The sound insulation capacity of some panels made of polymeric materials manufactured by 3D printing

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Abstract. The soundproofing of certain spaces is necessary primarily to combat noise pollution generated by high-intensity noise sources. One of the ways to reduce the unwanted propagation of high-intensity sound waves is based on the use of panels made of polymeric materials. The expansion in recent decades of the manufacturing processes of parts by 3D printing has led, among other things, to the identification of ways to change the properties of the materials included in the parts manufactured by 3D printing and to modify, in this way, including the sound insulation properties of such materials. For the development of experimental research aimed at allowing the study of the sound insulation capacity of small panels made by 3D printing from polymeric materials, a relatively simple equipment was designed. Equipment includes an enclosure in which the sound source, the small panel, and the sensor of a device used to evaluate the characteristics of sounds. Experimental tests were carried out on panels made of polylactic acid. The experimental results were mathematically processed with the help of specialized software. An empirical mathematical power function model was determined. This empirical mathematical model highlights the intensity of the influence exerted by the thickness of the panel by the speed and volume of the sounds on the acoustic pressure level. It was found that the strongest influence is exerted by the volume of the sound wave.

Introduction

The sound corresponds to a mechanical vibration with a certain frequency and intensity transmitted through a gaseous, liquid, or solid acoustic medium. In principle, it is considered that the frequency of sound sensed by the human ear is between 20 and 20,000 Hertz. From the point of view of vibration frequency, near sounds are infrasound and ultrasound, respectively. When some sounds are appreciated by people as unpleasant, because of their frequency or because of too high intensity, they are called *noises*.

We can talk about *noise pollution* when the noise-producing source cannot be eliminated or removed. This pollution can adversely affect the health of people or other organisms. It is necessary to use solutions that diminish the intensity of the ultrasound transmission process to reduce the negative influence of noise pollution.

There is a wide range of solutions capable of reducing the intensity of the noise transmission process. One of these ways considers insulating materials from a sound point of view [1–4]. Plastic materials are sometimes used as soundproofing materials.

In principle, plastic materials are non-metallic materials with an amorphous structure obtained by melting together several constituents (resins, plasticizers, dyes, lubricants, fillers, and auxiliary materials). Plastic materials are easily shaped at temperatures usually in the range of 140-180 ° C. The technology of obtaining plastic materials by joining several molecules of the same type is called *polymerization*, and the results of its application are *polymers*. The parts made of polymeric materials can be manufactured by different processes (by pressing, drawing, injection, thermoforming, etc.). Currently, a group of technologies in a remarkable expansion are the technologies based on adding materials, being *additive manufacturing technologies*. One of these technologies is *fused deposition modeling*, which involves the successive addition of layers obtained by advancing and depositing a polymer in a molten state.

For sound insulation, polymer panels manufactured through a fused deposition modeling process can be used in certain situations.

Therefore, it was normal for some researchers to turn their attention to the properties of polymeric materials manufactured by 3D printing processes that could reduce noise pollution. Thus, the problem of manufacturing by 3D printing some lattice structures capable of contributing to the reduction of noise intensity was addressed by Franklin et al. [3]. They used experimental tests, simulations of the studied processes, and appropriate methodologies to reveal the ability of the lattice structures to dampen vibrations with frequencies between 0 and 30,000 Hz.

Perrot and Hoang undertook research to improve the conditions for modeling the sound insulation properties of some structures made of cellular foams and the possibilities of manufacturing such structures [4]. They noted that 3D printing variants of cellular foams are still too expensive for widespread use.

Equipment for the study of sound insulation properties of some panels made of polymeric materials by 3D printing was presented in work [5].

The research, the results of which are presented in this paper, aimed to carry out experimental tests regarding the influence of the thickness of polymer panels, respectively the frequency and intensity of sounds, on the sound insulation capacity of polylactic acid panels manufactured by 3D printing.

