MATERIALE PLASTICE
https://revmaterialeplastice.ro
https://doi.org/10.37358/Mat.Plast.1964

Numerical Analysis of Plastic Perforated Panel for Acoustic Protection

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Abstract: *Acoustic protection is an important aspect in various industrial, commercial and residential applications. In order to reduce the transmission of noise, perforated panels are frequently used as a barrier. The present study aims to conduct a numerical analysis of plastic perforated panels for acoustic protection. The study employed a finite element method (FEM) approach and focused on the propagation of acoustic waves through perforations of varying diameters (30 mm, 40 mm, 50 mm, 60 mm, 70 mm and 90 mm) and at different frequencies (250 Hz, 500 Hz, 1000 Hz and 1500 Hz). The numerical analysis was conducted using the finite element software ANSYS. This work offers numerical analysis models of acoustic wave propagation, which can be used by those interested in similar problems, for different environments, in closed or open spaces. The results showed that the perforation diameter and frequency play a crucial role in the performance of the plastic perforated panels as an acoustic barrier. The results of the author's research pointed out that the plastic materials can be used successfully in the construction of acoustic barriers. Next to it, the findings of this study can provide valuable insights for engineers and designers in the selection and optimization of plastic perforated panels for acoustic protection applications.*

Keywords*: acoustic wave, acoustic pressure, FEM, acoustic protection panel, acoustic panel of plastic materials*

1. Introduction

Acoustic protection is a critical aspect in many industrial, residential, and commercial settings. The use of perforated panels has gained popularity in recent years as an effective means of reducing unwanted sound levels [1]. Plastic perforated panels, in particular, offer the advantage of low weight and high durability. However, the design of these panels needs to be optimized to ensure their effectiveness in providing acoustic protection [2]. This is where numerical analysis can be of great help, by providing a cost-effective and time-efficient means of simulating the behavior of perforated panels under different sound loads [3].

In this study, numerical analysis is used to investigate the performance of plastic perforated panels for acoustic protection. The 3D finite element method (FEM) is utilized to model the mechanical structure of the panel and simulate the propagation of acoustic waves through the perforations [4]. The boundary conditions of the model are defined based on the known properties of the panel material and the surrounding environment. The analysis includes a series of simulations with different perforation diameters and sound frequencies.

The objective of this research is to provide a comprehensive understanding of the behavior of plastic perforated panels under different sound loads, and to offer insights into the optimal design parameters that can ensure maximum acoustic protection. The results of this study will be useful for engineers, architects, and acousticians involved in the design and implementation of acoustic protection systems. The findings will also be of interest to researchers and scholars who are investigating the effectiveness of perforated panels in reducing unwanted sound levels.

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2. Materials and methods

This article is based on the numerical and experimental research results conducted by the authors with the aim of understanding the propagation of sound waves, in the conditions of generating plane waves (the source is located at a great distance from the measurement point) and the creation of acoustic protection panels.

The specialized literature presents a series of constructive solutions for acoustic panels from which the interested party can be inspired in choosing a solution, but, regardless of the chosen solution, it must be investigated numerically and experimentally.

Compared to analytical solutions, when these exist or can be approached without major difficulties, numerical analysis is the solution to break the impasse. In addition, numerical analysis also has the advantage of offering the interested party the possibility of post-processing the results graphically, which allows for a quick and overall visualization of parameters such as the acoustic pressure field, the transmission loss field, the acoustic pressure gradient, etc [5].

The research carried out by the authors focused on the small or medium-thickness acoustic insulation panels made of metal and plastic materials. The constructive solution of these is represented by a flat plate with perforations made with a certain density on the surface. Such an acoustic insulation panel is shown in Figure 1.

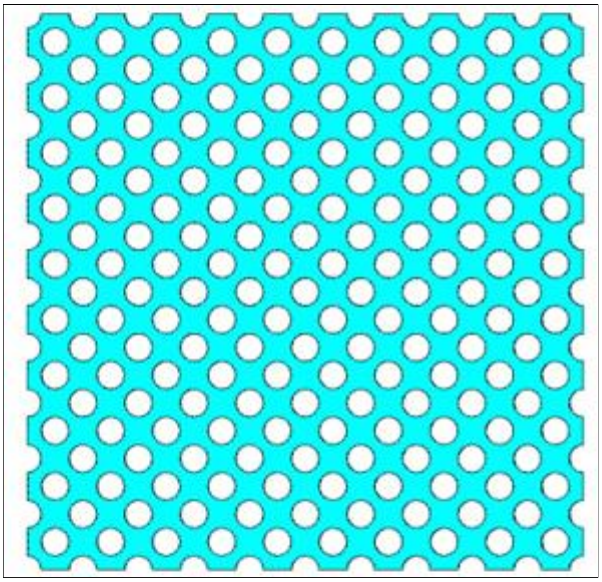


Figure 1. Acoustic insulation panel with holes

This type of acoustic panel has the advantage that, in addition to acoustic insulation, it allows for sufficient air circulation. This requirement can become very important depending on the location of the panels.

