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Sound transmission loss of vacuum insulation panels

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The sound transmission loss of a variety of vacuum insulation panels (VIP) was measured in the laboratory. Core materials of the VIP include silica, polyurethane, micro fleece, and glass fibers. Mass law behavior and minima due to bending-wave coincidence and thickness resonance have been observed. Destroying the vacuum may reduce the sound insulation drastically. Since in practical applications the VIP need protection, the predominant interest lies in the transmission loss of multi-layered assemblies, e. g. VIP sandwiched between aluminum plates. Calculations performed by the software LAYERS show that with additional "decoupling" layers (air, rubber) the coincidence dip can be avoided or shifted to higher frequencies, where it is less critical. Preliminary experimental realizations indicate the important role of a proper gluing of the layers. According to further LAYERS calculations, attachment of VIP to massive walls and protection by a plaster layer does not change the transmission loss of the wall appreciably, except for the VIP with the soft polyurethane core material.

1 Introduction

Vacuum insulation panels (VIP) are increasingly used for thermal insulation of buildings, e. g. in floors and terraces, in walls and façades [1]. Therefore it seems appropriate to investigate also their acoustical properties, since until recently, hardly anything was known in this respect [2]. The main results of a research project [3] carried out at the Fraunhofer Institute for Building Physics (IBP) are reported below. More details may be found in [4].

2 VIP variants

A total of 30 vacuum insulation panels with various core materials have been examined (Table 1). Their size was approximately 1.0 x 0.6 m²; the cover consisted of a metallized high-barrier foil of 0.1 kg/m². The last column of the table gives the weighted sound reduction index R_w according to the mass law. It was calculated for 'field incidence' with maximum angle Θ_{max} = 78° from

$$R_w \approx 20\lg(1 + 3.4\,m) \qquad (1)$$

with the mass per area, *m*, in kg/m² and rounded to the nearest integer [5].

Core Material	Thickness [mm]	Mass [kg/m²]	$R_{w\ \text{Mass Law}}$ [dB]
Silica	10 .. 33	2.2 .. 5.7	19 .. 26
Open-Pore Polyurethane	20 .. 30	1.5 .. 2.2	16 .. 19
Micro Fleece	7 .. 14	1.7 .. 3.0	17 .. 21
Coarse Glass Fiber	4	1.7	17
Powder Variant	15 .. 33	3.8 .. 5.8	23 .. 26

Table 1 VIP Variants

3 Transmission loss of single VIP

3.1 Measurements

The transmission loss of single VIP was measured in a door testing facility, where the standard test opening was reduced by a highly insulating screen. Due to the small size of the samples the accuracy of the measurements is diminished in comparison to routine measurements with standard sizes, in particular at lower frequencies. Nevertheless, the accuracy was considered sufficient for the objectives of research. Tendencies above 315 Hz or even better above 800 Hz should be reliably recognizable. Supplementary measurements on foils and a steel plate support this belief.

Typically, the results show mass law behavior with a subsequent decline to a minimum. The weighted sound reduction indices R_w lie between 18 dB and 29 dB, partly above and partly below the mass law values in table 1.

In addition, the transmission loss was measured after piercing some small holes into one side of a VIP and thus destroying the vacuum. Figure 1 shows an example (VIP with porous silica, 10 mm thick) including the mass law curve as a reference. Surprisingly, a similar VIP showed a different behavior after piercing. The change of acoustic properties appears to be highly non-uniform among the panels tested. However, as a rule the effect was a deterioration of the transmission loss, in the extreme case up to 19 dB in R_w.