Generation and Propagation of Sounds

Sounds can be generated by vibrating a solid body using different forms of energy. Thus, sounds are generated mechanically, electromechanically, hydraulically, pneumatically, etc. As mentioned, sounds can be transmitted through solid, liquid, and gaseous media. When sound passes from one medium to another, part of its energy can be reflected, a part is dissipated (absorbed) in the second medium, and another part passes through that medium (Fig. 1). The propagation of sounds takes place through successive contractions and elongations of some areas in the environment in which the sounds propagate.

If the flow corresponding to the incident energy is denoted by E_i, by E_a – the flow of absorbed energy, and by E_r – the flow of reflected energy, the sound absorption coefficient α at the level of the separation surface between two media can be calculated using relations of the form:

$$\alpha = \frac{E_a}{E_i} \tag{1}$$

or

$$\alpha = 1 - \frac{E_r}{E_i} \tag{2}$$

The different media traversed by the sound contribute to a gradual reduction in its intensity. In such conditions, *an acoustic impedance* can be defined as a quantity with the help of which the opposition of an environment to the propagation of acoustic waves is evaluated:

$$Z = \frac{p}{vS} \tag{3}$$

where p is the sound pressure, v is the velocity of the sound wave, and S - the surface through which the wave propagates.

Different sizes can be used to evaluate the intensity of sounds, one of which is the *sound pressure level* or sound intensity (expressed in decibels). Such a quantity represents the sound intensity level to a reference value.

The intensity of the sound wave absorption process depends not only on the properties of the material through which the sound wave passes, but also on some properties of the sound. Different materials exhibit distinct sound attenuation properties. Materials that absorb a greater amount of acoustic energy are considered soundproof materials.

Equipment for Evaluating the Sound Insulation Capacity of Some Panels Made of Polymeric Materials

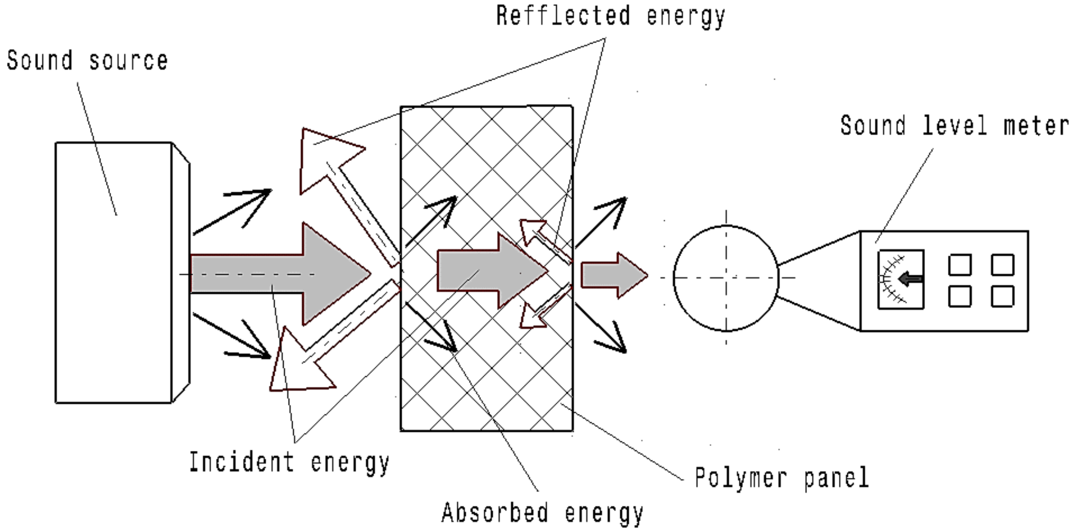

Fig. 1. Schematic representation corresponding to sound propagation from the source to the sound level meter, passing through the polymer panel.

One of the objectives pursued through the research, the results of which are presented in this paper, was to design equipment that would allow the evaluation of the sound insulation capacity of some panels made of polymeric materials.

It is known that for the evaluation of the sound insulation capacity of different materials, equipment incorporating the so-called Kundt tube can be used [6]. Since the accessible Kundt tubes allowed the use of relatively small test sample, the problem of designing and making specialized equipment for evaluating the sound insulation properties of the materials of polymer test samples with surfaces of 100x100 mm^2 and thicknesses of 1-6 mm was formulated.

