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Research Paper

Influence of the Plaster Physical Structure on Indoor Acoustics

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The article presents the main results of research on plaster samples with different physical parameters of their structure. The basic physical parameter taken into account in the research is plaster aeration. Other physical parameters were also considered, but they play a minor part. The acoustic properties of the modified plaster were measured by the sound absorption coefficient; the results were compared with the absorption coefficient of standard plaster. The influence of other physical, mechanical and thermal properties of plaster was not analyzed. The effect of modified plasters on indoor acoustics was also determined. To this end, an acoustic problem with impedance boundary conditions was solved. The results were achieved by the Meshless Method (MLM) and compared with exact results. It was shown that the increase in plaster aeration translated into an increase in the sound absorption coefficient, followed by a slight decrease in the noise level in the room. Numerical calculations confirmed this conclusion.

Keywords: plaster; aeration; sound absorption coefficient; acoustic impedance; architectural acoustics.

1. Introduction

The influence of wall impedance on the room acoustic climate is an important real problem, and it is theoretically interesting. To improve the acoustic indoor climate, various sound-absorbing materials are placed on the walls of the room (CUCHARERO *et al.*, 2019). Appropriate distribution of the proper sound absorbing material on the walls of public facility improves the acoustics in the theater, cinema and so on. This is enforced by environmental and public health legislations.

Some natural porous granular materials are shown to have good sound absorption and structural strength; these are sands, clay, expanded minerals, gravel soils, etc. These materials combine good acoustic properties, sometimes mechanical strength, and above all very low production costs. The acoustic and mechanical properties of these materials were improved in various ways. It may be done for example by the addition of ultra-fine sand (SHEBL *et al.*, 2011), volcanic pearlite with nanoparticles of precipitated calcium carbonate (BONFIGLIO, POMPOLI, 2007), rubber waste (recycled tires, STANKEVIČIUS *et al.*, 2007), short-fibre reinforcement (KULHAV *et al.*, 2018). These types of materials are considered as an alternative to sound-absorbing foam materials.

In this paper the modified micro-structured plaster is examined in depth. Aeration is one of the main directions of the modification; preliminary studies were conducted in (BRAŃSKI *et al.*, 2013). The purpose of the work is to analyze the effect of plaster aeration, through its absorption coefficient, on the room acoustics. For this purpose, an acoustic boundary problem with impedance boundary conditions is considered. It is assumed that the walls of the room are covered with plaster (they are impedance) and the floor is hard. So, the knowledge of the sound absorption coefficient or acoustic impedance of the plaster is needed. There are many techniques for obtaining this data (MONDET *et al.*, 2020; PIECHOWICZ, CZAJKA, 2012; 2013), but here is used the tube method described in the norm (ISO 10354-2:1998, 1998).

Another problem is the description of the acoustic field in a room with impedance walls. To this end, to solve the problem several methods were applied, for example exact one (Brański *et al.*, 2017) and several numerical methods (Brański, 2013). But numerical methods, based on the wave equation, play a key role in solving complex acoustic problems, e.g. (Meissner, 2012; 2013).

Recently, to the solution of the above problem the MLM has been developed in many versions. In the (You *et al.*, 2020) instead of point collocation in the classical formulation, the weak variational formulation in Galerkin's version was used. Radial Basis Functions (RBFs) are both the basis and the weight. Instead of the global version of Galerkin, the local version was used and the advantage of this method over classic Finite Element Method (FEM) was pointed out.

The MLM method can also be generated without RBF. For this purpose in (Qu, 2019) and (Qu, He, 2020) the Finite Difference Method (FDM) was used. But this method gives the solution in the form of discrete values. It is not convenient for engineers, because the solutions of the problem at each point of the domain requires additional approximation. Moreover, FDM is not effective at high acoustical frequencies.

MLM is also part of hybrid methods. In the article (Li *et al.*, 2020) in the standard FEM, instead of polynomial interpolation on elements, interpolation with the base RBF on triangular elements was used. The advantage of the new FEM version has been demonstrated, especially in external acoustic problems.