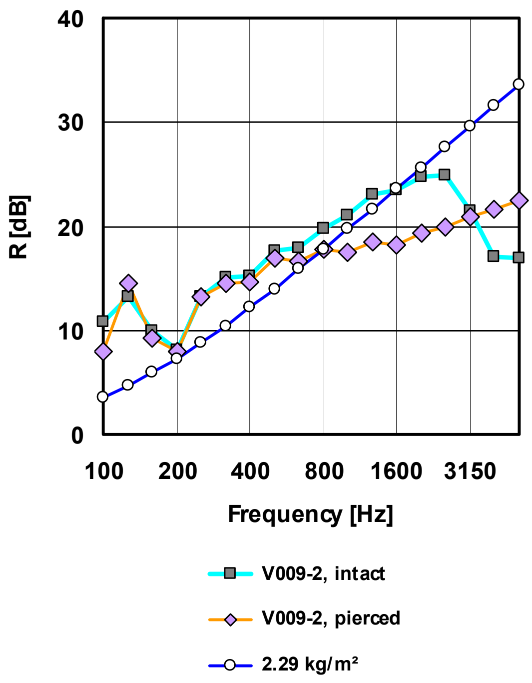

Figure 1
Measured sound reduction index of a VIP (porous silica, 10 mm thick) before and after perforating the cover.
For comparison: mass law (2.29 kg/m²)

3.2 Numerical Modeling

The IBP software LAYERS [6] based on [7] was used for simulating the measured transmission loss results. For low frequencies the mass law is obtained, since the layered structure is assumed as infinite. Each VIP is modeled as a homogeneous plate; the cover is not considered separately. Mass density was known, bending stiffness and loss factor were estimated from the measured coincidence dip. Poisson's ratio was set to 0.25 for all VIP.

Measured and calculated values approximately agree above 800 Hz (see Figure 2 as an example). The general behavior of the VIP can be roughly described as "mass law followed by coincidence dip". On this level no particular "vacuum effect" is observed. A closer look reveals various deviations, such as the exact depth of the coincidence minimum or the second minimum at 5 kHz in Figure 2, which are not consistent with the assumption of a homogeneous isotropic plate with frequency-independent properties.

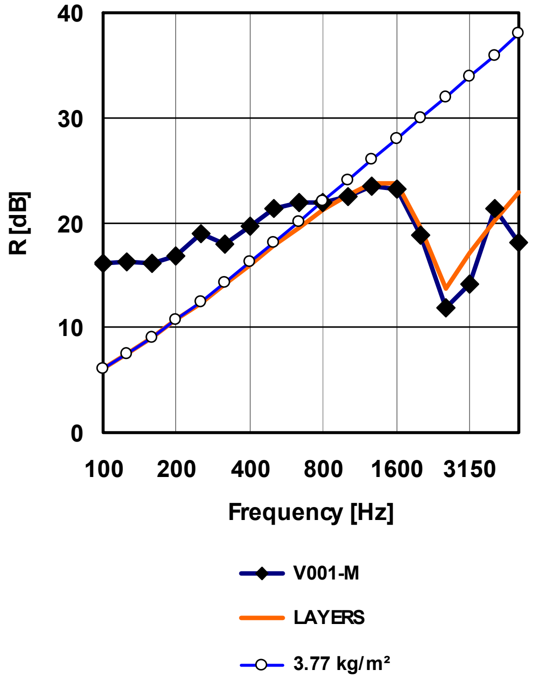

Figure 2
Measured sound reduction index of VIP (average V001-M of two porous silica VIP, 20 mm thick),
LAYERS calculation and mass law (3.88 kg/m²)

As an exception, the 30 mm thick VIP with soft open-pore polyurethane shows a minimum at 5 kHz, which is not a bending-wave coincidence dip but due to the first thickness resonance. Hence, this plate can no longer be considered as acoustically thin.

3.3 Modal analysis

In order to estimate loss factors and elastic constants experimental modal analysis was performed on freely suspended VIP using a scanning laser vibrometer and a loudspeaker for excitation. For intact VIP, the measured loss factors amount to a few percent (3% on average), Young's modulus ranges from 0.05 GPa to 0.5 GPa and Poisson's ratio is typically 0.3 or 0.4. The elastic constants have been determined from a few modes by the IBP software MODULI [8] assuming an isotropic homogeneous plate. The eigenfrequencies of the modes used were all below 250 Hz. Hence these results are valid for low frequencies.

There are significant differences between these Young's moduli and those used in the LAYERS calculations, which were chosen for matching the transmission loss in the kHz regime. Obviously, the elastic constants and consequently also the loss factors seem to be frequency dependent. A more detailed modeling should probably consider some anisotropy or even inhomogeneity.