The author’s focus on such panels made of plastic materials was based on the observation that some properties of modern plastic masses are comparable to those of metals and that, in general, they offer a lower mass and can be a more economical solution.

Additionally, the utilization of plastic materials allows for a more flexible and versatile design, making it a suitable choice for various acoustical applications.

2.1. Materials

The study aimed to compare and to evaluate the acoustical performance of various materials commonly used in the construction of acoustic panels. The two metal materials, steel and aluminum, were selected due to their widespread use in the industry and their well-established properties. Polyethylene and polyvinyl chloride, on the other hand, were chosen as representative examples of modern plastic materials, which have gained popularity in recent years due to their lightweight and cost-effectiveness [6].

A comprehensive evaluation of the physical and mechanical properties of these materials was performed and the results are presented in Table 1. This information provides valuable insights into the suitability of these materials for acoustic insulation purposes and serves as a reference for future studies in this field.

Table 1. Properties of materials

Material properties	[SI]	**Materials**			
		Steel	Aluminium	PVC	Polyethylene
Young's modulus	[MPa]	$2{\cdot}10^{11}$	$7{\cdot}10^{10}$	$2.3{\cdot}10^{9}$	$1.3{\cdot}10^{10}$
Poisson ratio	[-]	0.30	0.30	0.30	0.30
Density	[kg/m^3]	7850	2700	1350	914
Speed of sound	[m/s]	5000	4996	1305	3772

The studied acoustic panel, as shown in Figure 1, had the dimensions of 0.6 m x 0.6 m x 0.0015 m with a hole diameter of 0.03 m.

Furthermore, the research also delved into the examination of sound wave propagation through a hole in the panel. The study considered different values of frequencies and hole diameters to determine the impact on sound isolation. A square panel was used for the study, with a side length of 0.4 m, a central hole, and an embedded side as depicted in Figure 2. The panel was designed with a thickness of 0.01 m to allow for the analysis of the loss of acoustic pressure along the direction of propagation.

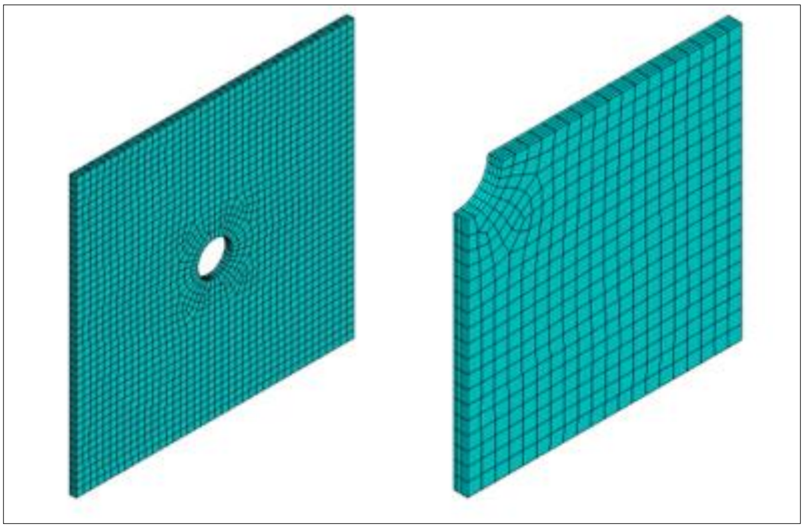


Figure 2. Testing acoustic panel

This panel was tested through numerical simulations, which allowed for a comparison of the behavior of panels made from different materials. The panel shown in Figure 1 was studied both numerically and experimentally, only for its steel construction version.

2.2. Numerical investigation

Numerical research in the field of acoustics knows several methods. Among these, we mention the finite element method, the boundary element method and more recently, the meshless/meshfree methods. In this article, the numerical investigation with the finite element method is presented.

The power of its analysis, to which is added the graphic post-processing of the results, make the finite element method the most suitable means of approaching complex problems, such as propagation, attenuation, coupling with mechanical structures and others, related to acoustic waves.

The equation of acoustic waves is expressed as follows [7]:

$$\frac{1}{c^2}\frac{\partial^2 P}{\partial t^2} - \nabla^2 P = 0 \quad (1)$$

or, in the Helmholtz form,

$$\frac{\omega^2}{c^2}\bar{P} + \nabla^2 \bar{P} = 0 \quad (2)$$

where:
- c = speed of sound in the propagation medium;
- P = acoustic pressure ($P = P(x, y, z, t)$);
- t = time.

For the harmonic variation of pressure, the equation is given by:

$$P = \bar{P} \cdot e^{j\omega t} \quad (3)$$

where:
- $\bar{P}$ = amplitude of pressure;
- $\omega = 2\pi f$;
- f = frequency of acoustic wave;
- $j = \sqrt{-1}$.

In matrix form, the equation (1) is written as:

$$\frac{1}{c^2}\frac{\partial^2 P}{\partial t^2} - \{L\}^T(\{L\}P) = 0 \quad (4)$$

where $\{L\}$ is the matrix operator:

$$\nabla \cdot (\ \ ) = \{L\}^T = \begin{bmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \end{bmatrix} \quad (5)$$

and

$$\nabla(\ \ ) = \{L\} \quad (6)$$

where P is the pressure vector.