There are also a large number of other approaches to indoor acoustics. The most advanced mathematically are those based on the fundamental solution (FS) of the differential equation of the boundary problem (Qu *et al.*, 2019) or integral solution (Chen *et al.*, 2019; Chen, Li, 2020); integral solutions also contain the FS. The FS in singular and this is the basic difficulty in calculating the appropriate integrals. The undoubted advantage of such solutions is reducing the problem to operation on the boundary, which reduces the problem to be solved by one order.

However, the most useful and the state-of-the-art methods are MLM with RBF (Prędka *et al.*, 2020, Prędka, Brański, 2020; Brański, Prędka, 2018). In these articles adapted MLM is used to solve the boundary acoustic problem. Finally, the influence of the plaster aeration and plaster thickness on the interior acoustic field is described.

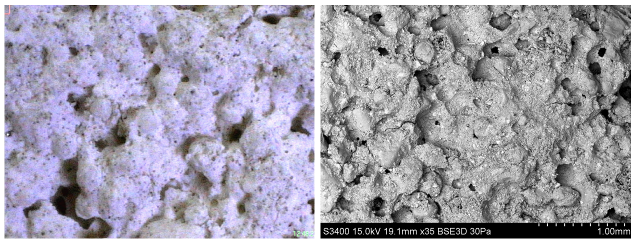
2. An aeration of the plaster

The basis for obtaining modified plaster is standard plaster. The main physical parameters of the standard plaster are porosity, density, particle size, and so on. The first two physical parameters, i.e. porosity and density, are changed by aeration. Hence, standard and modified plasters are made of the same components. In tested samples the aeration is achieved by proper mixing of the components; other aeration methods are also possible. In this way aerations $a = 50\%$, $a = 60\%$, and $a = 70\%$, are achieved.

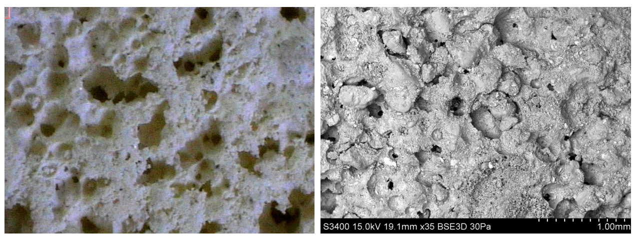
3. Measurement of the absorption coefficient

To measure the sound absorption coefficient α of the plaster sample, an impedance Tube Kit (50 Hz to 6.4 kHz) type 4206 is used. The considered frequency range has been divided in two subranges: 50–1500 Hz (measurement results in large tube – shorter curves in Figs 2–4) and 500–6400 Hz (measurement results in small tube – longer curves in Figs 2–4). As can be seen the frequency subranges overlap. In the case of plasters with above aerations, absorption coefficients α_{50}, α_{60}, and α_{70} are measured respectively. For comparison, an absorption coefficient α_S of the standard plaster (with sand) of constant thickness is added. Pictures of plasters surfaces are shown in Fig. 1. Results of absorption coefficients are depicted in Figs 2–4. Detailed results are presented in Table 1.

a)



b)



c)

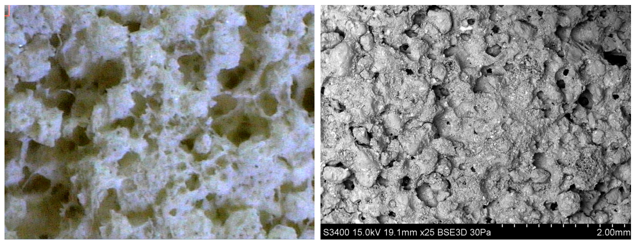


Fig. 1. Photos of the plaster surfaces for different aeration: a) $a = 50\%$, b) $a = 60\%$, c) $a = 70\%$.

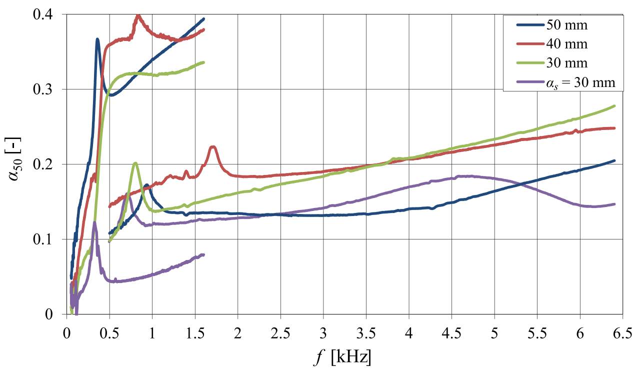


Fig. 2. Absorption coefficient α_{50} *versus* frequency f with different sample thickness h.

