Semi-graphical method for plotting a frequency characteristic of impact noise level's reducing

A I Gerasimov and I P Saltykov

1 Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

E-mail: vincesalt@mail.ru

Abstract. The article describes the application of rolled floor materials for sound insulation of impact noise by the floors. A detailed classification of such materials is given, including such materials as linoleum, rubber linoleum and carpet. The described method is appropriate for testing the floor to obtain the frequency characteristics of the normalized level of impact noise of the whole structure and for the frequency characteristics of improvement of sound insulation due to the use of roll coverings. Methods for normalized impact noise level indices calculation in case of composite construction and only roll covering are also briefly described. A new semi-graphical method for constructing the frequency response of reducing the level of impact noise by floor covering for inserted floors is presented. A computational model for solving the contact problem of the impact noise isolation by floor in the form of an oscillatory system, consisting of an absolutely solid body and a two-layer elastic medium, is presented. The solution of the contact problem for obtaining an adjustment for reducing the normalized level of impact noise due to the application of a roll material is shown. The equation for frequency of crumpling for the linoleum surface crumpling in the process of standard striking machine's impact is shown. The effect of local crumpling occurs and the growth of sound insulation starts in two-layer floor from this frequency's value. The analysis of calculations accordingly the proposed calculation method is carried out. The practical algorithm for semi-graphical method and for the frequency response plotting of impact noise sound insulation improving by the roll floor covering is proposed. Graphs of the magnitude of impact noise improvement by the most common roll materials, that can be used to obtain the frequency response of impact noise isolation by a two-layer floor, are given.

1. Introduction

Nowadays, the residential and public building practice witnesses the widespread implementation of interfloor slabs constructions with the roll flooring coverings. The different linoleum's types, including the rubber linoleum, and carpeting, are among them (either with a nap or without it).

The floor covering materials should have a range of important requirements. They are: strength, elasticity, noiselessness, low abradability, water-repellency, humidity resistance, heat insulation, sound insulation, high aesthetics, and efficiency [1-3]. The roll flooring materials can be classified by their function and by their application domain; as also, by their structure and by the base's type (bottom layer) [4-7]. By their function floor coverings are divided into domestic, commercial and semi-commercial, that's depends mostly from the intensity of people movement.

The effectiveness of such kinds of floors application needs the practical calculation and estimation method for the impact noise sound insulation floor capacity. As for the airborne noise insulation, the practice shows roll floorings low efficiency in terms of insulation; as in this case, the crucial role is...
played not by the elastic properties of top layer, but by the value of surface density of the bearing slab construction [8, 9]. When this occurs, the slab's surface density should be not less than 400 kg/m², accordingly the Russian normative acoustical codes.

In relation to the above, it appears to be significant to carry out the analyses of frequently used roll flooring coverings with regard to the impact noise isolation [10-12], especially on the basis of relatively new semi-graphical method for performing the frequency characteristics of impact noise level decreasing, due to the roll flooring materials.

2. Materials and Methods

The layers variants of roll coverings are rather various [5, 6]. The structure of coverings can be distinguished between homogenous (one-layered) and heterogeneous (multilayered, composite). The homogenous linoleum are: natural, glyptal (alkyd), and coloxylin (nitro-linoleum). The natural linoleum is a floor coating, which includes linseed oil, wood resin, wood or cork powder, limestone meal, pigment dyes and jute fabric.

The glyptal (alkyd) linoleum has a base out of fabric material. There, the alkyd resins are used as a binding agents, these components are biologically harmless. So why this linoleum is eco-friendly and safe for humans and animals. The covering's advantages are the high persistence to wear (abradability) and the long term of exploitation. The deficiencies are: the low degree of water resistance and the decay of a fiber base under the soaking. The material lose it's resilience and becomes brittle.

Coloxylin one-layered linoleum is produced out of nitrocellulose. The material has a resistance to high humidity, high elasticity and wide range of colors. However, there are the substantial deficiencies. It becomes brittle when being exposed by low temperatures and becomes to burn under the warm temperatures. So it is absolutely unacceptable for apartment dwelling premises, for schools and kindergartens.

The heterogeneous (multilayered) floor coverings list consists of polyvinylchloride, rubber linoleums and also, carpet flooring. The polyvinylchloride one combines the top decorative and protective layer with the thickness of 50÷100 [mk] and the bottom layer of the base. The upper layer is manufactured from the plastic mixture, with the polyvinylchloride (PVC) or vinyl, as the main component. Also it contains the binding agent, plasticizing agents, thinners, fillers and colorants. Polyvinylchloride, which has a thermal plasticity and linear structure of macromolecules, is used as a binder. The calcium carbonate (chalk, marble powder), talc, barite (heavy spar), kaolin are mainly used as a filler.

