Experimental Studies of the Elastic-Dissipative Properties of Structural Materials and the Calculation of Sound Insulation of Building Partitions Based on Refined Characteristics by the SEA Method

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Abstract. An analytical solution to the problem of sound and vibration transmission through structures, taking into account the energy exchange with adjacent structures, requires determination of the elastic-dissipative properties of structural materials: the elastic modulus and the loss factor. In this work, the parameters of the elastic modulus and the loss factor of three known building materials are investigated and experimentally established in comparison with previously obtained data of other authors. For the automation and accuracy of measuring the internal loss factor, a new measurement technique was transferred using Zetlab software and digital equipment. The calculation of sound insulation of a single-layer enclosing structure is performed based on the method of statistical energy analysis (SEA) using the measured data of the elastic modulus and loss factor. In order to determine the reliability of the data obtained for the elastic modulus and the coefficient of internal loss of structural materials, a comparison was made of the values of sound insulation of a single-layer panel made of gypsum fiber board, obtained by means of experimental research, using the calculated values of sound insulation calculated using the elastic modulus and the coefficient of internal losses from literature sources and using the calculated sound insulation values calculated using the measured values of the modulus of elasticity and the internal loss factor.

1. Introduction

The solution of the problems of calculating and designing sound insulation in buildings by the method of statistical energy analysis (SEA) is based on reliable values of the elastic-dissipative properties of structural and sound-insulating materials.

The fundamental characteristics of materials when calculating sound insulation are the modulus of elasticity and the coefficient of internal loss. Currently, the market for building materials used for sound insulation is quite diverse. However, manufacturing companies do not always provide the characteristics necessary for the development and design of structures with specified sound insulation parameters. In this regard, the development of measurement methods and experimental research to determine the elastic modulus and the coefficient of internal losses of various structural materials is relevant.
To automate and improve the measurement accuracy, there is an urgent need for the use of modern technologies when measuring elastic-dissipative properties, which make it possible to create multifunctional measuring systems and automate measurements based on personal computers.

2. Relevance, significance of the issue with a brief review of the literature

Methods for measuring the dynamic characteristics of structural materials and measurement results for a number of traditional structural materials are given in the book by L. Cremer [1]. In [2], a review of the measurement data of the dynamic characteristics [1,3,4,5,6] was carried out, which showed a significant scatter of data. For structural materials, the modulus of elasticity of the material is practically independent of frequency and ranges from 2 to 30 GPa for concrete and masonry; up to 210 GPa for metals, up to 10 GPa for wood-based materials and about 60 GPa for glass. Measurement and refinement of the dynamic characteristics of modern structural materials using modern digital vibroacoustic equipment is an urgent task for the development of methods for vibroacoustic calculations of buildings.

The existing methods of measuring the elastic modulus and the coefficient of internal losses of structural materials, which ensure the measurement accuracy, are considered. It was revealed that they differ from each other in the type of vibration of the samples under study (bending or longitudinal), in the nature of vibration excitation (forced or free), in the mode of operation (resonant or nonresonant) [1]. The simplest and most suitable for measuring the coefficient of internal losses is the method of forced resonant oscillations [2]. To measure the modulus of elasticity of structural materials, it is advisable to use the method of standing bending waves. The standing bending wave method is used when testing materials from which long-length samples can be made.

The scientific significance of the issue is the proposed experimental methods for measuring the coefficient of internal losses and the modulus of elasticity of structural materials, the experimentally obtained values of the modulus of elasticity and the coefficient of internal losses for structural materials, as well as the solution of the particular problem of calculating sound insulation by the SEA method using the obtained data, the coefficient of internal losses and the modulus of elasticity.

3. Problem formulation

To create a reliable method for measuring the elastic-dissipative properties of structural materials, it is required to carry out experimental studies to measure the elastic modulus and the internal loss coefficient based on new measuring instruments with subsequent comparison of the data obtained in laboratory measurements of the internal loss coefficient and elastic modulus with the data given in the literature [1,2,3]. Next, it is required to calculate the soundproofing capacity of the enclosing structures using the obtained data, the coefficient of internal losses and the elastic modulus by the SEA method, followed by experimental verification.

4. Experimental studies of elastically dissipative properties of structural materials by resonance methods

4.1. Measurement of the modulus of elasticity along the length of the standing and flexural waves

Various methods are used to determine the dynamic modulus of elasticity, which provide the required accuracy and reliability of measurements. These methods differ in the type of vibrations of the samples under study (bending or longitudinal), the nature of the excitation of vibrations (forced or free), and the mode of operation (resonant or nonresonant vibrations) [1]. The simplest and most reliable method for measuring the modulus of elasticity is the method based on the excitation of standing bending waves in a semi-infinite rod. In a semi-infinite rod made of the material under study, a standing bending wave was excited in pure tone, while the bending wavelength was measured and the elastic modulus was calculated [2].