To obtain the finite element matrix, can be write the integral equation (4),

$$\int_V \frac{1}{c^2}\delta P \frac{\partial^2 P}{\partial t^2} dV + \int_V (\{L\}^T \delta P)\,(\{L\}P) dV = \int_S \{n\}^T \delta P (\{L\}P)\, dS \quad (7)$$

where:
- V is the volume of the analyzed domain;
- S is the surface that delimits the domain;
- δP is the infinitesimal virtual variation of pressure;
- $\{n\}$ is the unit normal to surface S.

Considering surface S as the fluid-structure interface, the relationship between the normal pressure gradient at surface S and the structure acceleration is represented by equation 8, where $\{u\}$ is the nodal displacement vector at the fluid-structure interface.

$$\{n\} \cdot \{\nabla P\} = -\rho_0 \{n\} \left(\frac{\partial^2}{\partial t^2}\{u\}\right) \quad (8)$$

The matrix form of equation (8) can be written as:

$$\{n\}^T(\{L\}P) = -\rho_0\{n\}^T\left(\frac{\partial^2}{\partial t^2}\{u\}\right) \tag{9}$$

Taking into account equations (8) and (9), equation (7) becomes:

$$\int_V \frac{1}{c^2}\delta P\frac{\partial^2 P}{\partial t^2}\mathrm{dV} + \int_V(\{L\}^T\delta P)\,(\{L\}P)\mathrm{dV} = -\int_S \rho_0\delta P\{n\}^T\left[\frac{\partial^2}{\partial t^2}\{u\}\right]\mathrm{dS} \tag{10}$$

By expressing the parameters in equation (10) in terms of the shape functions $\{N\}$ and $\{N'\}$, equation (10) becomes:

$$\begin{gathered}\int_V \frac{1}{c^2}\{\delta P_e\}^T\{N\}\{N\}^T\mathrm{dV}\{\ddot{P}_e\} + \int_V\{\delta P_e\}^T[B]^T[B]\mathrm{dV}\{P_e\} + \\ + \int_S \rho_0\{\delta P_e\}^T\{N\}\{n\}^T\{N'\}^T\mathrm{dS}\,\{\ddot{u}_e\} = \{0\}\end{gathered} \tag{11}$$

Taking into account that some variables are constants or can be considered constants, equation (11) becomes,

$$\begin{gathered}\frac{1}{c^2}\int_V\{N\}\{N\}^T\mathrm{dV}\{\ddot{P}_e\} + \int_V[B]^T[B]\,\mathrm{dV}\{P_e\} + \\ +\rho_0\int_S[N]\,[n]^T\{N'\}^T\mathrm{dS}\{\ddot{u}_e\} = \{0\}\end{gathered} \tag{12}$$

Which, in matrix form, can be written as:

$$[M_e^P]\{\ddot{P}_e\} + [K_e^P]\{P_e\} + \rho_0[R_e]^T\{\ddot{u}_e\} = \{0\} \tag{13}$$

where:
- $[M_e^P] = \frac{1}{c^2}\int_V\{N\}\{N\}^T\mathrm{dV}$ - matrix of fluid masses;
- $[K_e^P] = \int_V[B]^T\,[B]\mathrm{dV}$ - fluid stiffness matrix;
- $\rho_0[R_e] = \rho_0\int_S\{N\}\{n\}^T\{N'\}^T dS$ - matrix of mass coupling.

The final form of the equation that takes into account losses at the interface is:

$$[M_e^P]\{\ddot{P}_e\} + [C_e^P]\{\dot{P}_e\} + [K_e^P]\{P_e\} + \rho_0[R_e]^T\{\ddot{u}_e\} = \{0\} \tag{14}$$

where:
- $[C_e^P] = \frac{\beta}{c}\int_S\{N\}\{N\}^T\mathrm{dS}$ - fluid damping matrix.

The numerical analysis was carried out using the finite element method and the facilities offered by the Ansys program. FLUID 30, a dedicated finite element from the Ansys library, was used to model the acoustic propagation domain represented by air.

FLUID 30 (Figure 3) is a 3D finite element used in the Ansys program for the numerical analysis of fluid dynamics and acoustics. It is a solid element with 8 nodes, designed specifically to model the propagation of acoustic waves in air. The FLUID 30 element can capture the behavior of air at different frequencies and is capable of simulating the transfer of energy and pressure through the fluid medium [7]. The use of FLUID 30 in numerical simulations of acoustic panels allows for an accurate representation of the behavior of air and a precise prediction of the performance of the panel in terms of acoustic isolation and sound transmission.