The linoleum with a sub-base deserves a special attention, as it's bottom layer ties directly to the underlay or slab surface and has it's additional functions, like thermal- and sound insulating. Such kind of linoleum is known as a thermal- and a sound insulating one (PVC TSI). PVC TSI linoleums divides into four types, that's depends from the type of the sub-base material: bast and jute fibers supported; synthetic fibers supported; with a bottom layer from the mixture of secondary wood fibers refinement; TSI foamed.

The rubber linoleum is a double layered roll material. The bottom layer is made from the mix of bitumen and the rubber crump. The upper layer contains the artificial caoutchouc in combination with the colorants. Rubber material is used mainly as a floor covering in public buildings with a large flow of people. It's upper layer's material has a temperature difference tolerance, elasticity, low abradability and resistance to moisture.

Carpet is a soft floor covering, which initially was a form of a covering from the wool fabric. Today, it is a multilayered composite material with a pile, or without it (so calls "palas"). The structural composition of carpet with a nap: pile, primary base, reinforcing layer, and a secondary base. Resilience and resistance of the floor carpet covering are determined by the density and the length of pile. The more durable covering has a thick pile and a lower system of knitting. Pile is fabricated from wool, polypropylene and polyamide. Jute, artificial jute and latex are most often used for the sub-base. Partly or entirely natural wool in the composition has a high strength; it is widespread
and easy to paint. The presence of artificial fibers in the wool, such as nylon, significantly increases its strength. The standard ratio of wool to the synthetic fibres is 80 and 20 percent, respectively.

Polypropylene is a cheaper material than wool or nylon. Commercial polypropylene covering with small stitches (boucle) does not wear out, is easy to clean and is suitable for offices and similar areas with a high traffic.

Polyester is resistant to moisture and dirt (to a greater extent than nylon), but it wears out rather rapidly. It is usually used in the production of the relatively inexpensive coverings.

The impact noise insulation of the interfloor slab is characterized by the normalized impact noise level. Frequency response measurement for the normalized impact noise level is taken either in field or laboratory conditions [5, 7].

To test the sound insulation properties of floor coverings, reverberation chambers are used. They have two vertically adjacent rooms, which are separated by a slab plate. The material's test specimen is sequentially placed at four points of the floor slab.

A striking machine is installed on the sample. It produces 10 impacts per second by the sample of material with its five cylindrical hammers with a diameter of 30 mm, with a spherical surface in their lower part, when they fall from a height of 40 mm. The radius of the spherical surface of the hammer is 500 mm, the effective mass of it is 0.5 kg.

A measuring microphone is installed in the lower room, so that the each position of the impact machine corresponds to at least three microphone positions. The audiometer, which is connected with the microphone, allows to register the sound pressure level.

The normalized impact noise level \( L_n \) under the slab is determined in 1/3 octave frequency bands in the range 100-3150 Hz by the formula:

\[
L_n = L_j + 10 \log \frac{A_2}{A_0}, \text{ dB} \tag{1}
\]

where \( L_j \) - is an average level of impact noise under the slab, [dB]; \( 10 \log \frac{A_2}{A_0} \) - is a correction, which considers the acoustic features of the lower room; \( A_2 \) - is an equivalent sound absorption area of the lower room, [m]\(^2\], by formula (2); \( A_0 \) - is a value of the average sound absorption area, \( A_0 = 10 \) [m]\(^2\].

\[
A_2 = 0.16 \frac{V}{T}, \text{ m}^2 \tag{2}
\]

where \( V \) - is the volume of the lower room, [m]\(^3\]; \( T \) - is the reverberation time, [s].

The frequency response of improving the isolation of impact noise by the floor \( \Delta L_n \) is calculated after the determination of the reduced level of impact noise under the slab without the floor structure, \( L_{n0} \), and the one with the construction, \( L_n \):

\[
\Delta L_n = L_{n0} - L_n, \text{ dB} \tag{3}
\]

It is known [5, 7, 9, 10], that the normalized index of impact noise isolation is the index of the reduced level of the impact noise, \( L_{\text{nw}} \). In accordance with Russian standards, this index is found by the grapho-analytical way and its value is equal to the sound insulation of the shifted normative curve (\( L_n^0 \) in the table 1) at the frequency of 500 Hz.

The frequency response of reducing the normalized impact noise level \( \Delta L_n \) does not depend on the reduced impact noise level of the bearing part of the floor \( L_{n0} \) (if the latter has a solid cross-section). By contrast, the impact noise isolation improvement index \( \Delta L_{\text{nw}} \) can significantly depend on the sound insulation from the slab impact noise at a specific frequency.

