Sound insulation properties of sandwich panels

V I Erofeev¹ and D V Monich²,³

¹ Mechanical Engineering Research Institute of the Russian Academy of Sciences, 85 Belinskogo street, Nizhny Novgorod, 603024, Russian Federation
² Nizhny Novgorod State University of Architecture and Civil Engineering, 65 Ilyinskaya street, Nizhny Novgorod, 603950, Russian Federation
³ dmitriy.monich@mail.ru

Abstract. The sound transmission via building enclosures of finite dimensions has a resonant and inertial components. The resonant transmission of sound takes place in the mode of self-induced vibrations depending on the degree of self-coordination of its own wave field with sound fields present in the air on both sides of the enclosure. The most effective method of sound insulation enhancement of sandwich panels is to reduce the resonant transmission of sound by acoustic separation of the layers. This design solution provides the greatest reduction of the resonance frequency “mass – spring – mass”. Experimental studies for determining the intrinsic sound insulation of sample sandwich panels have been conducted in reverberation chambers in a diffuse sound field. The acoustic separation of sandwich panel layers allowed for the increase of the airborne noise insulation index up to 4 dB: from $R_w = 38$ dB to $R_w = 42$ dB (for samples with polystyrene foam cores). For the sample with mineral wool core, the increase of the airborne noise insulation index was 8 dB: from $R_w = 39$ dB to $R_w = 47$ dB. The results obtained allow us to develop rational constructive solutions for enclosures of civil and industrial buildings of sandwich panels, taking into account the spectrum of insulated noise. Improving the sound insulation of sandwich panels is provided without a significant increase of their mass and thickness.

1. Introduction
Noise levels in cities increase annually, which has a negative effect on people's health [1]. Therefore, noise control inside buildings and the surrounding area is an urgent task [2-4]. New materials used to reduce noise levels inside buildings [5], [6]. One of the first scientists who was studying sound transmission via multi-layer enclosures was L. Beranek [7]. The paper [8] summarizes a study of sound transmission via infinite multi-layer enclosures. The papers [9], [10] studied sound transmission via sandwich panels in order to determine how this process is affected by different physical and mechanical factors of the elements of the subject enclosures. Experimental and theoretical studies of sandwich panel sound insulation properties for their parameter optimization are described in paper [11-13]. A vast scope of experimental studies of the sound insulation properties of sandwich panels with different types of the core is reported in the paper [14]. The papers [15-18] studied theoretical models of sound transmission via double-wall sandwich panels with various combinations of middle layer and air gaps. Comparison of the theoretical and experimental results of sound insulation of double-wall sandwich panels with air gaps is reported in the paper [19]. The purpose of this study is to identify ways to reduce the resonant transmission of sound through a sandwich panel.
2. Methods

2.1. Theory of self-coordination of wave fields

A description of sound transmission via multi-layer enclosures of finite dimensions was given by the theory of self-coordination of wave fields [20, 21]. In this case, the resonant transmission of sound and the inertial transmission of sound via enclosures are considered. The resonant transmission of sound takes place in the mode of self-induced vibrations depending on the degree of self-coordination of its own wave field with sound fields present in the air on both sides of the enclosure. The inertial transmission of sound takes place in the mode of forced vibrations depending only on the mass and the geometrical dimensions of the enclosure.

Based on the analysis of the reference literature and papers by the authors hereof [22], one can assert that three-layer sandwich panels with a core of rigid polystyrene foam or mineral wool feature insufficient sound insulation properties stipulated by sound insulation reduction in the bandwidth close to the system frequency “mass – spring – mass” (f_{msm}). In subject enclosures with 30 – 150 mm thickness, an abrupt reduction of sound insulation is observed in the frequency band of 200 – 1000 Hz. Now, we consider possible ways of the sound insulation increase of sandwich panels (under recognition of the finiteness of their dimensions), generalized after the results of theoretic studies carried out by the authors based on the theory of self-coordination of wave fields in the form of the diagram in Figure 1.

![Diagram of Methods of sound insulation enhancement of sandwich panels](image-url)

**Figure 1.** Methods of sound insulation enhancement of sandwich panels.
2.2. **Object of study**

It has been established that the most effective method of sound insulation enhancement of sandwich panels is to reduce the resonant transmission of sound by acoustic separation of the layers [22]. This method is highlighted in Figure 1 by bold lines and gray fill. Acoustic separation in this paper is understood as introduction into the sandwich panel structure of one or several glued-in thin layers of elastic material splitting the core in several parts or between the core and the cladding sheets suggested by the authors – see Figure 2. Gypsum fibre boards were used as external cladding sheets \( h_1 = 12.5 \) mm, \( 1150 \) kg/m\(^3\) density). The core was made of mineral wool with elasticity module: \( E = 0.8 \) MPa, \( 25 \) kg/m\(^3\) density, as well as of polystyrene with elasticity module: \( E = 8.5 \) MPa, \( 15 \) kg/m\(^3\) density. The thickness of the core was \( d = 50 \) mm. The separation layers were made of roll material of a resilient polyether synthetic fiber \( h_0 = 4 \) mm, \( \rho = 75 \) kg/m\(^3\) density, elasticity module \( E = 0.3 \) MPa). The claddings, the core and the acoustic separation layers (samples in Figure 2: (b), (c), (d)) were glued to one another with polymeric glue.