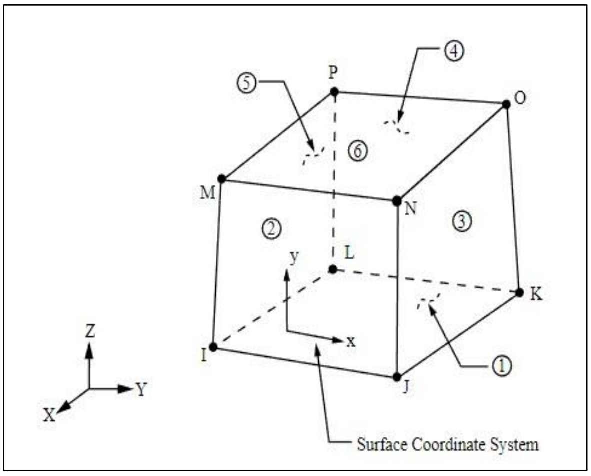


Figure 3. FLUID 30 finite element

The research also included preliminary stages where two other types of finite elements, FLUID 221 and FLUID 220, were tested and depicted in Figure 4. These finite elements were evaluated for their suitability in modeling the acoustic domain and their ability to accurately capture the behavior of sound waves as they propagate through the panel [8]. The results from testing these elements helped to inform the choice of using FLUID 30 for the final analysis.

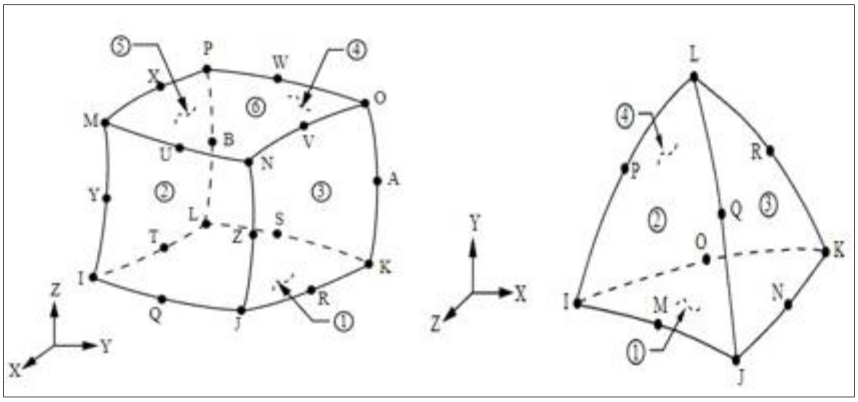


Figure 4. FLUID 220 (a) and FLUID 221 (b) finite elements

The progression of the research was based on the use of the FLUID 30 finite element, as the tests conducted did not result in significant advantages to the use of the other finite elements for the same level of discretization [9]. On the other hand, consideration was given to creating computational models that are accessible to those interested, even in the case of using other software besides Ansys.

The FLUID 30 finite element was used with its two options: the mechanical structure present for the air in the holes and in the proximity of the panel's baffle, and the mechanical structure absent for the rest of the air domain behind the panel [10].

In the tests regarding wave propagation through the holes, the domain behind the panel was limited to 0.1 m, with the main focus being on the domain represented by the air in the holes. In the numerical analysis of the experiment, the domain was extended to 0.5 m behind the panel, in accordance with the conditions of the experiment.

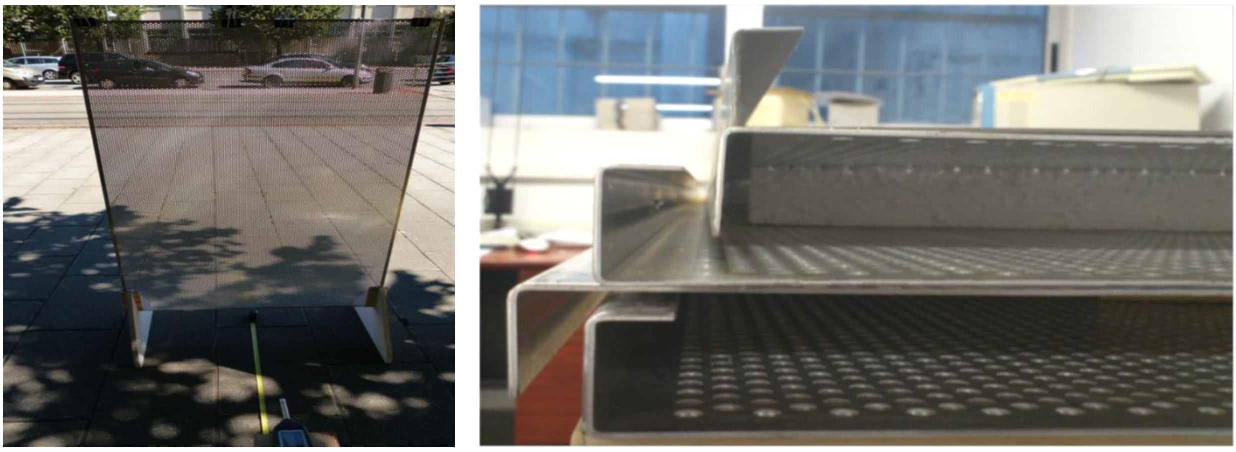
The finite element analysis took into account the justified recommendation from the specialized literature that the finite element size should be less than or equal to the λ/6, where the λ is the length of the considered frequency [11]. This requirement was met by adopting a new, much smaller but constant size of the finite elements for all cases considered, in order to make a comparative analysis of the results. In all cases, the tests for wave propagation through the hole (Figure 2) were done with finite elements with a size of 0.01 m and thus, a λ / Ø ratio of more than 1 was achieved, where Ø is the diameter of the hole.