Therefore, the value \( \Delta L_{\text{nw}} \) is determined using the frequency response of the reduced impact noise level, \( L_{nR} \), for the reference bearing part of the floor with this floor covering using \( L_{nR0} \) by the formula:

\[
L_{nR} = L_{nR0} - \Delta L_n, \text{ dB} \tag{4}
\]

where \( L_{nR0} \) - is the normalized impact noise level of the reference bearing part of the floor, [dB], which is shown in table 1.
The index of the normalized impact noise level of the reference bearing part of the floor, \( L_{nwR0} \), is 78 \([\text{dB}]\).

The index of improvement of impact noise insulation by floor covering is determined by the formula:

\[
\Delta L_{nw} = L_{nwR0} - L_{nwR} = 78 - L_{nwR}, \quad \text{dB};
\]  

(5)

where \( L_{nwR} \) is the calculated index of the reference bearing part of the floor with the coating, \([\text{dB}]\).

Thus, this technique allows to evaluate the sound insulation quality of the floor, regardless of which floor slab it is laid on. The index of improvement of impact noise insulation by floor covering is the main acoustic characteristic that allows to judge the effectiveness of the application of rolled materials for impact noise protection.

**Table 1.** Frequency spectra of the reference curve and the normalized impact noise level of the reference bearing part of the floor.

| Characteristic, \([\text{dB}]\) | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 |
|---------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| \( L_{nwR} \)                  | 62  | 62  | 62  | 62  | 62  | 61  | 60  |
| \( L_{nwR0} \)                 | 67  | 67.5| 68  | 68.5| 69  | 69.5| 70  | 70.5|
| **Total**                      |     |     |     |     |     |     |     |     |
| Average geometric frequencies of the 1/3 octave bands, \([\text{Hz}]\) | 630 | 800 | 1000| 1250| 1600| 2000| 2500| 3150|
| Characteristic, \([\text{dB}]\) |     |     |     |     |     |     |     |     |
| \( L_{nwR} \)                  | 59  | 58  | 57  | 54  | 51  | 48  | 45  | 42  |
| \( L_{nwR0} \)                 | 71  | 71.5| 72  | 72  | 72  | 72  | 72  | 72  |

Also, to determine the frequency response of insulation from impact noise by a roll material, \( \Delta L_n \), the semi-graphical calculation method can be used, which is based on a physical model with two contacting bodies: the impacting mass (the hammer of the impact machine) and the construction of the floor with the roll covering.

Let’s consider a double-layered construction of the floor, that consists of a load-bearing reinforced concrete slab and a linoleum coating (Figure 1).

**Figure 1.** The Design model for solving the contact problem of the impact noise isolation with a two-layer floor in the frequency range \( f > f_{crum} \). \( f_{crum} \) is the frequency of local crumpling): 1 - is the hammer of a standard impact machine; 2 - is the radius \( r_0 \) of the contact area \( Q_0 \) in the 0z plane; 3 - is a single-layer load-bearing slab; 4 - is a floor covering; 5 - is the contact area in the 0z plane.
The computational model for solving the contact problem of the impact noise isolation by the floor slab is an oscillatory system consisting of an absolutely solid body with mass $m_0$ (the striker) and a two-layered elastic medium (linoleum + plate).

The solution of the problem is based on the method of displacements of the elasticity theory. The vertical movement of points in the system was determined by a simultaneous solution of the equation of the motion of an absolutely solid body and the wave equations:

$$-m_0 \cdot \omega^2 \cdot a_z = P_z + u_1(x_1, y_1, -h_1) \cdot R_z$$

$$\left\{ \begin{array}{l}
\frac{\partial^2 u_1}{\partial x^2} + \frac{\partial^2 u_1}{\partial y^2} + \frac{\partial^2 u_1}{\partial z^2} + S_1 \cdot u_1 = 0 \\
\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} + S \cdot u = 0
\end{array} \right.$$  

under boundary conditions

1. $z = -h_1 \quad \{u_1(x_1, y_1, -h_1) = a_2; \; (x, y) \in Q_0; \}
2. z = h; \; \sigma_z = 0, -\infty < x, y < + \infty.$

where $u_1(x, y, z)$ – vertical movement of points of the top layer (linoleum) of $h_1$, [m]; thickness;

$S_1$ and $S$ - are the dynamic stiffness of the floor covering and the load-bearing floor slab, [N· m$^{-3}$];

$R_z$ - is a dynamic reaction of an elastic medium to a unit of displacement in the contact area $Q_0$, [N· m$^{-3}$];

$m_0$ - is a weight of the hammer of a standard impact machine, [kg];

$\omega$ - is a circular frequency, [Hz];

$a_2$ - is a movement of the hammer of the striking machine, [m];

$P_z$ - is hammer force of a standard striking machine, [N].