![Figure 2. Structural design solutions of the sandwich panel: (a) two cladding sheets separated by the air gap; (b) standard sandwich panel (without acoustic layers separation); (c) sandwich panel with acoustic separation of the core in two equal parts; (d) sandwich panel with acoustic separation of the cladding sheets from the core.](image)

2.3. **Reverberation chambers**

Experimental studies for determining the intrinsic sound insulation of sample sandwich panels have been conducted in reverberation chambers of the acoustics laboratory of the Nizhny Novgorod State University of Architecture and Civil Engineering. The arrangement of the complex of acoustic measurement chambers used for conduction of experiments is shown in Figure 3. Sound insulation measurements at the impact of a diffuse sound field were conducted in accordance with a standard method, as per ISO 10140-2 [23]. For measurements, precision acoustic measurement instrumentation “Larson&Davis” was used (spectrum analyser 2900 B, measurement microphones \( \frac{1}{2} '' \), type 2559). The measurement microphones in the source and the receiver chamber were installed subsequently in eight points. In the source chamber of \( 150 \) m\(^3\), volume sound pressure levels were generated within a range of \( 100 - 120 \) dB. In the receiver chamber of \( 66 \) m\(^3\), the volume of the signal exceeded the background noise by at least \( 15 \) dB in all frequencies of the subject band (80 – 4000 Hz, in one-third-octave frequency bands).

The sound transmission loss of the enclosure \( R, \) dB at the impact of the airborne noise was calculated in accordance with the formula [23]:

\[
R = L_1 - L_2 + 10 \log \left( \frac{S}{A} \right),
\]

where \( L_1, L_2, \) dB are the energy average sound pressure levels in the source chamber and in the receiver chamber, respectively; \( S, \) m\(^2\) is the square of the sample enclosure section (in this case, \( S = 2.4 \) m\(^2\)); \( A, \) m\(^2\) is the equivalent sound absorption of the receiver chamber.
The sound insulation of sandwich panel samples of 2.4 m$^2$ surface was measured (length 2.0 m, height 1.2 m). Figure 2 shows structural solutions of multi-layer sandwich panels, the sound insulation properties of which were experimentally studied in the framework hereof.

3. Results and Discussion
The value of the resonance frequency of the system “mass – spring – mass” in a standard sandwich panel (without acoustic separation of the layers) is calculated after the following formula:

$$f_{nom} = 0.16 \sqrt{\frac{E(\mu_1 + \mu_2)}{d \mu_1 \mu_2}},$$

(2)

where $E$ is the dynamic elasticity module of the core material of the sandwich panel, MPa; $\mu_1$ and $\mu_2$ are the superficial density values of the first and the second cladding sheet, respectively, kg/m$^2$; $d$ is the distance between the external cladding sheets, m.

In order to consider the influence of the acoustic separation of the layers of sandwich panels, the resonance frequency of the system “mass – spring – mass” is calculated after the formula:

$$f_{nom} = 0.16 \sqrt{\frac{E_0(\mu_1 + \mu_2)}{d \mu_1 \mu_2}},$$

(3)

where $d$, $\mu_1$ and $\mu_2$ are the same as in formula (2); $E_0$ is the equivalent dynamic elasticity characterizing the acoustic separation of the layers of the sandwich panel, Pa.

Equation (3) gets the new value $E_0$ characterizing the degree of acoustic separation of the sandwich panel layers which is determined after the formula:

$$E_0 = kE,$$

(4)

where $E$ is the same as in formula (2); $k$ is the dimensionless empiric factor accounting for the acoustic separation of the layers ($k \leq 1$, see Figure 4).
The value of the factor \( k \) for different core structure of the sandwich panel is calculated after the formula obtained by substituting formula (5) for formula (4):

\[
k = \frac{f_{\text{min}}^2 \mu_1 \mu_2 d}{0.026E(\mu_1 + \mu_2)},
\]

(5)

where \( f_{\text{min}} \) is the resonance frequency of the system “mass – spring – mass”, Hz; \( d, E, \mu_1 \) and \( \mu_2 \) are the same as in formula (2).

The diagram in Figure 4 has been plotted based on the results of a sequence of experimental studies of the sound insulation of sandwich panels with acoustic separation of the layers conducted in the acoustical laboratory of the Nizhny Novgorod State University of Architecture and Civil Engineering in 2014 – 2018. For a standard sandwich panel (without acoustic separation): \( E_0 = E \), factor \( k = 1 \). For the sandwich panels with acoustic separation of the layers, the value of the factor \( k \) is dependent on the elasticity module of the core material.

