# The use of textile membranes in architectural acoustics. An overview.

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**Summary**
The structural skins, based on textile membranes became very popular building materials in the modern architectural design. Their great potential lays in their high tensile strength, flexibility (such as a possibility to create organic shapes), long lifespan, translucency, minimum weight and low material and maintenance costs. Looking at their acoustic properties, probably the most interesting are acoustical components such as multilayer membrane-type structures and micro perforated and double- leaf absorbers. This paper summarizes the use of textile membranes in architectural acoustic nowadays and in the past, discusses advantages and disadvantages in terms of sound insulation, acoustic permeability and sound absorption and shows several interesting case studies where structural skins were used with great success.

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## 1. Introduction

The great potential of structural skins, based on textile membranes lays in their flexibility and possibility to create organic shapes, in their high tensile strength, little weight, low material and maintenance costs. Many of them allow for sufficient penetration of daylight into building interior, which enables functioning of the architectural space without additional artificial lightning during daytime. All the mention factors make structure based membranes very popular in their usage as building materials in the modern architectural design.
Probably the most interesting structures in nowadays architecture are acoustical components such as multilayer membrane-type structures and micro perforated and double-leaf absorbers. Membrane structures and membrane materials are very often used as for coverage of large indoor spaces. Most common are temporary or permanent roof structures for sports halls or stadiums or places for music festivals or large receptions.
There are a lot of different kinds of textile membranes: woven, non-woven, knitted etc. Their acoustic properties in relation to architectural design can be investigated from different points of view. The most common are studies of their properties in relation to (1) room acoustics, e.g. sound absorption and (2) building acoustics, e.g. sound insulation. Both, room acoustic and building acoustic design contribute to overall acoustic comfort [32, 33].

## 2. Material and acoustic properties of skin structures

### 2.1. Sound absorption

Sound absorption is defined as the level of conversion of the incident sound energy to another form according to law of the energy conservation. This energy is usually converted to heat due to viscosity, friction and non-adiabatic sound propagation. However, in practice the acoustic pressure is quite low compared to the atmospheric pressure and the heat produced by absorption is therefore quite low. Soft, porous materials typically absorb part of arriving sound energy.

The absorption of a material is in room acoustic design typically determined by the absorption coefficient $\alpha$ [-], which is defined as a ratio between the sound energy absorbed by a material surface $E_a$ and the incident sound energy $E_i$. $\alpha$ can vary between 0 and 1 (or sometimes expressed as 0% - 100%). Values of material absorption vary with the angle of incidence and the statistical value of α is an average value over all possible angles of incidence. Measurements of the average overall sound absorption are performed in so called diffused field, e.g. reverberant room.

From the point of view of physics, different types of absorption mechanisms exist. Porous materials absorb sound waves at high and middle frequencies, typically above 500 Hz (i.e. sounds with a short wave length); membranes are good sound absorbers at low frequencies less than 200 Hz (i.e. sounds with longer wave length). Other type of absorbers are different resonators (e.g. Helmholtz resonator) are typically absorbing sound in a particular frequency or at certain narrow frequency range.In reality, absorption is caused not only by building materials, but any object in a room such as furniture, people etc. Nonwoven fabrics have typically low sound absorption coefficient at low frequencies. To absorb low frequency sounds would due to their long wavelength result in very think structures (for sounds <100Hz it would mean 1 meter thick porous structure).

On the other hand, in case of middle and high frequencies, improvement of the sound absorption can be reached by the thickens of the material (typically couple of centimeters). One of the typical solutions is therefore increase of the thickness of nonwoven samples.

To increase the sound absorption in low and mid frequency range is solved by adding the air space behind the textile membrane structure [3, 4].

Thick curtains, blankets or similar materials absorb sound thanks to their texture, which consist of lots of small deeply penetrating connected pores. While sound waves propagate in these fiber structures a part of the sound energy is due to friction and viscous resistance within the pores and by vibration of the small fibers converted to heat. Absorption of these structures can relatively easily reach values of alpha > 0.9 (resp. < 90%).

When speaking about porous materials, it is important to understand, that a good thermal properties require different type of material than acoustically absorptive materials. In case of the thermal insulation, pores should be closed (such as polystyrene); while in case of acoustical absorption they should be intercommunicating (not plastered mineral wool). [5].

Sound absorption at low frequencies is based on a different principle. Typical is usage of panel membranes. These are after a hit of a sound wave forced into vibration and convert a part of the acoustical energy into heat. The actual amount of absorbed sound energy depends on a stiffness of the panel. In case of high stiffness, vibration of the panel will be small. Flexible and light membranes absorb, in general, larger amount of sound energy.

