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Research Paper

Mathematical modeling of sound insulation for sound suppressing lightweight structured panels (SSLWSP)

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Abstract

The article presents SSLWSP panels, the feature of which is a small weight and good soundproofing properties. The article acquired the model of sound insulation for SSLWSP panels. The modeling of sound insulation is based on the sound-permeability model of thin isotropic sheet material, from which SSLWSP panels are made. An experimental verification of the obtained sound insulation model showed the convergence of experimental and theoretical values. The best convergence of theoretical and experimental data falls on the frequencies corresponding to a speech range.

Keywords: *Soundproofing; Damping; Noise; Noise Protection; the Intensity of Sound Streams; Sound Permeability.*

1. Introduction

The modern techno sphere creates sound streams in the course of its functioning, which have pleasant sounds that normalize the work of a human body. Besides, there is a considerable number of audio streams carrying useful information, but there are sound streams that are devoid of information and unpleasant for perception i.e. noise. The manifestation of noise harmful effect on a human body is very diverse [1]. Therefore, the protection from noise is an urgent problem currently. Various methods are used to solve this problem, among which one can distinguish soundproofing.
The methods of soundproofing assume the placement of barriers (acoustic fencing) between a sound source and a man [2]. The authors developed a sound-suppressing lightweight structured panel SSLWSP [3, 4]. This panel has a rather small surface density (less than 1.2 kg/m2) and it provides sound insulation of more than 30 dB (for an octave band with a mean geometric frequency of 8,000 Hz). Figure 1 shows the appearance of SSLWSP panel, which consists of three elements made from sheet material (Fig. 2) The section of the assembled SSLWSP panel is shown on Fig.

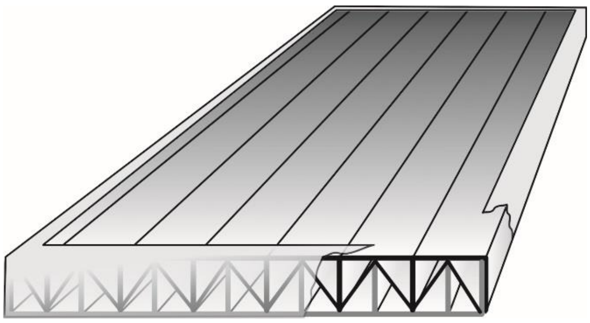

Fig. 1: the Appearance of SSLWSP Panel.

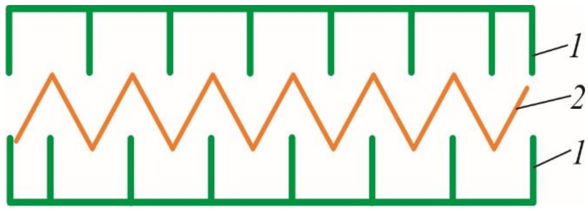

Fig. 2: Main Elements of SSLWSP Panel. 1 – External Element, 2 – Average Layer.

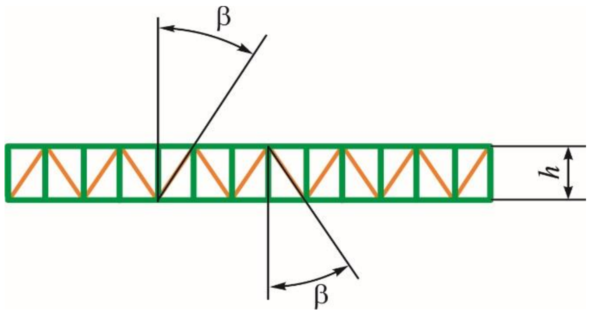

Fig. 3: SSLWSP Panel Section.

Polymers, cardboard, paper, wood, metal, etc. can be used as sheet materials. You need to know their acoustic characteristics, for example, the amount of own sound insulation in the process of SSLWSP panel development during the design stage. The mathematical model of SSLWSP panel sound insulation can be developed on the basis of wave process analysis in its structure. The elements of the structure, made of sheet materials, are thin-walled slabs, which can be considered as an elastic isotropic layer.