The main requirements that such equipment had to fulfill were the following:

1. To allow the locating and clamping a test sample in the form of a panel of polymeric material, with an area of 100x100 mm^2 and with thicknesses of up to 6 mm;

2. To include a source of sounds whose characteristics (frequency, volume) can take values between certain limits;

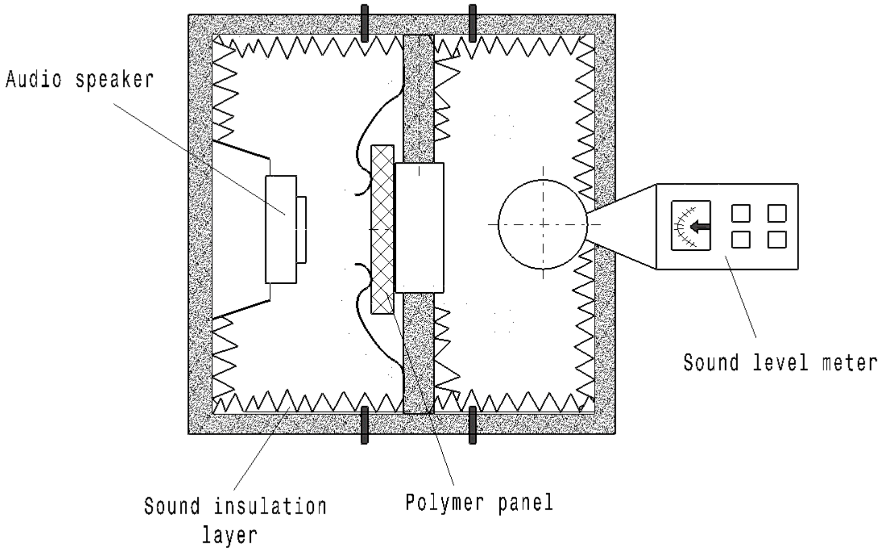

Fig. 2. Schematic representation of the equipment for investigating the sound insulation capacity of some polymer panels.

3. To include a sound level meter;
4. The different components involved in the generation of sounds and, respectively, in their measurement can be located inside an enclosure to avoid disturbing the results by sounds from outside the equipment;
5. As far as possible, ensure conditions to avoid the sounds reflected by the walls of the enclosure affecting the results of the measurements.

The equipment represented schematically in Fig. 2 was designed to obtain information about the sound insulation capacity of some panels made of polymeric materials. In principle, the equipment includes three distinct compartments, which can be assembled with the help of hook fasteners. In the first compartment, a speaker will have to generate a sound commanded via Bluetooth through a program opened on a mobile phone or a computer. In the second compartment, a polymer sample having a certain thickness can be oriented and fixed. The sensor of a sound level meter (type HY1361 - China) enters the third compartment.

The walls of the three compartments were made of wood to ensure, as much as possible, an avoidance of the results being affected by the sounds existing outside the equipment. Also, to reduce the influence of the sounds possibly reflected by the walls of the compartments, the inner surfaces were covered with a layer of material also characterized by a high sound absorption capacity.

An image of the equipment can be seen in Fig. 3.

Fig. 3. Image of equipment used to study the influence exerted by some factors on the transmission of sound through small panels manufactured by 3D printing.

In Fig. 4, it can be observed how pockets were generated in the sample during its manufacture by 3D printing. This way of printing was done in the idea of having not only a 100% infill of the part so that the insulation can be better, but also in the idea of creating a resistance structure for the part considering the next usage of such a part in construction for example.