A lot of information on the development of textile structures with a special kind of structures such as spacer fabric flat-sheet membranes-weft-knitted and warp-knitted can be found in the literature [6]. Weft-knitted fabrics behave like a typical porous sound absorber, while warp-knitted fabrics express the behavior of micro-perforated panel absorber. To increase the sound absorption at high frequencies it is very important to place layers in correct order in the give structure. The sound absorption coefficients of the warp-knitted spacer fabrics backed with weft-knitted fabrics are higher than weft-knitted spacer fabrics with back layer of warp-knitted fabrics. Placing of more layers on top of each other has effect just up to 4 layers. To get higher sound absorption coefficients at low and middle frequencies, air cavity between two layers can be replaced by multilayered warp-knitted spacer fabrics [3].

Textile membranes are also widely used in automotive industry. Using of textiles to cover interior parts of the cars can provide passive sound absorption and it is considered as one of the solutions on noise reduction in the interior of modern automobiles. Previous research studies confirmed that knitted structures with a little porosity and small pore sizes have good sound absorption, therefore thicker knitted fabrics with little amount of pores are suitable material which you can use in the space of driver and passengers to absorb undesirable noise - denser knitted and thicker fabric structures has obviously higher sound absorption coefficients [7].

The problem of some indoor spaces covered by membrane structures lays in their low sound absorption. This can lead to a long reverberation time, which degrades the quality of acoustic environment.

Membrane structures are mostly used to form the ceilings and roofs. Using of double-membrane structures can help in improvement of acoustic conditions thanks to improvement of their acoustic performance. The double-leaf membranes may be used as special sound absorbing elements that can be used as a partition without massive back wall [8, 9].

Commonly used absorbers based on membranes are normally formed by single membrane, which is suspended parallel to a massive back wall. An air cavity within a gap is formed in such structures. Since the membrane itself has not a large absorptivity, the absorption in the cavity plays an important role, unless the membrane acoustically permeable. In the study case from Kiyama [10], was the absorptive cavity formed by back wall. This cavity provides mass-spring resonance absorption. In the mention study it has been concluded, that these walls must have at least mass of a concrete wall.

In the literature also other experiments can be found, with a focus on the examination of the mass-spring resonance absorption with lighter back walls. Equivalent absorption characteristics using a light-weight double-leaf membrane instead of massive back wall and with adjusting of parameters of the structures has been reported in [9, 10, 11, 12, 13].

The vibration sound absorption theory was described by Zhang in 2008 [14], who describes the possibility of tuning of the vibration eigenfrequencies by varying the membrane and mass properties. In membranes the restoring force grows because of the tension applied to the membrane. The first resonance frequency and the transmission loss peak frequencies depend on the attached mass. The second resonance frequency is influenced by the property of membrane [15].

The sound absorption of membranes is influenced by changes in flow resistance values too. When flow resistance is low, sound absorption is about 1.0 in the whole frequency range. The decrease of absorption with increasing frequency is caused by higher values of flow resistance. On the other hand, effect of mass of the membrane appears mainly at low frequencies. The energy loss of the permeable membrane decreases at low frequencies due to the effect of finite mass [1]. In 1998 the angular dependence on sound absorption of permeable membranes was studied by Sakagami. The result of the study says, that the sound absorption increases with the angle of incidence [2].

### 2.2. Sound transmission loss

Sound insulations of textile structures is always assumed to be very bad. The study of Narang from 1995 shows that the installation of polyester blankets in a cavity of lightweight walls built of plasterboard using steel supporting structure can increase their sound transmission loss. The blankets are effective in the frequency range of 100-5000 Hz [20]. The calculation of sound insulation below the coincidence frequency is possible using the mass low. However, this formula is determined for infinite plates. Therefore, the effects caused by finite size of plate, such as resonant vibration and frequency dependent radiation efficiency, are not taking into account. [24] The statistical analysis of related experiments showed another important fact, that the transmission loss of sound wave of a particular frequency was mostly dependent on the fabric cover factor. Thickness and weight of the fabric have not such significant influence [25].

Transmission loss of double-panel structures which are lined with foam, dependents on the way of attaching the foam to the front wall panel: (1) The foam is directly attached to the panel, the frame wave is dominant because of the direct excitation of solid phase of insulation by the facing panel. Also the match of impedance between the frame wave and the panel is much better. On the other hand when there is an air space between the insulation and the wall panel, well-damped airborne waves are better excited in the lining in comparison with excitation in the frame and also shear waves. Therefore, to maximize the transmission loss, unattached boundary conditions are preferred [8].