Regarding the use of boundary conditions, being plane waves, was not necessary the use of special finite elements to avoid reflection of acoustic waves at the domain boundary, such as FLUID 129 and FLUID 130 finite elements from the Ansys library [12].

The 3D finite elements with 8 nodes, referred to as SOLID 185 from the Ansys library, were used to model the mechanical structure of the panel. To avoid reflected waves on the boundary, the acoustic impedance of the respective medium (air) was used along the direction of propagation. The boundary conditions on the other faces of the 3D domain (air and structure) were specified as the normal velocity equal to zero at the respective surfaces, taking into account the plane wave nature of the acoustic waves. The finite element model was loaded with acoustic pressure applied to the entire surface of the structure and air, on the face oriented perpendicular to the direction of wave propagation. This acoustic loading can be done in units of acoustic pressure expressed in decibels (dB) or pressure (Pa) [13].

2.3. Experimental investigation

The experiment on the propagation of acoustic waves through a steel panel with holes with a diameter of 0,03 m and a thickness of 0,0015 m (Figure 5), was carried out within Erasmus program at University of the Basque Country (UPV) from Spain.



a b

Figure 5. The steel panels with holes used in experiment

In Figure 5, the steel panel with the described characteristics in Subsection 2.2 is presented. The noise source had a stationary character and was placed approximately 50 m away from the measurement location. The experimental in measuring the acoustic pressure in front of the panel at its level and 0.5 m behind it. The experimental measurements were performed using a sound level meter, type SOLO 11605. The sound level meter was calibrated before starting the measurements and after completing them.

The experiment presented in Figure 5 has provided valuable validation for the numerical investigation conducted in a previous study. The results obtained from the experiment show that the measured values of acoustic pressure are in good agreement with the simulated values, with acceptable errors.

Based on the validation of the numerical model with the steel panel, the study was extended to investigate the behavior of other materials presented in the previous sections. The successful validation of the model with the steel panel provided confidence in the accuracy of the simulation results and allowed for the investigation of other materials with different properties and behaviors.

2.4. Finite element models

The research on the propagation of acoustic waves through holes was carried out using the finite element model shown in Figure 6, using the following hole diameters: 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, and 90 mm. Owing to the symmetry of the analysis domain, the model presented in Figure 6 and used in the undertaken research is a simplified one, being half of the adopted one [14].

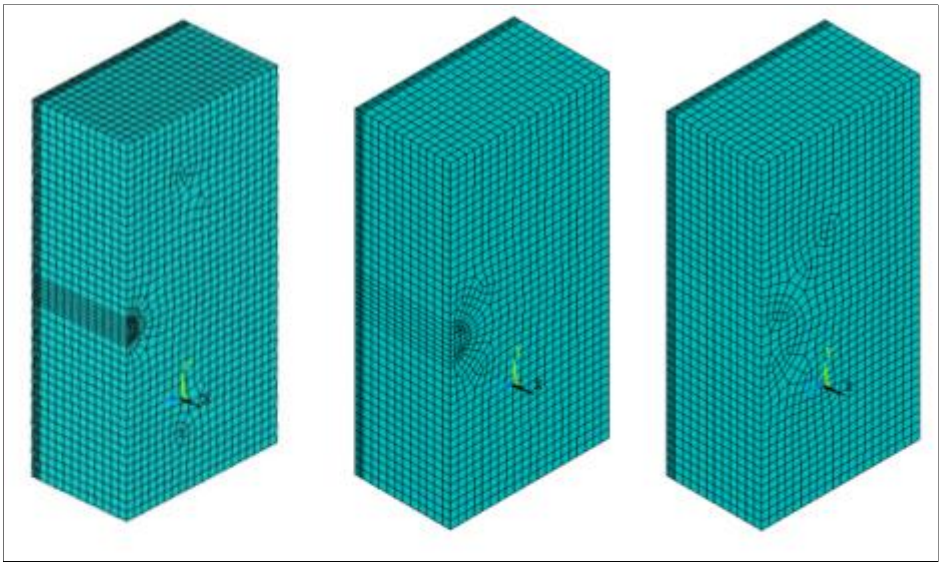


Figure 6. Finite element models for numerical tests

The frequency series considered in the analysis of acoustic waves through holes were: 250 Hz, 500 Hz, 1000 Hz, and 1500 Hz.

The finite element models presented and used by the authors are based on their own experience gained through numerical simulation of experiments carried out in specialized laboratories in Spain.

Based on the results obtained from the experimental investigation and the finite element models presented in Figure 6, numerical simulations were performed for each of the four materials (steel, aluminum, polyethylene and PVC) to evaluate their effectiveness as acoustic protection barriers. The simulations provided a comprehensive understanding of the acoustic performance of the perforated panels made from different materials and with different hole diameters.

3. Results and discussions

The simulations provided a comprehensive understanding of the acoustic performance of the perforated panels made from different materials and with different hole diameters. The results showed that the acoustic properties of the panel were influenced by the material properties, hole diameter and thickness of the panel.