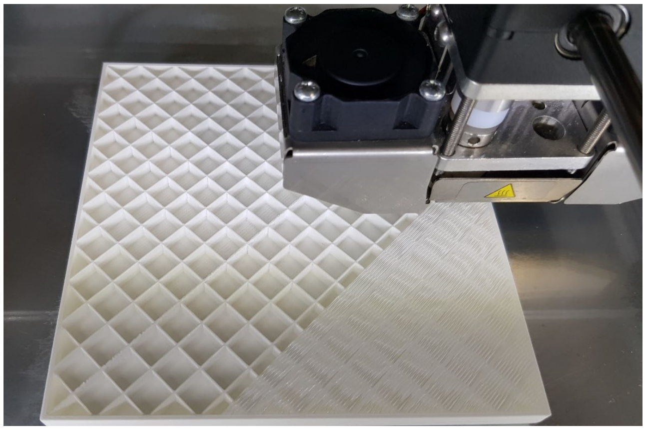

Fig. 4. Image taken during 3D printing of the 6mm thick panel with 10% grid infill.

Modeling Some Research Elements Using the Finite Element Method

A type of harmonic analysis was used to obtain a map of the sound pressure inside a closed enclosure. The 3D model assumes the existence of a speaker box in which there is a panel with a thickness of 1 mm manufactured by 3D printing. The design is similar to the one used in the experimental tests. A 100% cushion box enclosure was modeled (Fig. 5) because the surrounding acoustic environment serves as the domain in which the acoustic waves propagate. Therefore, a mesh of acoustic elements must surround the geometric body considered. In this way, the whole design distributes a certain topology to all elements to have a network control option available.

As excitation, it was necessary to choose between Mass Source, Surface Velocity, Diffuse Sound Field and other types. It was preferred Mass Source because it best suited the experimental setup. Excitation can be applied to vertices, edges or surfaces by introducing a pressure wave inside the system. The mass source is given by the Helmholtz equation (link) and if it is applied to a surface, one can divide the mass flow by the area it is applied to. A plane wave was simulated in this way [link]. By suppressing the speaker and the test sample, the analysis mode treated the geometry as infinitely rigid, replacing it with voids that will act as sound reflectors. The maximum value of 15 kHz was set for the maximum range using a linear frequency. A far-field sound pressure level (SPL) plot was requested, assuming a 100mm sphere radius and 360o at the end of the theta angle, using the perfectly matched layers (PML) option to model the far-field radiation limit (Fig. 6).

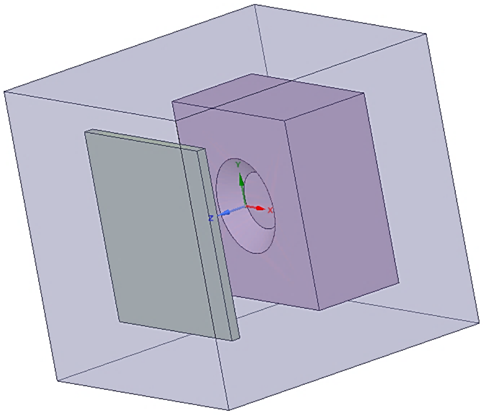

Fig. 5. Proposed 3D model design with 100% cushioned enclosure.

Air was the preferred propagation medium and we added a second enclosure designed to absorb the outgoing acoustic radiation without reflection coupled with PML elements. By adding a second coordinate system relative to the global one the orientation from the main axis (Y) was changed to be defined by the global Z and a construction surface was requested to be able to see the distribution of the results inside the enclosure.

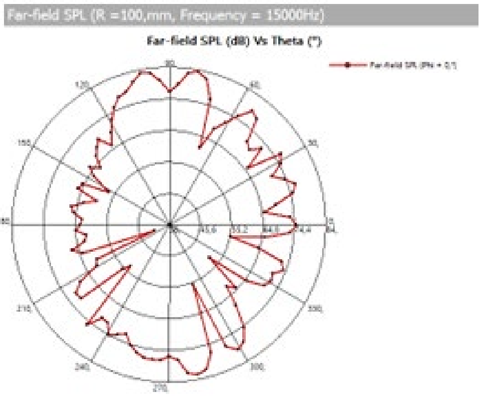

Fig. 6. Far-field sound pressure level at 360º distribution plot.

Fig. 7 highlights the pressure distribution that builds up inside the enclosure, reaching a value of 0.342652 MPa in the center of our panel.