The design of the measuring stand for determining the modulus of elasticity was based on a rod made of the material under study, the free end of which was placed in a damping mixture of sand and
sawdust (Fig. 1). In this experiment, specially prepared rods of different thicknesses, width \( b = 0.1 \) m, length \( l = 2.00 \) m, and a box with a damping medium measuring 0.4 x 0.6 x 1 m were used.

In the rods, a bending wave at the frequency under study was excited by an electrodynamic exciter with a harmonic signal. In the open part of the rod, a standing wave was formed due to the flexural wave incident on the open end and reflected from it, which made it possible to reveal the distance between the nodes of the standing wave and the value of half the flexural wavelength at a given frequency (Fig. 1).

To ensure smooth absorption of the flexural wave energy at the other end of the rod, it was placed in a damping medium, where it was filled with three zones. At the entrance of the rod, sawdust was poured into the box, the middle part was filled with sawdust with sand, and the rest with sand. The free end of the rod is suspended on thin threads. The excitatory tract was composed of an electrodynamic exciter, a sound generator and an amplifier. The receiving path consisted of a spectrum analyzer and an accelerometer.

To measure the modulus of elasticity in a rod excited by an electrodynamic exciter, the wavelengths were measured as twice the distance between adjacent nodes of the standing flexural wave.

From the elementary theory of flexural waves in rods, a formula is known for determining the phase velocity of a flexural wave:

\[
\begin{align*}
    c_n &= \sqrt{\frac{2\pi f B}{m}} \\
    \text{(1)}
\end{align*}
\]

where \( f \) – frequency Hz; \( B \) – bending stiffness of the rod; \( m \) is the mass of a unit of bar length.

From formula (1), we can obtain an equation for determining the elastic modulus of the rod material from the measured value of the half-length of the flexural wave:

\[
\begin{align*}
    E &= \left(\frac{\lambda}{2}\right)^4 \frac{48\rho f^2}{\pi^2 h^2} \\
    \text{(2)}
\end{align*}
\]

where \( \lambda \) – wavelength, m; \( h \) – thickness of the rod, m; \( \rho \) – density, kg / m\(^3\).

Three sheet materials were selected for measurements: glass with a thickness of 6 mm, gypsum fiber sheets (GFS) with a thickness of 10 mm, and solid fiberboard (SFB) with a thickness of 5 mm. The choice of known materials is due to plans for conducting vibroacoustic experiments on models of structures and fragments of buildings. The measurement results for the three materials are summarized in Tables 1-3.
The parameters of the modulus of elasticity of structural materials were investigated and experimentally determined: for gypsum fiber sheets – $5.93 \cdot 10^9$ Pa, fiberboard – $5.45 \cdot 10^9$ Pa, glass – $6.13 \cdot 10^9$ Pa. Comparison of the measured values of the modulus of elasticity of the studied structural materials with the data given in the literature [1, 2, 3] shows that they are in good agreement, taking into account the error in the measurement conditions, for example, the modulus of elasticity for glass [1, 2, 7] according to the literature data is $6 \cdot 10^9$ Pa, and the measured value is $6.13 \cdot 10^9$ Pa, and for gypsum fiber board and fiberboard there are no values of the modulus of elasticity in the literature, but there is a value of materials with similar properties, namely gypsum board $7 \cdot 10^9$ Pa and pressed wood panel $4 \cdot 10^9$ Pa. This allows us to conclude that the technique presented in the work and the measuring stand can be widely used when measuring the elastic modulus of structural materials. However, it is necessary to clarify these data, as well as to measure other known materials used in the building envelope.
4.2. Measurements of the internal loss factor using software Zetlab

A method based on the analysis of the resonance curve and its width was used to measure the loss factor, $\Delta f$:

$$\eta = \frac{\Delta f}{f_{res}}$$  \hspace{1cm} (3)

The width of the resonance curve is measured at 0.707 times the resonant amplitude. If the frequency dependence of the vibrations of the structure is expressed on a logarithmic scale, then at each resonance frequency the width of this resonance curve can be determined at the level of 3dB from its top (Fig. 2).

First, the internal loss factor was measured using a frequency meter, it was found that it is technically impossible to set the exact value of the resonance frequency and the width of the resonance curve on the frequency meter, which greatly complicates the measurements, since for an accurate determination of the internal loss factor, the value of the resonant frequency must be determined with an accuracy of 0.001.