4 Façade panels with integrated VIP

4.1 Measurements

As a possible application of VIP in buildings some preliminary versions of façade panels with integrated VIP were investigated. The face sheets consisted of aluminum (2 or 2.5 mm thick). Starting from the basic three-layer configuration Aluminum – VIP – Aluminum it was attempted to decouple the face sheets from the core by inserting one or two additional soft layers. Astonishingly, all measured transmission loss curves turned out to be rather similar with a minimum around 500 Hz and $R_w \approx 30$ dB, which is about 3 dB less than the mass law value.

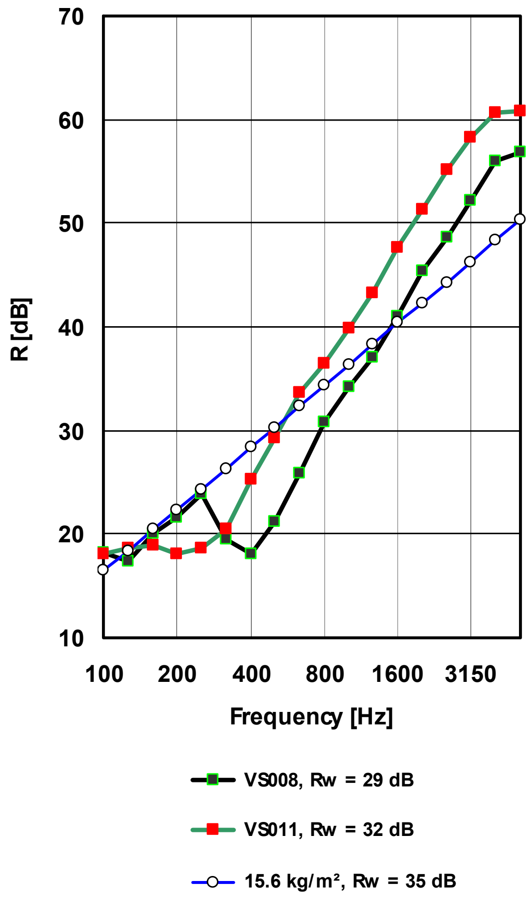

Figure 3
Measured sound reduction index of two façade panels
and mass law (15.6 kg/m²)

Figure 3 shows the results for two variants with five layers, Aluminum – Rubber – four VIP side by side – Rubber – Aluminum, one (VS011) with the layers glued to each other and without frame, one (VS008) with a frame but without glue. The layer thicknesses were 2 mm (Aluminum), 1 mm (rubber), and approx. 11 mm (VIP). Since these panels were designed for the windows testing facility, their size was 123 x 148 cm². Gluing obviously results in an improvement amounting to 3 dB in R_w, but does not completely eliminate the minimum. The weighted sound reduction index still falls short of the mass law value $R_w = 35$ dB. As will be evident from the theoretical studies described below, this is probably due to deficiencies of the gluing. A detailed interpretation of the two measured transmission loss curves is difficult, because the contact conditions between the layers are poorly defined.

4.2 Theoretical studies

Multilayered panels with aluminum face sheets and a VIP core were also studied theoretically. It was assumed that the layers are in perfect contact with each other. The basic three-layer configuration Aluminum – VIP – Aluminum shows a pronounced coincidence minimum at 630 Hz (see Figure 4), which is caused by the increased total bending stiffness compared to the VIP alone. The weighted sound reduction index is only 20 dB, 14 dB below the mass law value. After insertion of two air layers the minimum is shifted to higher frequencies. However, it is no longer due to a bending-wave coincidence but caused by a thickness resonance. Therefore, the thinner air layers lead to a higher resonance frequency. With two air layers 0.1 mm thick R_w can be raised to 32 dB.

Since such thin air layers are not easily realized in practice, alternatives are desirable. Figure 5 shows the effect of two 1 mm thick rubber layers. They cause the mass law to be valid over three more octaves; R_w reaches the mass law value of 34 dB. The two rubber layers can be substituted by one with appropriate thickness without significantly changing the transmission loss. However, a "perfect" contact between the layers is required. Otherwise – like in the experiments described above – the acoustic performance will not meet the expectations.