2. Mathematical model of sound insulation properties for sheet material

The wave processes occurring in SSLWSP panel are based on the process of a sound wave passage through an elastic isotropic layer. Many of the materials used to make SSLWSP panel have the isotropy property.
Let's consider the process of a sound wave passing through a thin plate (Fig. 4), made of isotropic material. The motion of an elastic isotropic layer is described by the system of equations in Lame form [5]:

$$\left.\begin{aligned}(\lambda+\mu)\frac{\partial}{\partial y}\left(\frac{\partial v}{\partial y}+\frac{\partial \xi}{\partial z}\right)+\mu\left(\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)=\rho_1\frac{\partial^2 v}{\partial t^2}\\(\lambda+\mu)\frac{\partial}{\partial z}\left(\frac{\partial v}{\partial y}+\frac{\partial \xi}{\partial z}\right)+\mu\left(\frac{\partial^2 \xi}{\partial y^2}+\frac{\partial^2 \xi}{\partial z^2}\right)=\rho_1\frac{\partial^2 \xi}{\partial t^2}\end{aligned}\right\} \tag{1}$$

where v, ξ – are the displacements along the corresponding Y and Z axes; $\lambda=\frac{E\sigma}{(1+\sigma)(1-2\sigma)}$ and $\mu=\frac{E}{2(1+\sigma)}$ are the elastic Lame constants; E – the Young modulus, σ – the Poisson coefficient, ρ_1 – the density of a thin plate material.

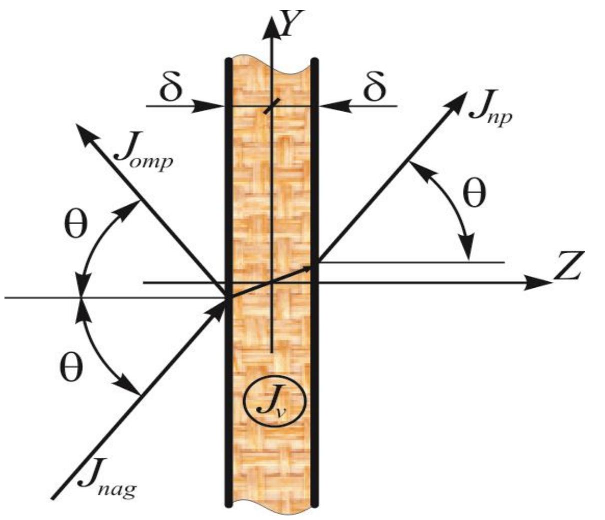

Fig.4: The Scheme of Sound Stream Passage through Sheet Material. δ – Half Of Sheet Material Thickness, θ – The Angle of the Sound Stream Incidence, J_{nag} – The Energy of the Incident Sound Stream, J_{omp} – the Energy of the Reflected Sound Stream, J_{np} – The Energy of the Sound Flow That Passed through the Sheet Material, J_v – the Energy of the Sound Stream Absorbed by Sheet Material.

The consideration of a thin plate material internal friction is performed through the introduction of the complex Young modulus instead of the usual Young's modulus E

$$\overline{E}=E(1+i\eta) \tag{2}$$

Where η the loss factor of a thin plate material is, $i=\sqrt{-1}$ is a fake unit.
The solution of equation system (1) makes it possible to determine the law of a thin plate vibrational motion and, using this solution, it is possible to determine the coefficient of sound permeability τ_θ of sound wave oriented incidence. The coefficient of sound permeability τ_θ can be expressed in terms of sound pressure amplitude ratio in passed wave to the incident wave.

The magnitude of the ratios of sound pressure amplitudes can be determined from the condition of vibrational velocity equality of a thin plate surface and the surrounding air, which is in contact with this plate. The vibrational velocity of a thin plate surface and the air near this plate occurs under the influence of symmetric and anti-symmetric pressures.
The solution of the system (1) allows us to determine the coefficient of sound permeability

$$\tau_\theta=\frac{1}{\left(1+\eta\frac{c_u^4}{c^4}Q(\sin\theta)^4\cos\theta\right)^2+\left(1-\frac{c_u^4}{c^4}(\sin\theta)^4\right)^2(Q\cos\theta)^2} \tag{3}$$