Figure 7 show the numerical results obtained from the finite element simulations of the acoustic pressure inside the perforation at different diameters, focusing on the polyethylene plastic material. The data is plotted for a single frequency of 250 Hz and showcases the changes in acoustic pressure as the diameter of the perforation varies. The results provide insights into the acoustic behavior of the polyethylene plastic material at various perforation sizes and can be useful in the development of effective acoustic protection solutions.

Figure 8 provides a visual representation of the acoustic pressure variation for the polyethylene material, at the same diameter sizes as Figure 7, but at a different frequency, specifically 500 Hz. This data was collected through the numerical simulations conducted using the finite element models, as previously described.

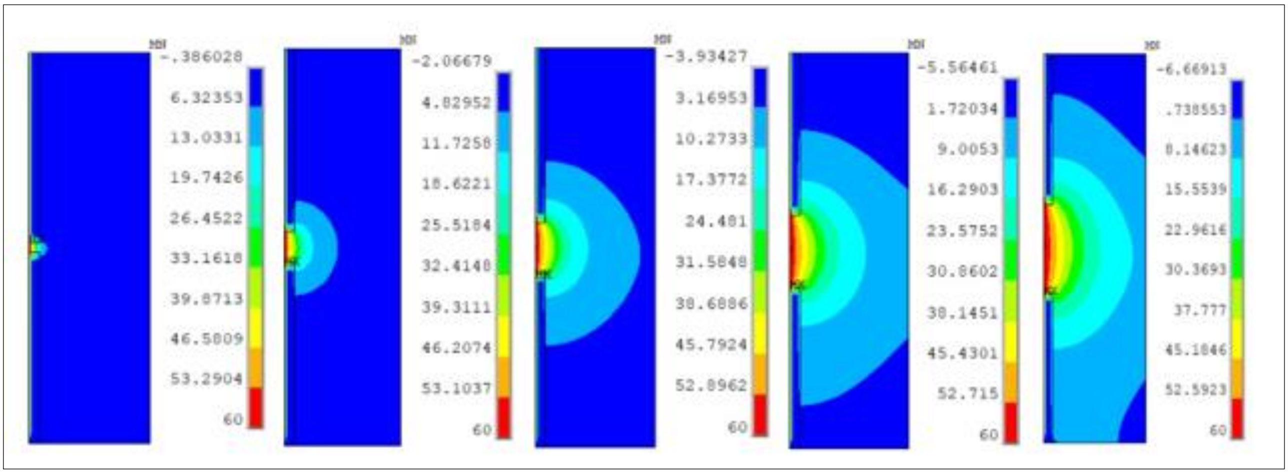


Figure 7. Acoustic pressure for polyethylene at different diameters and f=250 Hz

The visualization of the acoustic pressure patterns across the different diameters and frequencies provides valuable insight into the behavior of the perforated panel, particularly in regards to its acoustic protection properties.

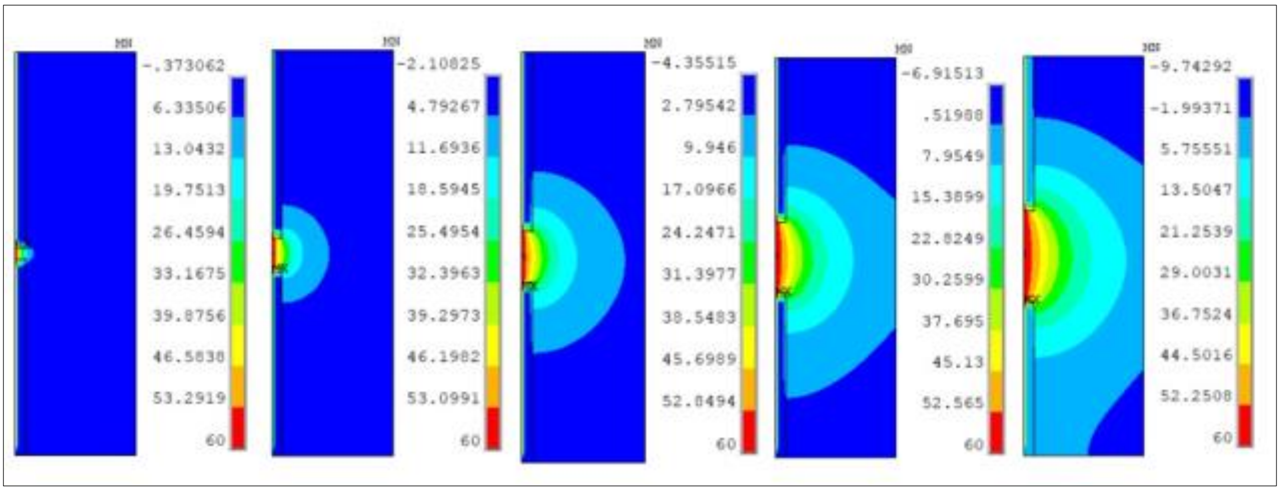


Figure 8. Acoustic pressure for polyethylene at different diameters and f=500 Hz

The values presented in Table 2 reveal slight differences in behavior between the different materials analyzed, but clearly demonstrate the benefits of using plastic materials with lower pressure loss.