For the automation and accuracy of measuring the internal loss factor, a new measurement technique was transferred using Zetlab software and hardware. The stand for measuring the coefficient of internal losses consisted of a rod of the material under study suspended on thin long threads (Fig. 3). We attach a sensor (accelerometer) to the suspended sample at a distance of 0.5 m from the edge at half the length of the rod. An electrodynamic exciter is connected to the edge of the sheet. With the help of a vibrometer and the Zetlab program, a graph of the dependence of vibration acceleration on frequency was obtained in the interval from 0 to 1000 Hz, the frequencies at which resonance occurs in the structure were determined. Having determined the resonance frequency and the width of the resonance curve, the internal loss coefficient $\eta$ was calculated using the formula (3). For this experiment, specially prepared rods with a width of $b = 0.1$ m and a length of $l = 1$ m were used. Samples from gypsum fiber sheets had a thickness of 10 mm, glass – 6 mm and fiberboard – 5 mm.

**Figure 2.** To the determination of the characteristics of the damping of an oscillatory system with friction along the width of the resonance curve.

**Figure 3.** Stand for measuring the coefficient of internal loss
1 – test sample;
2 – accelerometer;
3 – spectrum analyzer ZET 017-U8;
4 – point of application of exciter;
5 – electrodynamic exciter of oscillations;
6 – amplifier;
7 – generator;
8 – personal computer.
The graphs of the vibration acceleration versus frequency were obtained, knowing the values of which it is not difficult to determine the exact value of the internal loss coefficient. The results of measurements of the modulus of elasticity for the three materials are summarized in tables 4-6.

**Table 4.** The results of measuring the GVL loss factor.

| Measurement No. | Frequency (Hz) | Wavelength (m) | Wave speed (m/s) | Loss factor, \( \eta \) |
|-----------------|----------------|----------------|-----------------|------------------|
| 1               | 14.333         | 1.65           | 23.67721123     | 0.057            |
| 2               | 94.833         | 0.64           | 60.9034287      | 0.0023           |
| 3               | 158            | 0.5            | 78.61230702     | 0.001            |
| 4               | 240.167        | 0.40           | 96.92117371     | 0.001            |
| 5               | 450.167        | 0.29           | 132.6932484     | 0.00059          |
| 6               | 705            | 0.24           | 166.0567587     | 0.0006           |

Average value at frequencies above 100 Hz: 0.0008

**Table 5.** Results of measuring the loss coefficient of fiberboard.

| Measurement No. | Frequency (Hz) | Wavelength (m) | Wave speed (m/s) | Loss factor, \( \eta \) |
|-----------------|----------------|----------------|-----------------|------------------|
| 1               | 10.9           | 1.65           | 23.67721123     | 0.057            |
| 2               | 65.337         | 0.64           | 60.9034287      | 0.0023           |
| 3               | 94.173         | 0.5            | 78.61230702     | 0.001            |
| 4               | 132.175        | 0.40           | 96.92117371     | 0.001            |
| 5               | 303.854        | 0.29           | 132.6932484     | 0.00059          |
| 6               | 451.03         | 0.24           | 166.0567587     | 0.0006           |
| 7               | 643.376        | 0.19           | 122.95          | 0.00055          |
| 8               | 830.055        | 0.17           | 139.66          | 0.000485         |
| 9               | 1041.07        | 0.15           | 156.41          | 0.00032          |

Average value at frequencies above 100 Hz: 0.00055

**Table 6.** Glass loss factor measurement results

| Measurement No. | Frequency (Hz) | Wavelength (m) | Wave speed (m/s) | Loss factor, \( \eta \) |
|-----------------|----------------|----------------|-----------------|------------------|
| 1               | 26.333         | 1.441704942    | 37.96441624     | 0.006            |
| 2               | 87.5           | 0.790901739    | 69.20390214     | 0.003            |
| 3               | 171.167        | 0.565479073    | 96.79135648     | 0.0018           |
| 4               | 287.669        | 0.436194339    | 125.4795893     | 0.0016           |
| 5               | 404.833        | 0.367695744    | 148.8553713     | 0.0005           |
| 6               | 652            | 0.289736199    | 188.908002      | 0.0004           |
| 7               | 1061.5         | 0.227073554    | 241.0385777     | 0.00047          |

Average value at frequencies above 100 Hz: 0.00095

As you can see, from tables 4-6, the loss factor has higher values in the low frequency region, but at frequencies above 100 Hz, at which vibroacoustic calculations for buildings are performed, the dependence of the loss factor on frequency is significantly less and the calculations can be carried out using average values at different vibration modes.