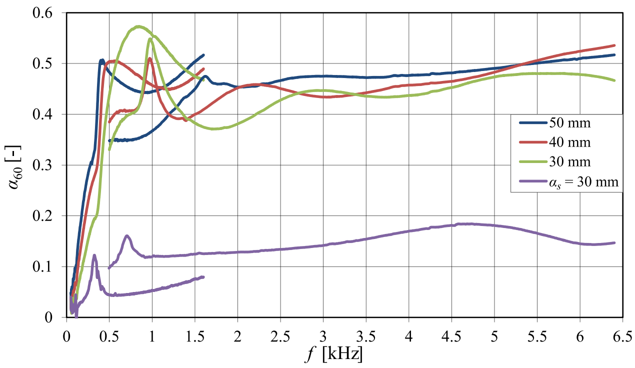


Fig. 3. Absorption coefficient α_{60} *versus* frequency f with different sample thickness h.

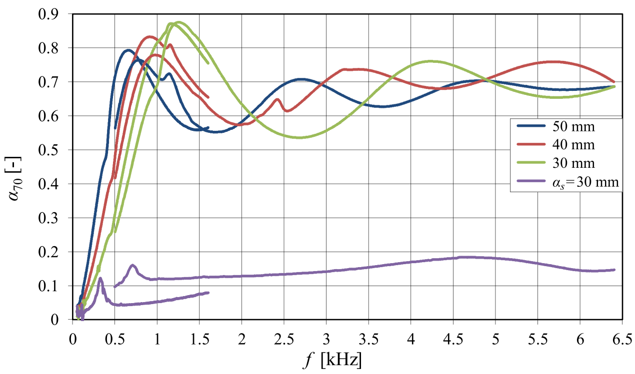


Fig. 4. Absorption coefficient α_{70} *versus* frequency f with different thickness h.

By analyzing Figs 2–4, the main conclusion can be drawn, i.e. if the aeration increases, the sound absorption coefficient also increases. This conclusion is obvious and is consistent with the physical causes of the sound absorption effect of porous materials. However, as can be seen from Table 1, some value of $\alpha < 0.5$, and therefore plaster even with $a = 50\%$ aeration, is not sound-absorbing material. Table 1 also shows that the influence of sample thickness h on the absorption coefficient α is small; generally α increases slightly with increasing thickness h; deviation from this rule may be due to a measurement error.

Table 1. The value of for different thickness of the sample h.

h [mm]	f [Hz]					
	125	250	500	1000	2000	4000
	s					
30	0.0176	0.0512	0.0710	0.0866	0.1285	0.1699
40	0.0173	0.047	0.0761	0.0983	0.1716	0.1887
50	0.0154	0.0516	0.0531	0.0718	0.1114	0.1507
	α_{50}					
30	0.0381	0.0842	0.1993	0.2451	0.1619	0.2084
40	0.0617	0.1560	0.2513	0.2724	0.1740	0.2075
50	0.1179	0.2006	0.2004	0.2482	0.1344	0.1405
	α_{60}					
30	0.0497	0.1520	0.3843	0.5489	0.3811	0.4372
40	0.0871	0.2262	0.4442	0.4775	0.4518	0.4575
50	0.1253	0.2812	0.4155	0.4060	0.4536	0.4765
	α_{70}					
30	0.0418	0.1781	0.2863	0.7550	0.6339	0.7488
40	0.0598	0.1781	0.4470	0.8010	0.5744	0.6950
50	0.0982	0.2868	0.6409	0.6803	0.5835	0.6453

4. Boundary acoustic problem with impedance boundary conditions

To determine the suitability of modified plasters, the acoustic field in the room is calculated with impedance conditions on the walls expressed by the sound absorption coefficient α. The problem is chosen so that it can be solved exactly (Brański *et al.*, 2017). An approximate solution to this problem is given in (Brański, Prędka, 2018; Prędka, Brański, 2020), but for other coefficients α than those obtained for plasters. An approximate solution was achieved by the MLM method adapted to such boundary problems with Hardy's non-singular radial base functions (H-RBF). For simplicity, the 2D space is considered sufficient for qualitative analysis of the problem.