Fig. 8 shows recordings of sound pressure levels recorded at 15 kHz with a peak amplitude of 108.67 dB in amplitude. It can be seen that the space between the speaker box and the panel is the most affected. The edges of the enclosure are all blue, which ensures that our setup works by trapping acoustic radiation without reflecting it.

The authors acknowledge that this analysis is based on an ideal setup and further refinement may be necessary before using the results in other areas of research.

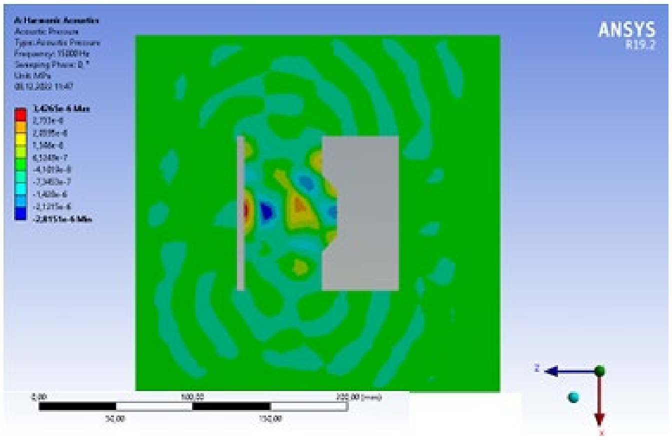

Fig. 7. Acoustic pressure accumulation at 15 kHz.

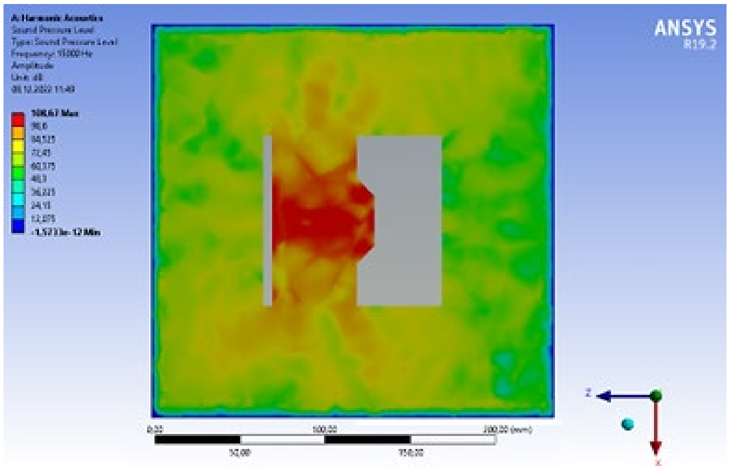

Fig. 8. Sound pressure level map at 15 kHz.

Experimentation of the Equipment for Evaluating the Sound Insulation Capacity of Some Polylactic Acid Panels

An experimental research plan was designed to highlight the influence of several factors on the sound insulation capacity of polylactic acid panels manufactured by 3D printing. These panels were manufactured under the working conditions recommended by the manufacturer of the printing equipment (Ultimaker 2 - Netherlands) with a 100% infill. As previously mentioned, the panels had an area of 100x100 mm^2 and thicknesses of 1 mm and 6 mm, respectively. The material used was PLA, polylactic acid as this is a usual material used in the printing process, but also being an organic material and the focus in the market and industry is on such materials.

Sound pressure level was used as the output parameter. This size was determined with the help of a sound level meter.

The input factors in the measurement process were the thickness t of the polylactic acid panel, the frequency f of the vibrations, and a size V relating to the sound volume. In this way, it was possible to plan the experimental trials according to the requirements of a full factorial experiment, type $L8$, with 3 independent variables at two levels of variation. Two-panel thicknesses (1 mm and

6 mm, respectively), two frequencies (500 Hz and 15,000 Hz, respectively), and two sound volume levels (10 % and 100 %) were used in this way. Generally speaking, the number of the independent variables can be bigger and more complex, but due to the usage of a Taguchi method for experimental research, there is possible to have like a concludent result with this L8 method type, minimizing a lot the number of the variables and the number of the trails for the experiments.

Both the values of the input factors and the results of the experimental tests can be seen in Table 1.

