panel 3. The specialized computer program could also facilitate the development of graphical representations in the form of diagrams of the time variations of some characteristics of the sounds received by the sensor of the device *D*. The graphical representations could be directly visible on the screen of a monitor *H*. To ensure maximum sound transmission conditions only through panel 3, the various inner surfaces of components *A*, *B* and *C* can be covered with layer 5 of sound-insulating material. In the case of 3D printing processes of parts made of polymeric materials, some properties of the materials can be modified by varying the values of the input factors in the additive manufacturing process. In this way, the proposed equipment could also be used to highlight the influence exerted by different factors on the sound insulation capacity of the polymeric materials used to manufacture panels with different constructive characteristics.

An image of the equipment designed following the previous considerations is shown in figure 3. Carrying out some preliminary tests proved the possibility of using the equipment to study the influence of input factors on the sound insulation capacity of small panels made of polymers by 3D printing.

4. CONCLUSIONS

The requirements to carry out some experimental tests intended to highlight the influence exerted by the different properties of some small panels made of polymeric materials on the sound insulation capacity of the materials used in the manufacture of the panels determined the undertaking of some steps to design one that would facilitate the development of experimental research under the mentioned conditions. Some principles from axiomatic design were used for the systematic identification of the equipment's requirements and for the identification of some solutions for the components that must meet the functional requirements. A first attempt to build a design matrix highlighted the fact that the proposed solution is close to that of a triangular matrix, considered acceptable at this stage but which is susceptible to improvements.

The assembly of the components that must ensure conditions to meet the functional requirements later led to the design of an equipment solution that would allow the study of the sound insulation capacity of small panels made of polymeric materials. Such small panels can also be manufactured by 3D printing processes. Since the identified solution corresponds to a coupled design, a reanalysis of the functional requirements was resorted to, thus arriving at a decoupled design deemed acceptable. This equipment solution can also be used in the future to study the influence exerted by the input parameters in the 3D printing process on the sound insulation capacity of small panels.

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CERINȚE PENTRU UN ECHIPAMENT DE INVESTIGARE A PROPRIETĂȚILOR DE IZOLARE FONICA ALE MATERIALELOR POLIMERICE IMPRIMATE 3D

Între proprietățile de interes ale materialelor polimerice imprimate 3D se află și capacitatea acestora de a asigura reducerea transmiterii undelor sonore, acolo unde anumite activități impun asa ceva. Pentru identificarea unei soluții constructive relativ simple de echipament capabil să asigure condiții pentru evaluarea capacității de izolare fonică a panourilor de mici dimensiuni din materiale polimerice, au fost utilizate cerințe funcționale în conformitate cu principiile proiectării axiomatice. Au fost identificate diverse soluții pentru a asigura îndeplinirea cerințelor funcționale. Astfel, a devenit posibilă conturarea treptată a unui echipament care să permită evaluarea capacității de izolare fonică a panourilor de mici dimensiuni din materiale polimerice, panouri fabricate prin imprimare 3D.

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