Were highlighted only the graphs depicting the variation of acoustic pressure for polyethylene due to its superior behavior in terms of pressure loss compared to the other three materials.

This finding suggests that polyethylene could be a promising material for the development of acoustic protection panels.

Table 2. Acoustic pressure values for steel and polyethylene, depending on the distance

x[m] / Ø [mm]	**Steel**				**Polyethylene**			
	250 Hz		500 Hz		250 Hz		500 Hz	
	30 mm	90 mm	30 mm	90 mm	30 mm	90 mm	30 mm	90 mm
0.0000	60	60	60	60	60	60	60	60
0.0025	53.392	57.484	53.486	57.541	53.398	57.490	53.487	57.543
0.0050	46.964	54.978	47.13	55.07	46.974	54.990	47.133	55.074
0.0075	40.899	52.496	41.12	52.603	40.914	52.513	41.124	52.609
0.0100	35.353	50.036	35.613	50.141	35.372	50.058	35.618	50.149
0.0200	19.31	40.827	19.619	40.791	19.339	40.868	19.627	40.807

0.0300	11.548	32.918	11.819	32.605	11.578	32.972	11.829	32.627
0.0400	7.7755	26.504	7.985	25.853	7.8035	26.565	7.9957	25.881
0.0500	5.5771	21.46	5.7185	20.454	5.6015	21.522	5.7299	20.486
0.0600	4.1527	17.533	4.2261	16.18	4.1733	17.592	4.238	16.215
0.0700	3.1679	14.466	3.1755	12.784	3.1847	14.52	3.1879	12.821
0.0800	2.4561	12.058	2.4014	10.068	2.4691	12.104	2.414	10.107
0.0900	1.9288	10.164	1.8156	7.8904	1.9382	10.201	1.8284	7.93
0.1000	1.5363	8.6861	1.3682	6.1532	1.5423	8.714	1.3811	6.1927
0.1100	1.2503	7.5641	1.0303	4.7935	1.253	7.5824	1.0432	4.8321
0.1200	1.056	6.764	0.78626	3.7744	1.0557	6.7725	0.79903	3.8115

From the comparative analysis of the graphical representations of pressure variation inside the hole for steel (Figure 9a) and polyethylene (Figure 9b), a very high similarity in the propagation of acoustic waves under the same conditions is observed, with the only difference being the panel material.

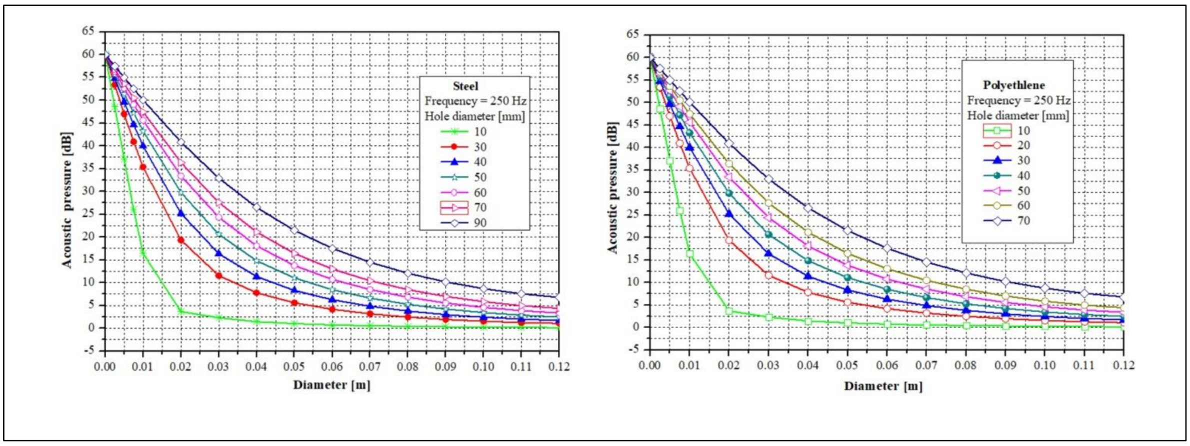


Figure 9. The pressure variation inside the hole for steel (a) and for polyethylene (b) at f=250 Hz

The same can be observed in Figure 10, which presents the graphical representation of pressure variation in the hole for steel (Figure 10a) and polyethylene (Figure 10b) at a frequency of 500 Hz.

The pressure values for aluminum and PVC panels are presented in Table 3. Similar to Table 2, there are small differences in behavior between the materials considered.