where $Q=\frac{\rho_1(2\delta)f}{\rho\cdot c}$ is a dimensionless complex;
$c_u=\sqrt{\frac{D\omega^2}{\rho_1(2\delta)}}$ is the bending speed of a thin plate surface; c the speed of sound in the air; $D=\frac{E(2\delta)^3}{12(1-\sigma)}$ – the cylindrical rigidity of a thin plate; $f=\frac{\omega}{2\pi}$ – oscillation frequency; ω – the circular frequency of oscillations.
The expression (3) can be somewhat simplified if we take into account the physical properties of the materials used to fabricate SSLWSP panels. In this case, the ratio of the flexural velocity to the sound speed in the air will be very small or $c_u \ll c$, then we will get the following

$$\tau_\theta=\frac{1}{1+(Q\cos\theta)^2} \tag{4}$$

Besides the oriented drop of a sound wave, the most interesting thing is the diffuse drop of sound waves. In the case of sound wave diffuse incidence, we can use the Paris formula [5] to determine the diffuse coefficient of sound permeability

$$\tau_1=\int_0^{\pi/2}\tau_\theta\sin(2\theta)d\theta=\frac{\ln(1+Q^2)}{Q^2} \tag{5}$$

The relation (5) makes it possible to determine the intensity of the passed sound wave through a thin plate

$$\tau_1=\frac{J_{np}}{J_{nag}} \text{ Or } J_{np}=J_{nag}\tau_1, \tag{6}$$

Where J_{np} is the passed wave intensity; J_{nag} is the incident wave intensity.
A sound wave, falling on a thin plate, leads it into an oscillatory motion, which is damped by the surrounding air. The dissipation energy passes to the thermal energy of the environment irrevocably. It was shown in [6] that the value of this energy can be determined on the basis of the loss factor ε, obtained by taking into account the process of damping with ambient air and sound energy absorption in the material itself

$$\varepsilon=\sqrt{\frac{1}{1+\frac{1}{\left(\frac{4}{3}\alpha+\frac{2}{3}Q\right)^2}}}=\frac{J_v}{J_{nag}} \text{ Or } J_v=J_{nag}\varepsilon \tag{7}$$

Where J_v – dissipation energy; α – the coefficient of material sound absorption.

3. Sound insulation mathematical modeling

Figure 5 shows a simplified diagram of a SSLWSP panel with the separation of sheet material three basic layers. The scheme was borrowed from [6]. Each layer of sheet material is a thin plate, for which the basic relationships between the energy fluxes of sound were determined above.

The energy of the incident sound stream J_1 on sheet 1 is distributed in other directions completely, both inside a SSLWSP panel and outside it. The reflected flux intensity J_2 from the sheet 1 is determined from the following formula:

$$J_2 = J_1 - J_3 = J_1 - J_1\tau_1 = J_1(1-\varepsilon) \tag{8}$$

where $J_3 = J_1\tau_1$ is the energy of the past flow through the sheet 1, in accordance with the relation (6).

The losses J_{n1} on the damping by ambient air in sheet 1 are determined on the basis of the relation (7) and make

$$J_{n1} = J_3\varepsilon = J_1\tau_1\varepsilon\,. \tag{9}$$

The intensity of the audio stream falling on sheet 2 will be the following one:

$$J_{1*} = J_3 - J_{n1} = J_1\tau_1 - J_1\tau_1\varepsilon = J_1\tau_1(1-\varepsilon) \tag{10}$$

The reflected sound flow from the sheet 2 is similar to the relation of the form (8) for the intensity and taking into account (10) it will be the following:

$$J_{2*} = J_{1*}(1-\tau_1) = J_1\tau_1(1-\varepsilon)(1-\tau_1) \tag{11}$$

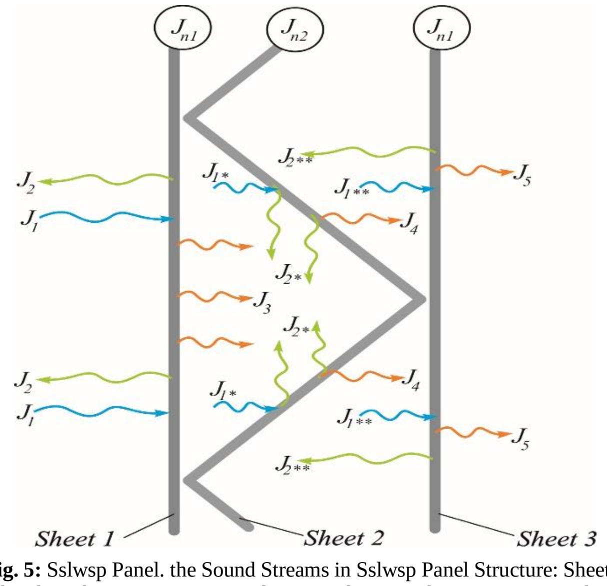

Fig. 5: Sslwsp Panel. the Sound Streams in Sslwsp Panel Structure: Sheet 1 - the Sheet that Perceives an Incident Sound Wave; Sheet 2 - An Inner Sheet; Sheet 3 - the Sheet through Which A Sound Wave Emerges; J_1 - the Main Stream Falling on the Sheet 1; J_2 – the Reflected Flow From the Sheet 1; J_3 – The Flow Passed through the sheet 1; J_{1*} – Поток, Падающий На Лист 2; J_4 – Поток, Прошедший Через Лист 2; J_{2*} – the Stream Falling on the Sheet 2; J_{1**} – the Stream Passed through the Sheet 3; J_{2**} – the Stream Reflected from the Sheet 3; J_5 – the Flow Passed through the Sheet 3; J_{n1}, J_{n2}, J_{n3} – the Losses of Energy From the Damping By Ambient Air, Represented By Sheet 1, 2 and 3, Respectively.

The sound stream passed through the sheet 2, taking account (10), will have the intensity, the formal record of which corresponds to the relation (8)

$$J_4 = J_{1*}\tau_1 = J_1\tau_1(1-\varepsilon)\tau_1 = J_1\tau_1^2(1-\varepsilon) \tag{12}$$

The loss of energy from the damping by the surrounding air will make and will be written in the same way as (9)

$$J_{n2} = J_4\varepsilon = J_1\tau_1^2(1-\varepsilon)\varepsilon\,. \tag{13}$$

A wave intensity incident on sheet 3 is similar to the expression (10)

$$J_{1**} = J_4 - J_{n2} = J_1\tau_1^2(1-\varepsilon) - J_1\tau_1^2(1-\varepsilon)\eta_1 = J_1\tau_1^2(1-\varepsilon)^2 \tag{14}$$

The flow that passed through the sheet 3 will have the following intensity

$$J_5 = J_{1**}\tau_1 = J_1\tau_1^2(1-\varepsilon)^2\tau_1 = J_1\tau_1^3(1-\varepsilon)^2 \tag{15}$$

The loss of energy from damping in the sheet 3 will be the following one:

$$J_{n3} = J_5\varepsilon = J_1\tau_1^3(1-\varepsilon)^2\varepsilon\,. \tag{16}$$

The reflected flux from the sheet 3 will have the following intensity similarly to (11)

$$J_{2**} = J_{1**}(1-\tau_1) = J_1\tau_1^2(1-\varepsilon)^2(1-\tau_1) \tag{17}$$

The flow leaving the sheet 3 has the intensity similar to (14)

$$J_{1***} = J_5 - J_{n3} = J_1\tau_1^3(1-\varepsilon)^2 - J_1\tau_1^3(1-\varepsilon)^2\varepsilon = J_1\tau_1^3(1-\varepsilon)^3 \tag{18}$$

The relationship (18) allows us to determine the coefficient of sound permeability for a SSLWSP panel in general and, consequently, can be written as follows:

$$\tau = \frac{J_{1***}}{J_1} = \frac{J_1\tau_1^3(1-\varepsilon)^3}{J_1} = \tau_1^3(1-\varepsilon)^3 \tag{19}$$

An own isolation of SSLWSP panel will be the following one taking into account (19)

$$R = 10\lg\left(\frac{1}{\tau}\right) = 10\lg\left(\frac{1}{\tau_1^3(1-\varepsilon)^3}\right) = -30\lg(\tau_1(1-\varepsilon))$$

Or

$$R = -30\lg\left[\frac{\ln(1+Q^2)}{Q^2}\left(1-\sqrt{\frac{1}{1+\frac{1}{\left(\frac{4}{3}\alpha+\frac{2}{3}Q\right)^2}}}\right)\right] \tag{20}$$