The mass law may be "saved" by aiming at a total ("effective") bending stiffness as small as possible so that the coincidence dip moves to frequencies beyond 3 kHz, where it is barely disturbing. Or, the face sheets are decoupled from the core in order to generally inhibit bending waves of the layered structure as a whole. This decoupling, however, may make the panel too soft in the thickness direction and thus lead to an undesirable thickness resonance. The 1 mm thick air layers are already too soft! But if one succeeds in providing for a sufficient stiffness in the thickness direction, the validity of the mass law can be considerably extended to higher frequencies.

Low bending stiffness and high stiffness in the thickness direction can be achieved not only by a suitable combination of homogeneous isotropic layers – as exemplified above – but also by a single homogeneous plate with anisotropic elasticity. This was demonstrated recently [9, 10] with the case of a fictitious medium with finite stiffness in the thickness direction (Voigt constant c_{33}) and vanishing stiffness in all other directions (all other $c_{ij} \approx 0$). Compared to an isotropic plate with the same c_{33}, the "gain" in mass law behavior is about five octaves. However, for the VIP types considered here an anisotropy of this kind does not seem to be a realistic option.

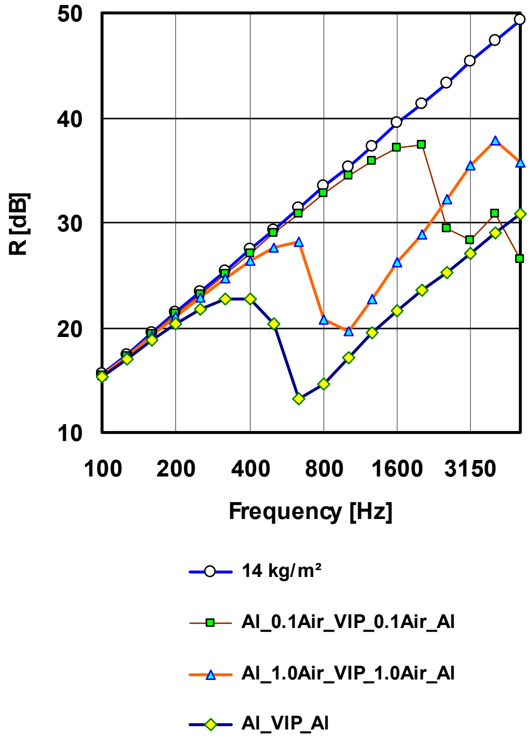

Figure 4
Sound reduction index of plates consisting of three or five layers with 15 mm thick VIP (calculated with LAYERS) and mass law (14 kg/m²). Air layers: 0.1 mm or 1.0 mm thick

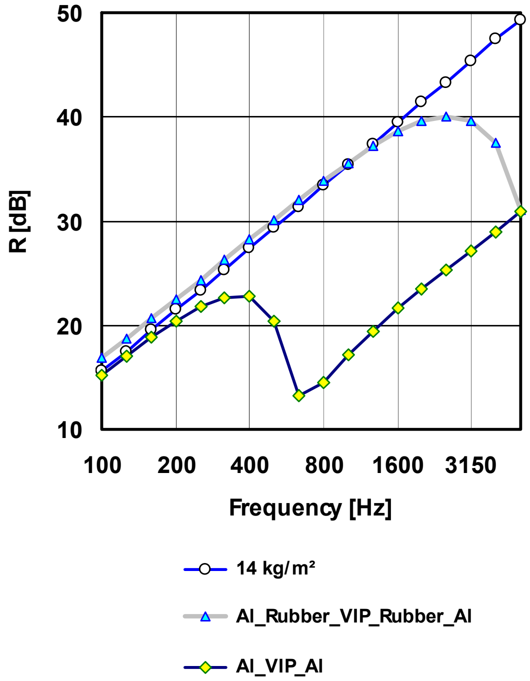

Figure 5
Sound reduction index of plates consisting of three or five layers with 15 mm thick VIP (calculated with LAYERS) and mass law (14 kg/m²). Rubber layers: 1 mm thick

5 Massive wall with attached VIP

A second possible application of VIP in buildings is the improvement of the thermal insulation of massive walls. The VIP attached to a wall will certainly have to be protected, e. g. by a plaster layer. If the acoustical properties of the layers involved are known, the sound transmission loss can be calculated easily with LAYERS. As an example a 25 cm thick porous-concrete wall (177 kg/m²) was chosen, since its transmission loss could be modeled by LAYERS rather well above 200 Hz [6]. Figure 6 shows the curve of the massive wall (MW) and nine curves of the system "massive wall – VIP – 10 mm plaster" with nine different VIP, modeled as described in section 3.2. In most cases, the transmission loss of the massive wall is little affected by the attachments. Only the polyurethane VIP V005 (30 mm thick) and V006 (20 mm thick), the vacuum insulation panels with smallest Young's modulus, induce a significant deterioration.