Let be an acoustic boundary problem in 2D; such geometry can be considered as a cross section of a certain room. In the steady state, the mathematical model of such a problem constitutes the Helmholtz equation and Robin and Neumann boundary conditions, i.e. acoustic boundary conditions

$$\mathsf{L}u(\mathbf{x}) = \Delta u(\mathbf{x}) + k_f^2 u(\mathbf{x}) = f(\mathbf{x}), \quad \mathbf{x} = \mathbf{x}' \in \Omega, \quad (1)$$

where $u(\mathbf{x})$ is the acoustic potential, k_f is the wave number, $k_f = \omega_f/c$, $\omega_f = 2\pi f$ is the angular exciting frequency f, $f(\mathbf{x})$ is the given function; it represents an acoustic source and in 2D it is given by $f(\mathbf{x}) = AH_0^{(2)}(k_f r)$, i.e., the 0-order Hankel function of the second kind (McLachlan, 1955), A is an intensity of the source.

In practice, the floor perfectly reflects sound (Neumann state ($\mathbf{N}$)), but the walls and ceiling are acoustically impedance (Robin ($\mathbf{R}$) conditions), so,

$$D_n u(\mathbf{x}) = 0, \quad \mathbf{x} \in \mathbf{N}, \tag{2}$$

$$D_n u(\mathbf{x}) + z_0(\mathbf{x}) u(\mathbf{x}) = 0, \quad \mathbf{x} \in \mathbf{R}, \tag{3}$$

where $z_0(\mathbf{x}) = (\omega\rho)/z(\mathbf{x})$ and D_n is the normal derivative directed outside of the domain.

The $z(\mathbf{x})$ is the acoustic impedance of the plaster and it is expressed *via* the absorption coefficient $\alpha(\mathbf{x})$ (Meissner, 2016; Piechowicz, Czajka, 2012; Kuttruff, 2000),

$$z(\mathbf{x}) = \rho c \frac{1 + (1 - \alpha(\mathbf{x}))^{1/2}}{1 - (1 - \alpha(\mathbf{x}))^{1/2}}. \tag{4}$$

5. Discretization of the boundary problem via MLM

The approximate solution of the problem is assumed as the series,

$$\widetilde{u}(\mathbf{x}') = \sum_v a_v \mathsf{R}(r_v'), \qquad r_v' = |\mathbf{s}_v - \mathbf{x}'|, \tag{5}$$

where a_v are certain coefficients, $\mathsf{R}(r_v)$ is Hardy-RBF $R(r) = (-1)^{\lceil\beta\rceil}(C^2 + r^2)^\beta$, $C > 0$, $\beta > 0$, $\beta \notin \mathbf{N}$, $\lceil\beta\rceil$ means the smallest integer, larger than β, C is the shape parameter (Prędka, Brański, 2020), $\mathbf{s}_\nu \in \overline{\Omega} = \Omega \cup \Gamma$, $\mathbf{x}' \in \Omega$, Fig. 5.

To calculate a_v, first in the domain $\overline{\Omega}$, the set of collocation points $\{\mathbf{x}_\mu\}$ is selected, where $\mu = 1, 2, ...,$ $m = n$, $\mathbf{x}_\mu' \in \Omega$, $\mathbf{x}_\mu \in \Gamma$, Fig. 5. Both kinds of points (collocation and influence) are selected in this same places. It isn't a problem because Hardy-RBF isn't singular. Next, the solution $\widetilde{u}(\mathbf{x}')$ substitutes to Eqs (1)–(3). Hence,

$$\sum_v a_v \left(D_x^2 \mathsf{R}(r_{v\mu}') + D_y^2 \mathsf{R}(r_{v\mu}') + k^2 \mathsf{R}(r_{v\mu}')\right) = f(\mathbf{x}_\mu'), \tag{6}$$

$$\sum_v a_v D_n \mathsf{R}(r_{v\mu}) = 0, \quad \mathbf{x}_\mu \in \mathbf{N}, \tag{7}$$

$$\sum_\nu a_\nu \left(D_n \mathsf{R}(r_{\nu\mu}) + z_0(x_\mu)\mathsf{R}(r_{\nu\mu})\right) = 0, \qquad \mathbf{x}_\mu \in \mathsf{R}, \qquad r_{\nu\mu}' = |\mathbf{s}_\nu - \mathbf{x}_\mu'|. \tag{8}$$