4. Experimental examination of sound insulation mathematical model

In accordance with [1], using a non-standard method, the sound insulation was determined by the sound pressure in the octave spectrum for the frequencies from 63 Hz to 8000 Hz. The scheme of the experimental unit is shown on Fig. 6. The experimental unit consists of a muffled chamber 2 with an internal sound-absorbing layer and an external sound-insulating layer. The muffled chamber 2 consists of two parts: semi-chambers, between which the test sample 4 was placed. The audio frequency generator 1 formed the necessary sound signal which was reproduced by the sound source The sound passed through the structure 4 was perceived by the microphone 5 connected to the sound level meter 6 (OCTAVA-110A).

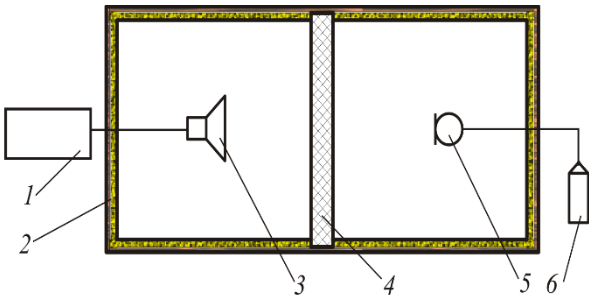

Fig. 6: Experimental unit to determine the Sound Insulation of SSLWSP Panels. 1 - the generator of Sound Frequencies; two - muffled chamber; three - sound source; four - Examined Structure; Five - Microphone; Six - Sound Level Meter.

The studies were carried out for various types of SSLWSP panels, the technical characteristics of which are shown in Table 1. The results of measurements are presented in Table 2 and on Fig. 7, Fig. 8, Fig. 9 and Fig. 10. The analysis of the obtained results shows the convergence of sound insulation and experimental data theoretical values. Especially good convergence of theoretical and experimental values is observed in the following speech frequency range: 250 Hz, 500 Hz, 1000 Hz, 2000 Hz [7]. This type of SSLWSP panels has an increased sound insulation in the octave bands of medium and high frequencies. These panels have structural rigidity, so they can be used alone as a soundproof coating and as a filler for frame panels in various housings, acoustic screens, and the cross-sections of building structures. An optimal thickness of the sheet material for SSLWSP panel production can be calculated by the method presented in [8].

Table 1:.Specifications of SSLWSP Panels

	Panel name	Sheet material	m_p, kg/m²	α	SSLWSP panel specifications $h \cdot 10^3$, m	β	M_p, kg/m²
1	SSLWSP-2	Paper	0,114	0,35	34	45°	1,372
2	SSLWSP-3/1	Paper	0,114	0,23	15	45°	0,909
3	SSLWSP-4	Paper	0,08	0,35	30	45°	0,754
4	SSLWSP-8	Expanded polystyrene	0,1	0,1	36	45°	0,726

Table 2:.Experimental Data of SSLWSP Panel Soundproofing, Db

	Panel name	f – one octave spectrum frequencies, Hz 63	125	250	500	1000	2000	4000	8000
1	SSLWSP-2	4,51	2,71	9,34	8,76	13,33	13,67	26,33	40,29
2	SSLWSP-3/1	1,70	1,34	6,93	6,28	8,79	8,58	19,91	38,87
3	SSLWSP-4	3,29	1,08	6,22	6,21	10,06	14,04	23,00	27,87
4	SSLWSP-8	1,27	0,45	4,38	5,04	6,15	6,37	17,86	20,91

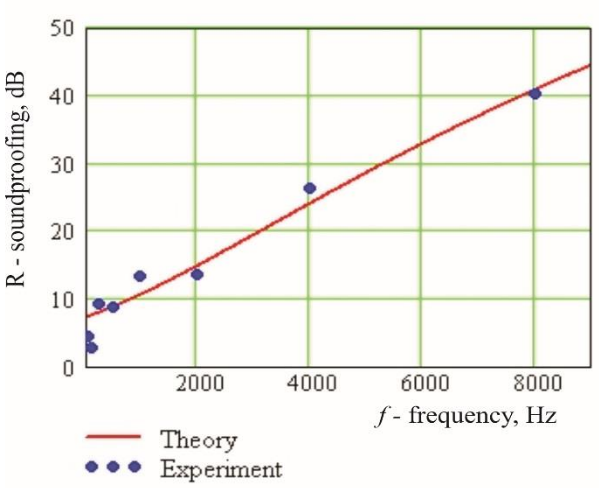

Fig. 7: Representation of Theory and Experiment for SSLWSP-2 Panel.