When solving the contact problem, a number of mathematical transformations are used (in particular, Fourier and Fourier-Bessel converters). At the final stage, the effective values for the square of the oscillatory velocity of the two-layer system, $V^2_{zL}$, and the reduction of the impact noise level (increase of insulation) are determined:

$$\Delta L_n = 10 \log \frac{V^2_z}{V^2_{zL}}$$  

where $V^2_z$ is the square of the vibrational velocity of the lower face (surface) of the two-layer floor construction.

3. Results and discussion

The results of calculations gave the equation of the crumple frequency, $f_{crum}$, for the surface of the linoleum in the process of standard striking car's hammer impact (with $m_0 = 500$ g), from which the effect of local buckling of two-layer floor occurs; so that an impact noise sound insulation's growth is begun, due to the material of covering.

$$f_{crum} = f_{cr} \cdot \left[ 2\pi \cdot \left( 1 + \frac{m_1}{m} \right)^{0.75} \cdot \left( 2 + \frac{S_1}{S} \right)^2 \cdot \left( \frac{\rho}{\rho_1} \right)^2 \cdot \left( \frac{S_1}{S} \right)^{-0.25}, \; Hz \right.$$  

where $\rho$ and $\rho_1$ - are the density of the material of the bearing part of the floor and the density of the floor covering material, [kg · m$^{-3}$]; $m$ and $m_1$ are the surface densities of the floor material and the floor support structure, [kg · m$^{-2}$], respectively; $f_{cr}$ - is the critical frequency of vibrations for two-layer floor, [Hz].

$$f_{cr} = \frac{1}{2\pi} \sqrt{\frac{S_1}{m}}, \; Hz;$$  

where $S_1$ and $m_1$ are the dynamic stiffness of the floor covering and the load-bearing floor slab, [N· m$^{-3}$]; thickness;
The physical and mechanical characteristics of local crumpling on impact are: the contact time \( \tau \), which depends on the elastic-viscous properties of the material, the delay time (the degree of delay), the complex elastic modulus \( E_q \) and the compliance \( J \). All these characteristics are interrelated and have the equal significance. So the compliance function is inversely proportional to the module function:

\[
E_q(i\omega) = \frac{1}{J(i\omega)}
\]

Analysis of the calculation results shows that the greater the value of \( E_q \) of the floor covering material, the less \( J \) and the duration (period) of contact during impact; the higher the frequency of crumpling, \( f_{crum} \); the less the value of increasing the impact noise insulation, \( \Delta L_n \), due to the floor covering material.

Based on the obtained research results, the practical grapho-analytical method for calculating and drawing the frequency response, \( \Delta L_n \), [dB], of floor covering, which is based on the obtained research results, is proposed. And it is carried out in the following order:
1. The floor covering material is defined;
2. The surface densities of the floor and floor support structure with their dynamic stiffness are determined;
3. The frequency of crumpling, \( f_{crum} \), [Hz], which is the beginning of the growth of \( \Delta L_n \) graph on the abscissas axis, is defined by formula 9;
4. In accordance with the frequency \( f_{crum} \) by table 2, the slopes of the \( \Delta L_n \) curve are found in the range of low, medium and high frequencies.

**Table 2. Physical and mechanical parameters of the roll flooring coverings.**

| Floor covering material | Density, \( \rho \), [kg\( \cdot \)m\(^{-3} \)] | Dynamic stiffness \( S \), [N\( \cdot \)m\(^{-3} \)] | Crumple frequency, \( f_{crum} \), [Hz] | Growth \( \Delta L_n \), \[\text{dB} \text{OCT}^{-1} \] in the frequency range, [Hz] |
|-------------------------|---------------------------------|----------------|----------------|---------------------------------|
| | Carpet with a pile of 3÷5 mm, on the base of sponge rubber and latex | 100÷150 | 2,0\( \cdot \)10\(^8 \) | 64÷80 | 4 | 10 | 18 |
| A | Linoleum PVC TSI on the sub-base from the mix of secondary and synthetic fibers, and on the sub-base from chemical fibers with a thickness \( \geq 4 \) mm | 100÷180 | 2,0\( \cdot \)10\(^8 \) | 64÷80 | 4 | 10 | 18 |
| | Linoleum PVC TSI on the sub-base from the mix of secondary and synthetic fibers, and on the sub-base from chemical fibers; | 200÷250 | 5,0\( \cdot \)10\(^8 \) | 80÷125 | 1 | 3 | 6 |
The same on the sub-base from jute and bast fibers, with a thickness of 2÷3 mm