Derivatives $D_x^2(\cdot)$ with respect to $\mathbf{x}$ should be understand as derivative with respect to $\mathbf{x}_\mu'$ and so on. The versor $\mathbf{n}$ is defined at $\mathbf{x}_\mu$, it is perpendicular to the boundary Γ and is directed outside the domain Ω.

6. Numerical calculations

The acoustic pressure is defined as $p(\mathbf{x}) = i\rho\omega u(\mathbf{x})$, $\mathbf{x} = \mathbf{x}' \in \Omega$, where ρ is the air density, $i = \sqrt{-1}$. Next, the sound pressure level is $L(\mathbf{x}) = 10\log(p(x)/p_0)^2$, where $p_0 = 2 \cdot 10^{-5}$ Pa. Further, the average sound pressure level L_m plays an important role, therefore

$$p_m = 1/n_i \sum_i p(x_i), \quad L_m(\mathbf{x}) = 10\log(p_m/p_0)^2, \tag{9}$$

where $i = 1, 2, ..., n_i$ is the number of calculation points, $\{\mathbf{x}_i\} \in \Omega$.

All calculations are made on condition $\varepsilon_m \le 5\%$ (Prędka, Brański, 2020), where

$$\varepsilon_m = \left|L_m - \widetilde{L}_m / L_m\right| \cdot 100\% \tag{10}$$

and $\widetilde{L}_m$ is an approximate solution, L_m is the exact solution (Brański *et al.*, 2017).

In addition, other values $\rho = 1.205\ \text{kg/m}^3$, $c = 344$ m/s, $\{a_x, b_x\} = \{0, 5\}$ m, $\{a_y, b_y\} = \{0, 2.5\}$ m, $\mathbf{x}_0 = \{x_0, y_0\} = \{2.5, 1.25\}$ m is the source location point; the remaining symbols are shown in Fig. 5.

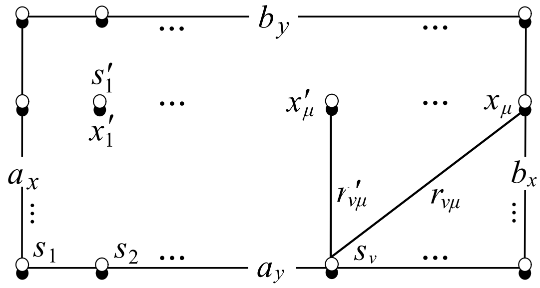


Fig. 5. Distribution of influence points "∘" and collocation points "•".

Assuming $\varepsilon_m \le 5\%$ given by Eq. (10), solution parameters are found and they are the number of elements in the series and distribution of influence points. Here, the latter parameter is omitted assuming an even distribution of influence points. Then $L(\mathbf{x})$ is calculated for the standard plaster $L_S(\mathbf{x})$ and aerated plasters, hence $L_{50}(\mathbf{x})$, $L_{60}(\mathbf{x})$ and $L_{70}(\mathbf{x})$ respectively. For selected frequencies $f = \{250, 1000, 4000\}$ Hz and the sample thickness $h = 30$ mm, the selected $L(\mathbf{x})$ are shown in Figs 6–8. Furthermore, average sound pressure levels $\widetilde{L}_m$ for all types of plasters and selected frequencies are shown in Table 2.

Table 2. The $\widetilde{L}_m$ for all types of plasters, $f = \{250, 1000, 4000\}$ Hz and $h = 30$ mm.