Comparison of the results of measurements of the coefficient of internal losses with the literature data shows that the loss coefficients measured using modern digital equipment turned out to be an order of magnitude lower than the values given in the literature, for example, the loss coefficient for glass [1, 2, 7] according to literature data is from 0.6 to 2 \( \times \) 10\(^{-3}\), and measured \( \eta = 0.00095 \), for GFS and fiberboard there are no values of the coefficient of internal losses in the literature, but there is a value of materials with similar properties, namely, gypsum board \( \eta = 6 \times 10^{-2} \) and pressed wood panels
\[ \eta = 1.3 \cdot 10^{-3}. \] This confirms the urgent need to measure and refine the values of the coefficient of internal loss of structural materials. It is also of interest to measure the dynamic characteristics of structural materials in vacuum in order to exclude the effect of losses on radiation when determining the coefficient of internal losses in the material.

5. Theoretical and experimental studies of sound insulation of enclosing structures based on refined elastic-dissipative characteristics of materials

5.1. Experimental studies in small acoustic chambers of TGASU of sound insulation of panels with a small number of system elements

Experimental studies were carried out in small acoustic chambers of the Tomsk State University of Architecture and Civil Engineering (TSUAB), which have two adjacent rooms: an insulated chamber – a lower-level chamber (LLC), with a volume of 2.8 m\(^3\) and a room with a sound source – a high-level chamber (HLC), with a volume of 1.8 m\(^3\); the test structure was mounted in the opening between the high-level (HLC) and low-level (LLC) chambers, the size of the opening in the chambers was 1.0x0.8 m. The high-level chamber was installed on the low-level chamber through elastic spacers, which reduces structural sound transmission. Walls, floors, doors and ceilings of LLC have high sound insulation due to the massiveness and multilayer structures. The inner shell of the LLC is structurally isolated from the enclosing structures of the laboratory premises. HLC walls and ceilings are lightweight, made of two-layer plywood panels with an air gap of 50 mm. The cutoff frequency of 400 Hz of the beginning of the measurement and calculation range was obtained taking into account the fact that the diffuseness of the sound field in small acoustic chambers of the TSUAB manifests itself starting from 400 Hz (for one-third octave bands). To compare the calculated and experimental data, a conditional sound insulation index \( R'_w \) was adopted.

5.2. Theoretical solution of the simplest vibroacoustic problems with a small number of system elements by the SEA method

The calculation of the simplest vibroacoustic problem with a small number of system elements is based on the SEA method \[2, 8-10\]. Let's solve the problem using a model structure as an example. As a structural subsystem, we will consider a GFS panel with a thickness of \( h = 10 \text{ mm} \), with dimensions \( a = 1 \text{ m}, b = 0.8 \text{ m} \). And as acoustic subsystems of a room with volumes \( \nu_I = 1.8 \text{ m}^3 \) and \( \nu_{II} = 2.8 \text{ m}^3 \).

The energy balance equations as a whole give a system of linear algebraic equations for the unknown wave energy in the subsystem \( W^b, W^A_I, W^A_{II} \).

In order to determine the reliability of the obtained data on the modulus of elasticity and the coefficient of internal loss of structural materials, a comparison was made of the values of sound insulation of a single-layer panel made of gypsum fiber board, obtained by (fig.4):

- experimental study (curve 1) \( R'_w = 34 \text{ dB} \);
- using the calculated values of sound insulation, calculated using the modulus of elasticity and the coefficient of internal losses from the literature \[1, 2\] \( (\eta_1 = 0.006; E_1 = 5.8 \cdot 10^9 \text{ MPa}; \rho_1 = 1240 \text{ kg/m}^3) \) (curve 2) \( R'_w = 35 \text{ dB} \);
- using the calculated values of sound insulation, calculated using the measured values of the modulus of elasticity and the coefficient of internal loss \( (\eta_1 = 0.0008; E_1 = 5.93 \cdot 10^9 \text{ MPa}; \rho_1 = 1246 \text{ kg/m}^3) \) (curve 3) \( R'_w = 34 \text{ dB} \).
Figure 4. Results of the measured and calculated values of sound insulation of a single-layer GFS panel.

6. Conclusion
In order to create and develop a method for measuring the coefficient of internal losses and elastic modulus for structural materials that are part of soundproof structures, theoretical and experimental studies of the simplest vibroacoustic system, consisting of three subsystems, have been carried out.

A comparative analysis of the experimental and calculated values of sound insulation of a single-layer partition made of gypsum plasterboard was carried out using the values of the internal loss coefficient and the elastic modulus measured according to the proposed method. The measured and calculated values of sound insulation are in good agreement, which confirms the rather high accuracy of the proposed method for measuring the internal loss coefficient and elastic modulus for structural materials.

7. References
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