**Figure 4.** Value of the factor \( k \) for sandwich panels with cores of polystyrene foam and mineral wool at different methods of acoustic separation.

During the calculation of the resonance frequency of the system “mass – spring – mass” for a sandwich panel with acoustic separation, it cannot be taken less than the limit value of the resonance frequency value (\( f_{\text{min}} \)), corresponding to the value of the resonance frequency for a double-layer enclosure (\( f_0 \)) with a thickness of an air gap equal to the thickness of the core, determined after the formula:

\[
f_{\text{min}} = f_0 = 600 \frac{\mu_1 + \mu_2}{d \mu_1 \mu_2},
\]

(6)

where \( \mu_1; \mu_2; d \) are the same as in formula (3).

Figures 5 and 6 show experimental frequency characteristics of the sound insulation of frameless sandwich panels, gypsum-board-clad, with different core versions of polystyrene foam and mineral wool, respectively.

Analyzing Figures 4 and 5, one could see that the standard sandwich panels with both tested types of the core material feature a distinct section of enhanced sound passage close to the resonant frequency of the system “mass – spring – mass” (\( f_{\text{min}} \)). This sound insulation drop limits the practical use of standard sandwich panels. For sandwich panels with polystyrene foam core of 50 mm thickness,
this drop corresponds to the frequency of $f_{\text{min}}^1 = 800\,\text{Hz}$ (see curve 1 in Figure 5). For sandwich panels with mineral wool core of 50 mm thickness, this resonance corresponds to the frequency of $f_{\text{min}}^1 = 315\,\text{Hz}$ (see curve 1 in Figure 6).

Due to the acoustic separation of the layers, there is a displacement of the resonant frequency of the system “mass – spring – mass” to the lower frequency band. Such a resonant displacement to the value of the resonant frequency of the sample with an air gap is observed for both sample types of the core (see curve 4 in Figure 5 and 6, $f_0 = 100\,\text{Hz}$). This value is a limit value for structures of such type since at equal limit conditions, in enclosures with an air gap, the cladding layers are connected only by the elasticity of the air enclosed between them.

The integration of a core with acoustic separation in the sandwich panel design extends the frequency band where the experimentally obtained data exceed the values of the mass law in the band above the resonance frequency $f_{\text{min}}$. For sandwich panel with polystyrene foam core and acoustic separation dividing the core into two equal parts, this band is $500 – 2000\,\text{Hz}$, the separation of both the claddings and the core extends the band limits to $400 – 2500\,\text{Hz}$ accordingly, whereas for a standard sandwich panel these limits are $1250 – 2000\,\text{Hz}$. For a sample with mineral wool core and acoustic separation of the latter into two equal parts, this band is $315 – 3150\,\text{Hz}$, the separation of both the claddings and the core extends this band to $125 – 3150\,\text{Hz}$, whereas for a standard sandwich panel it is $400 – 2500\,\text{Hz}$.
For all considered sandwich panel samples, the value of the sound insulation is close to the resonance frequency $f_{msm}$, independent on its position considerably lower than the mass law. Based on experimental results demonstrated in Figures 5 and 6, a conclusion can be made that the alteration of the value of the resonance frequency $f_{msm}$ allows for adjustment of the sound transmission through sandwich panels in a wide frequency band, without significant growth of the weight and the thickness of the samples (within 10 %).

The acoustic separation of sandwich panel layers allowed for the increase of the airborne noise insulation index up to 4 dB: from $R_w = 38$ dB to $R_w = 42$ dB (for samples with polystyrene foam cores). For the sample with mineral wool core, the increase of the airborne noise insulation index was 8 dB: from $R_w = 39$ dB to $R_w = 47$ dB.

4. Conclusions
1. The sound insulation of sandwich panels with different methods of acoustic separation of the core of mineral wool or polystyrene foam was studied experimentally. The efficiency of the acoustic separation method for the enhancement of the sound insulation of sandwich panels was demonstrated by means of comparison of the obtained results with the sound insulation of standard sandwich panels (without acoustic separation).
2. It has been established that the most effective reduction in the resonant transmission of sound occurs when acoustic separation is introduced between the sheets cladding and the core. This design solution provides the greatest reduction of the resonance frequency “mass – spring – mass” ($f_{msm}$).
3. Based on experimental data, values of $k$ factors were determined allowing to find out the resonant frequency of the system “mass – spring – mass” for sandwich panels made of different materials with acoustic separation types analyzed herein.
4. The use of acoustic separation for sandwich panels with mineral wool core is more effective than that for sandwich panels with polystyrene core.
5. The results obtained allow us to develop rational constructive solutions for enclosures of civil and industrial buildings of sandwich panels, taking into account the spectrum of insulated noise. Improving the sound insulation of sandwich panels is provided without a significant increase of their mass and thickness.

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