	α [–]	L_m [dB]
s	0.0512	75.4849
50%	0.0842	75.4384
60%	0.1520	75.3451
70%	0.1781	75.3099
1000 Hz		
s	0.0866	75.3244
50%	0.2451	75.2105
60%	0.5489	75.0269
70%	0.7550	74.919
4000 Hz		
s	0.1699	74.9837
50%	0.2084	74.9336
60%	0.4372	74.7571
70%	0.7488	74.6478

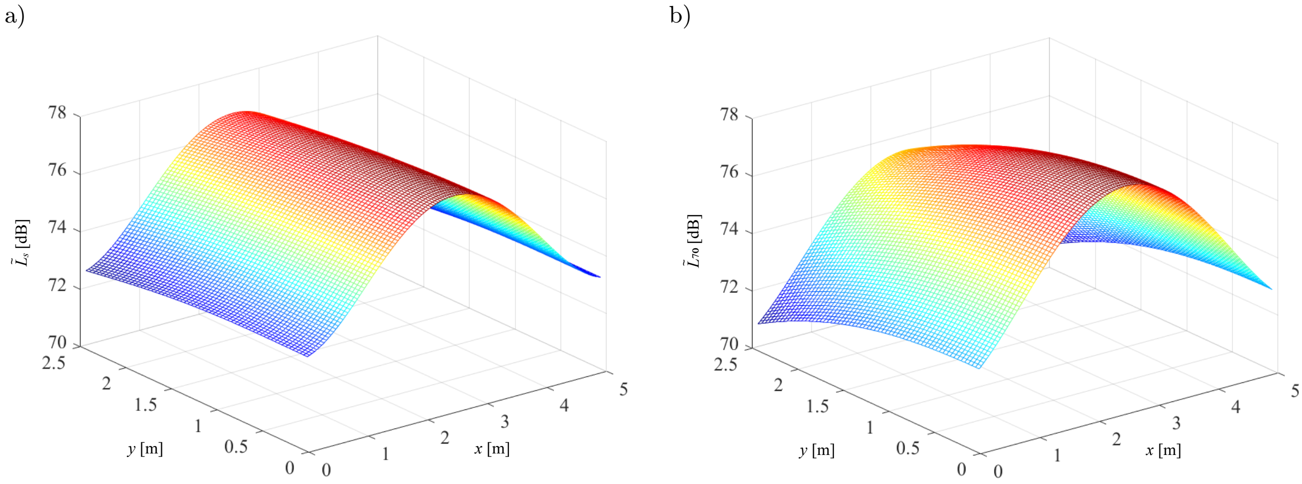


Fig. 6. The $L(\mathbf{x})$ for f = 250 Hz: a) standard, b) a = 70%.

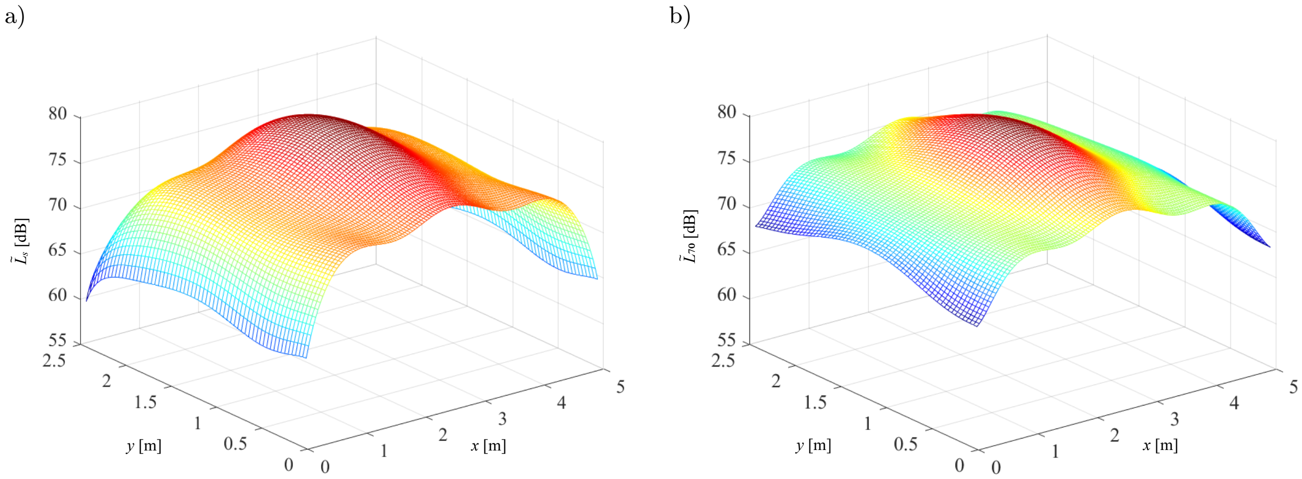


Fig. 7. The $L(\mathbf{x})$ for f = 1000 Hz: a) standard, b) a = 70%.