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |
| PVC-TSI linoleum on a foam base with a thickness of 2÷3 mm | 500 | 8·10^8 | 160÷315 | 1.0 | 1.5 | 4.5 |

Linoleum on the base of cork and jute fiber with a thickness of 2÷3 mm

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |
| 300÷500 | >10·10^8 | >315 | - | 1.5 | 4.5 |

As an example, the figures 2 and 3 show the calculated frequency characteristics of $\Delta L_n$ for floor covering materials A, B, C and D, which are constructed by the semi-graphical method. Later, it is possible to get the resulting graph of the normalized impact noise level, $L_n$, by combining the frequency response of the structural floor layer (for example, of a reinforced concrete slab), $L_{n0}$, with the graphs A, B, C and D, accordingly to formula (3). Then, the index of the normalized level of the impact noise under the floor, $\Delta L_{nw}$, can be found, due to the methods of normative documents.

![Figure 2](image-url)  

**Figure 2.** The frequency response of $\Delta L_n$, [dB], for materials A and B (table 1).
4. Conclusions
The material, which is presented in the article, allows to draw the following conclusions.

1. Design solutions for the application of various variants of rolled floor coverings are very diverse and depend on the operating conditions.

2. Sound insulation qualities of the floor covering material can be evaluated regardless of the material and of the floor slab, on which it is laid.

3. The effect of local crumpling is manifested in the two-layer floor and the growth of impact noise insulation due to the floor covering material begins, starting from the frequency of crumpling, \( f_{\text{crum}} \), when the linoleum surface being in the process of hitting it or walking.

4. The main physical and mechanical characteristics of local crumpling at impact are the contact time \( \tau \) and the time (degree) of delay of the complex elastic modulus \( E_q \) and the malleability \( J \).

5. Based on the proposed calculation algorithm and the physical and mechanical parameters presented in the article for certain floor covering materials, it is possible to obtain the frequency response of the floor covering \( \Delta L_n \) for the most common roll materials, as well as a graph of the normalized impact noise level, \( L_n \), for a complete floor structure over the entire normalized frequency range.

References
[1] Park S H and Lee J L 2017 J. Build. and Env. 116 173 https://doi.org/10.1016/j.buildenv.2017.02.005
[2] Park S H and Lee P J 2017 12th ICBEN Congress on Noise as a Public Health Problem (Zurich)
[3] Effects of floor impact noise on people – annoyance and physiological responses, https://www.researchgate.net/publication/319007518_Effects_of_floor_impact_noise_on_pe ople_-_annoyance_and_physiological_responses
[4] Gerasimov A I and Saltykov I P 2019 Premises of the Buildings from a Perspective of Physical
and Technical Parameters of Enclosing Structures (Moscow, Berlin: Direct-Media) p 175 DOI: 10.23681/496800

[5] Maderuelo-Sanz R, Morillas J M B and Escobar V G 2014 European J. of Wood and Wood Prod. 72(6) 833

[6] Gerasimov A I 2019 The Sound Insulation Designing of Interfloor Slabs with the Roll Floor Covering (Moscow; Berlin: Direct-Media) p 107 DOI: 10.23681/5613

[7] Bastos R F and da Silveira P M 2016 Conference: 41st IAHS WORLD CONGRESS (Portugal)
https://www.researchgate.net/publication/316361200_LINOLEUM_AS_FLOOR_COVERING_CHARACTERISTICS_APPLICATION_AND_MAINTENANCE

[8] Bouttout A and Amara M 2016 Int. J. of Arch., Civ. and Const. Science 10(1) https://doi.org/10.5281/zenodo.1338720

[9] Kreytan V G 1980 The Sound Insulation Providing in Process of Residential Buildings Construction (Moscow: Stroyizdat Publishing) p 171

[10] Nikol'skiy V N and Zaborov V I 1964 The Sound Insulation of Large Panel Buildings (Moscow: Construction Literature Publishing) p 243

[11] Pinte G, Boonen R, Desmet W and Sas P 2009 J. of Sound and Vibration 319(3–5) 768 https://doi.org/10.1016/j.jsv.2008.07.016

[12] Gerasimov A I and Saltykov I P 2019 E3S Web of Conferences 110, 01066 https://doi.org/10.1051/e3sconf/201911001066

[13] Skudrzyk E 1976 The Foundations of Acoustics (Moscow: Mir Publishing) p 520