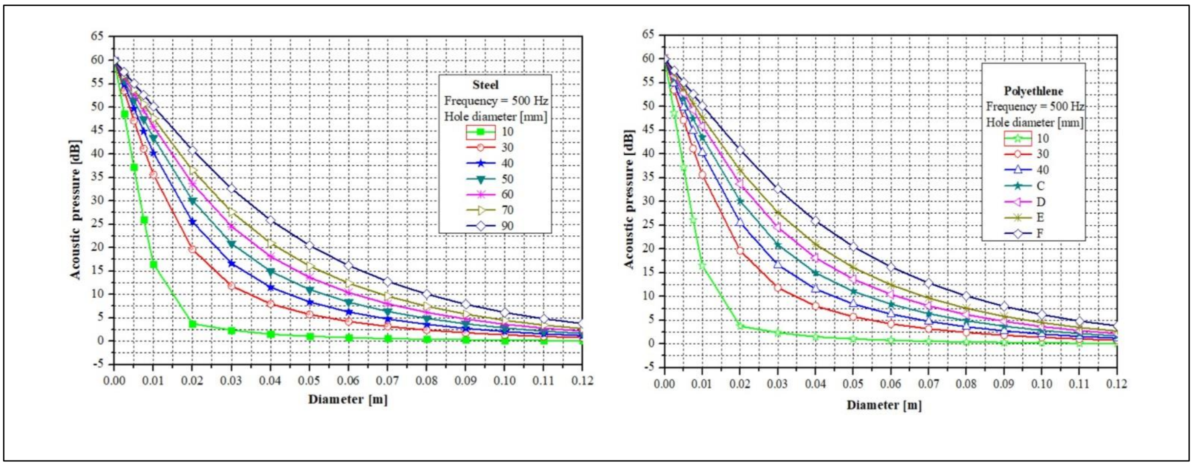


Figure 10. The pressure variation inside the hole for steel (a) and for polyethylene (b) at f=500 Hz

Table 3. Acoustic pressure values for aluminium and PVC, depending on the distance

x[m] / Ø [mm]	Aluminium				PVC			
	250 Hz		500 Hz		250 Hz		500 Hz	
	30 mm	90 mm	30 mm	90 mm	30 mm	90 mm	30 mm	90 mm
0.0000	60	60	60	60	60	60	60	60
0.0025	53.394	57.487	53.484	57.540	53.391	57.486	53.490	57.542
0.0050	46.967	54.984	47.126	55.068	46.962	54.982	47.137	55.073
0.0075	40.904	52.504	41.115	52.601	40.897	52.502	41.131	52.607
0.0100	35.359	50.046	35.606	50.138	35.35	50.043	35.626	50.147
0.0200	19.320	40.847	19.609	40.785	19.307	40.842	19.638	40.802
0.0300	11.560	32.946	11.809	32.597	11.549	32.942	11.840	32.619
0.0400	7.7882	26.539	7.9761	25.845	7.7804	26.537	8.004	25.871
0.0500	5.5900	21.500	5.7112	20.448	5.586	21.502	5.736	20.475
0.0600	4.1656	17.576	4.2202	16.175	4.1652	17.584	4.2423	16.202
0.0700	3.1808	14.512	3.1711	12.781	3.1834	14.525	3.1908	12.807
0.0800	2.4688	12.105	2.3983	10.067	2.474	12.123	2.4160	10.092
0.0900	1.9413	10.212	1.8137	7.8907	1.9486	10.233	1.8297	7.9145
0.1000	1.5486	8.7346	1.3673	6.1551	1.5575	8.7600	1.3820	6.1774
0.1100	1.2623	7.6127	1.0303	4.7967	1.2723	7.6406	1.0439	4.8174
0.1200	1.0677	6.8124	0.78698	3.7788	1.0785	6.8419	0.79982	3.7978

4. Conclusions

This study has evaluated the performance of the acoustic panels under various conditions, including variations in sound source distance, sound source frequency and sound wave propagation direction. The numerical analysis was performed using finite element 3D elements, called SOLID 185 from the Ansys library. The study considered several series of frequencies, including 250 Hz, 500 Hz, 1000 Hz, and 1500 Hz, and different perforation diameters, ranging from 30 mm to 90 mm. The results of these evaluations were then compared to each other to determine which material and design offered the best sound insulation performance. The simulations showed that polyethylene exhibited the best behavior in terms of pressure loss, indicating that it is the most suitable material for constructing panels that require minimal pressure loss. The graphs of pressure variation for polyethylene were highlighted in this study as they provided a clear visual representation of the best performing material in terms of pressure loss compared to other materials. The data was supported by tables that quantitatively compared the behavior of different materials, which helped to demonstrate the advantages of using plastic materials with lower pressure loss. Furthermore, the study observed the similarity of acoustic wave propagation for steel and polyethylene, emphasizing the importance of the material used in panel construction. This finding highlights the need to select appropriate materials for panel construction that can minimize pressure loss and acoustic wave propagation. Additionally, the findings of this research are expected to be of interest to engineers, architects, and other professionals involved in the design and construction of buildings and other structures that require effective sound insulation solutions [15]. The results will also be of use to manufacturers of acoustic panels, who can use the information to develop new products or improve existing ones. However, further experimental validation is needed to confirm these results and ensure their practical applications. Moreover, the numerical analysis and simulations presented in this study provide a valuable tool for designing and optimizing acoustic protection panels, allowing for cost-effective and efficient solutions to be developed. The models and methodology of the use of plastics, compared to metallic materials, are also valid for the newest types of materials, with plastic components, as is the case with functionally graded materials [16].

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Manuscript received: 23.02.2023