For a more appropriate interpretation of the experimental results, measurements were also performed without the polylactic acid panel, obtaining the following results: a) for V=10 % and f=500 Hz, I_s=95.2 dB; b) for V=100 % and f=15,000 Hz, I_s=95.0 dB; c) for V=100 and f=500 Hz, I_s=107.1 dB; d) for V=100 % and f=15,000 Hz, I_s=110 dB.

The experimental results were mathematically processed using specialized software based on the least squares method [7]. In this way, the following empirical mathematical power function model was obtained:

$$I_s = 123.027t^{0.0216}f^{-0.0725}V^{0.0734} \quad (4)$$

Table 1. Experimental conditions and results.

Exp. no.	Input factors (coded value/real value)			Output parameter
	Panel thickness, t, mm	Sound frequency f, Hz	Sound volume level V, %	Sound intensity I_s, dB
1	-1/1	-1/500	-1/10	99.2
2	-1/1	-1/500	+1/100	110.1
3	-1/1	+1/15000	-1/10	68.7
4	-1/1	+1/15000	+1/100	84.8
5	+1/6	-1/500	-1/10	97.1
6	+1/6	-1/500	+1/100	109.1
7	+1/6	+1/15000	-1/10	62.7
8	+1/6	+1/15000	+1/100	80.1

By considering the empirical mathematical model constituted by equation (1), the diagram in figure 9 was developed.

The analysis of the determined mathematical model highlights that, among the three input factors considered, the strongest influence is exerted by the sound volume level V since, in relation (4), the exponent with the highest absolute value is attached to this factor. As expected, an increase in the sound volume level V results in an increase in the sound intensity I_s. Increasing the frequency f of the sounds leads to a decrease in the intensity I_s of the sound since the exponent attached to the factor f in equation (4) has a negative value.

Summary

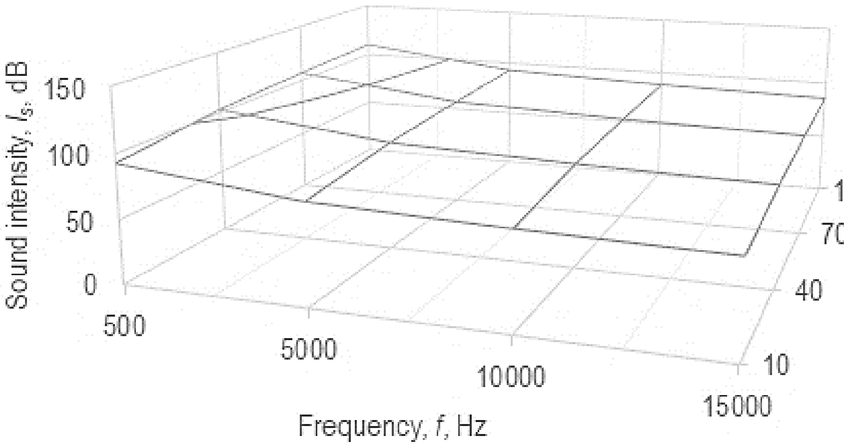

Fig. 9. The influence exerted by the frequency f and by the sound volume level V on the sound intensity I_s (t=1 mm).

The problem of evaluating the ability of some polymeric materials to contribute to the reduction of noise pollution is a current issue. For the experimental research of how different factors contribute to the variation of sound intensity after passing it through a polylactic acid panel, equipment was designed and made to provide conditions for the passage of sound through the polymer panel and the measurement of sound intensity with the help of a sound level meter. In the experimental tests, the panel thickness, frequency, and volume level of the sounds were considered input factors. An empirical mathematical model of the power function type was determined through the mathematical processing of the experimental results with the help of specialized software. It was found that the most significant influence on the intensity of sounds is exerted by the volume level of the sound passing through the panel. Increasing the frequency leads to a decrease in sound intensity after passing through the polylactic acid panel. In the future, it is intended to expand theoretical and experimental research on the influence of different factors on the variation of sound intensity after passing through panels made of different polymer materials or having different structural characteristics.

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