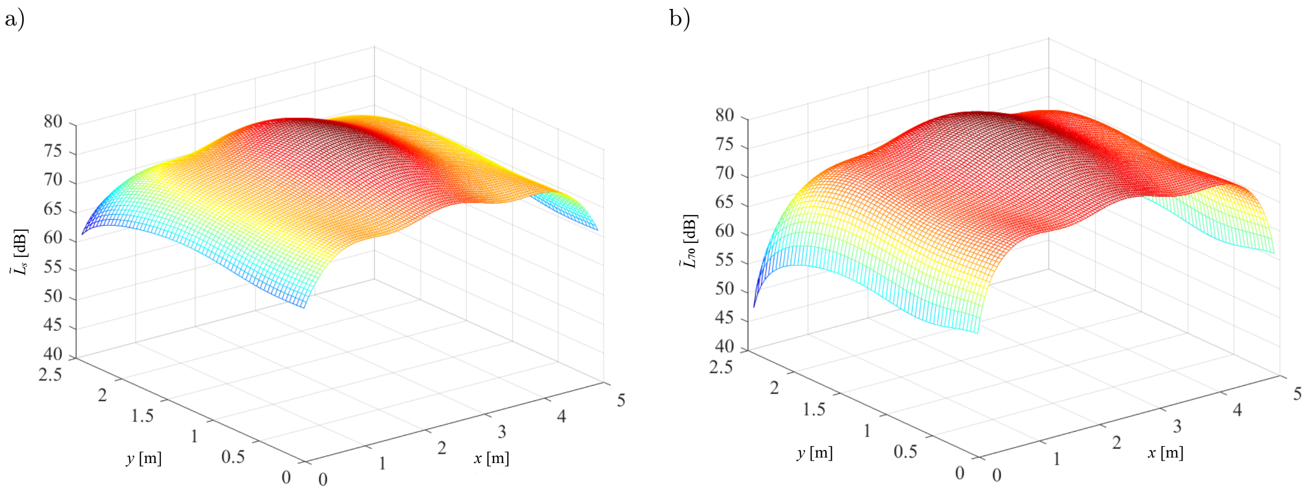


Fig. 8. The $L(\mathbf{x})$ for f = 4000 Hz: a) standard, b) a = 70%.

The analysis of the figures shows that the increase in aeration improves sound absorption and it is clearly visible near the walls and ceiling on which the plaster is applied. This absorption increases with increasing aeration (drawings with aeration a = 50% and a = 60% are omitted).

The increase in sound absorption near the walls covered with plaster does not significantly translate into a decrease in the average sound level in the domain. Table 2 shows that, compared to the standard plaster for f = 4000 Hz, even plaster with aeration a = 70% slightly reduces the value L_m.

7. Conclusions

The main conclusions that are drawn from the current studies can be enumerated.

1) The sound absorption of the modified plaster increases as aeration increases and this is caused by the increase in the porosity. However a significant increase in aeration does not cause a significant increase in sound absorption and it isn't suitable to use as the main acoustical material.
2) The increase in the thickness of the aerated plaster layer causes only a slight increase in sound absorption.
3) Modification of plaster by aeration causes deterioration of physical-mechanical properties such as compression.
4) Despite the drawbacks, aerated plasters can be used in buildings where historical architecture should be preserved, e.g. churches, historic buildings, theaters. In addition, it can also be used instead of suspended ceilings, for example in conference rooms and classrooms.
5) Considered plasters give the opportunity to create spatial absorbing structures by applying the plaster to openwork structures made of wire or plastic.

The conclusions ought to be useful to acousticians and interior designers.

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