This effect is well-known. The resonance frequencies can be estimated according to the mass-spring-mass model. The spring must not be too soft. The transmission loss minimum may be mitigated by an increase of the material damping of the VIP. However, the loss factors needed would be quite high.

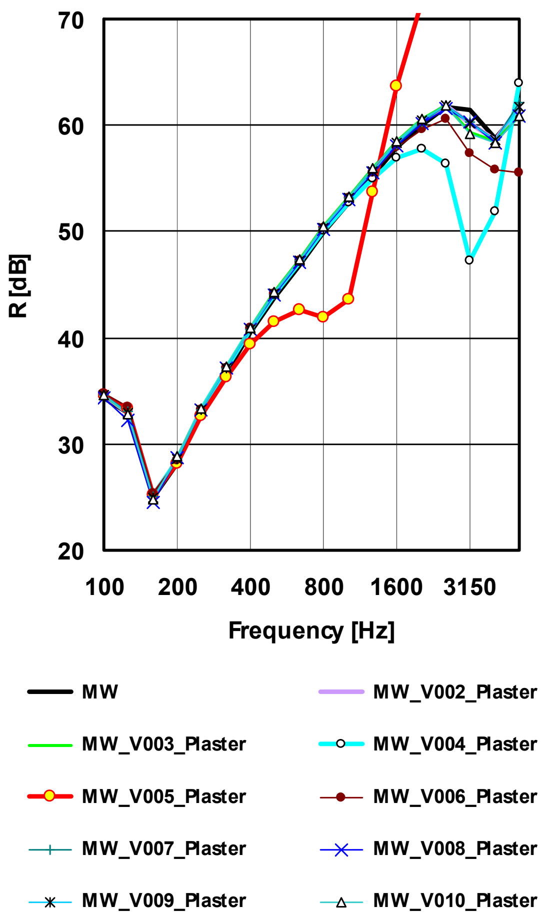

Figure 6
Sound reduction index of a porous-concrete wall alone (MW) and with attached plastered VIP V002 to V010 (calculated with LAYERS)

6 Conclusion and Outlook

The transmission loss curves of vacuum insulation panels can be approximately described as following the mass law until they bend off to a minimum, which is caused by the bending-wave coincidence or the first thickness resonance. This familiar overall behavior is as expected for homogeneous isotropic plates with frequency-independent properties. No spectacular features – possibly related to the evacuated interior – were observed. The transmission loss minima of the examined VIP were at 2 kHz or higher, partly above 5 kHz. If the vacuum of a VIP is destroyed, the sound reduction is generally reduced.

Experimental determination of elastic moduli from some low-frequency eigenmodes indicates that the elastic constants and loss factors of the VIP are presumably dependent on frequency to a certain extent. Anisotropy and even some inhomogeneity might also not be negligible for an accurate theoretical modeling of the transmission loss.

For practical applications the transmission loss of layered systems with internal VIP is important rather than that of a "naked" VIP. As a first example façade panels were investigated. Theoretical studies offer solutions for avoiding detrimental resonance effects within the frequency range of interest. Attempts of practical realizations have not yet been completely successful. The main reasons are presumably difficulties in gluing the layers.

A massive wall with an attached plastered VIP was the second practical example, which was treated purely by computation. Except for the two polyurethane VIP, which are rather soft, there was no essential decrease in the transmission loss of the porous-concrete wall.

The present investigation constitutes a first experimental and theoretical basis for building-acoustic implications of various types of VIP. Several questions remain unanswered concerning fundamental issues like anisotropy and frequency dependence of elastodynamic properties as well as practical problems to optimize multilayered constructions. Impact sound insulation involving VIP could be an additional practical subject worth investigating.

Acknowledgments

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