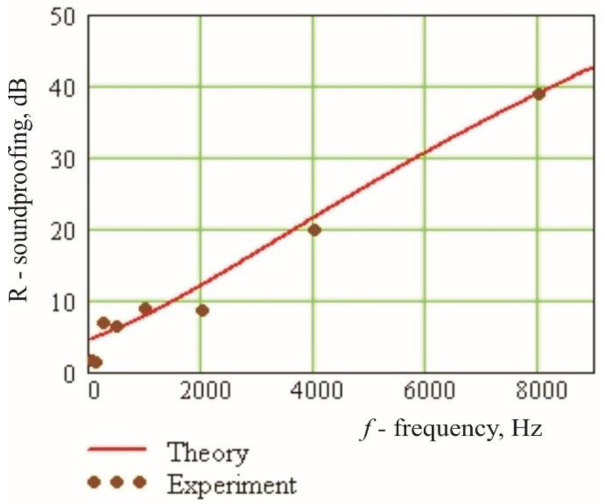

Fig. 8: Representation of Theory and Experiment for SSLWSP-3/1 Panel.

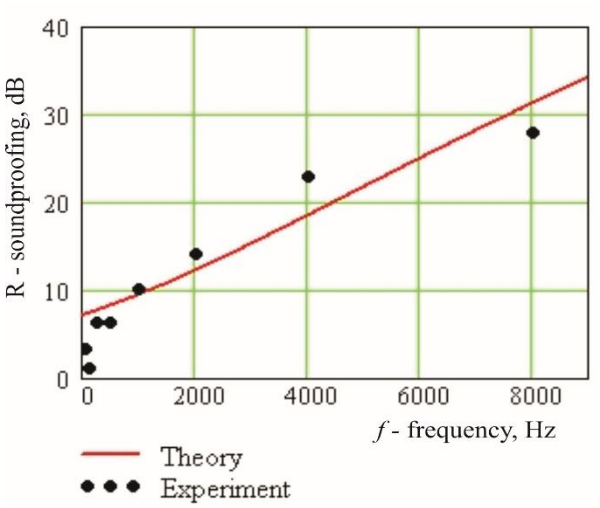

Fig. 9: Representation of Theory and Experiment for SSLWSP-4 Panel.

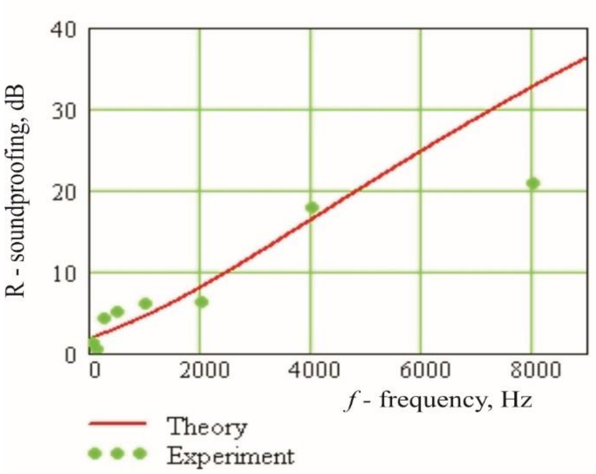

Fig. 10: Representation of Theory and Experiment for SSLWSP-8 Panel.

5. Summary

The obtained sound insulation model for SSLWSP panels can be used at the design stage of these panels to assess the magnitudes of their sound insulation. An experimental verification of the soundproofing model was carried out, and the analysis of the obtained results showed the convergence of theoretical values and experimental data. SSLWSP panels have an increased sound insulation in octave bands of medium and high frequencies. The best convergence of theoretical and experimental data falls on the frequencies corresponding to the speech range. A SSLWSP panel has structural rigidity, so it can be used independently, as a soundproof coating, and as a filler for frame panels in various casings, acoustic screens and the partitions of building structures.

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