#### 2.2.1 Attaching small weights to the membranes

Sound transmission through thin membranes could possibly be reduced in some frequencies by making them inhomogeneous. One way is to attach the small masses to the membranes – resulting in

so called membranes with additional weights (MAW) [21].
Several experiments were performed on sound insulation under conditions of normal incidence of sound. It has been found, that it is possible to improve sound insulation efficiency by attaching small weights to a membrane. This improvement has been observed in the frequency range from natural frequency of the whole membrane up to that of the partial area divided by the additional weights. This effect is not caused by the well-known mass law [23]. It is cause by the interference between modal shapes at the frequencies, which were mentioned earlier. The positive effect of this simple method is mostly in a lower frequency range and it is also possible to tune it [1]. Experiment of Hashimoto from 1996 showed that double-layer membrane consisting of ordinary membrane and MAW has 5-11 dB grater transmission loss values in the low frequencies in comparison with double-layered membrane made from two ordinary membranes. This effect is present when the thickness of air layer is between 100-500 mm [16].
Attaching small circular weights in the middle of square membrane structures helps to increase sound transmission loss in broad frequency range from 50 to 1000 Hz [17]. This frequency range is shifted to the 100-1000 Hz in case of circular membranes with additional circular weight attached to the center [18].

### 2.3. Permeability

A basic idea for representing the permeability comes from [19]. Permeability is expected to be the most significant parameter, which determines the acoustic properties of membrane structures. Membranes, which are used as a building materials have a certain degree of acoustics permeability, which has been disregarded in general membrane-vibration theory. The different permeability may have serious influence, especially on acoustic properties [11].
Sakagami in his work described two particular parameters for permeable membranes - increase of transmission loss and the drop in energy loss at low frequencies. This drop of energy loss can be described as an increased vibration, which makes the flow velocity in the membrane structure smaller. The effect of flow resistance is considered to have equivalent effect to addition of mass, which increase the transmission loss at low frequencies [2].
The improvement of sound absorption performance in high frequencies can be significant and can make the characteristics equivalent to those of cavity-backed porous absorbents. The permeability also influences sound properties of membrane at low frequencies. At middle frequencies, a mass-spring peak appears, when the permeability is very high and vanishes when it has lower values. There are some more variables which influence the sound properties of permeable membranes - flow resistivity, depth of cavity behind the membrane and mass of the membrane.
The parametric study of Takahasi from 1996 [22] shows the effect of tension, surface density and flow resistance of permeable membranes on sound transmission loss as well as sound absorption.

## 3. Acoustic comfort in tent structures

The tensile membrane structures are modern and innovative technologies used in building industry. Although membrane structures are able to cover huge spaces without using any column and beam and they are even able to save electricity for illumination because of their light transmission properties, they have also some shortcomings. Often reported problems are rain-noise problems, sound-insulation performance and thermal insulation [26]. Structures built with using of membranes have often several acoustical problems such as flutter echo, standing waves, sound focusing and strong late reflections (later than 100 ms), which significantly decrease speech intelligibility. The tensile membrane structures should ensure the optimal loudness, sound energy, clarity and speech intelligibility in every part of the space [27]. To ensure the acoustic comfort [30, 31] in such structures is not easy, since the technologies common for traditional structures do not work for lightweight structures. Therefore we have to take into account a lot of different variables resulting from behavior of tensile membranes [26].

## 4. Noise from the rain

Lightweight materials, such as textile membranes, used as roof structures can possibly cause acoustical problems during rainy weather. The actual sound pressure level is influenced by many parameters, such as strain of the membrane etc. Rain drops falling on the roof are source of unwanted noise. There are several researches that have aimed on the problem of noise from the rain, regarding lightweight roofs [28]. One of the possibilities of protection against rain noise is adding of the absorptive layers and damping materials to the lightweight membrane roof structure. Placing of additional membrane on the roof structure could have adverse effect, but adding of good shock-absorbent material has definitely strong influence on the rain noise reduction. Moreover it improves performance at high frequencies [29].

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**References**

[1] Hashimoto, N., Katsura, M., Yasuoka, M., & Fujii, H. (1991) Sound Insulation of a Rectangular Thin Membrane with Additional Weights. In Applied Acoustics, 33(1), p. 21-43

[2] Sakagami, K., Kiyama, M., Morimoto, M., & Takahashi, D. (1998) Detailed analysis of the acoustic properties of a permeable membrane. In Applied Acoustics, 54(2), p. 93-111

[3] Liu, Y. P., & Hu, H. (2010) Sound Absorption Behavior of Knitted Spacer Fabrics. In Textile Research Journal, 80(18), p. 1949-1957,.

[4] Seddeq, H. S., Aly, N. M., Marwa A, A., & Elshakankery, M. H. (2013) Investigation on sound absorption properties for recycled fibrous materials. In Journal of Industrial Textiles, 43(1), p. 56-73

[5] Rychtarikova, M. (2009). Building physics : Introduction to noise control and building acoustics. Bratislava: STU v Bratislave,

[6] Doyen, W., Mues, W., Molenberghs, B., & Cobben, B. (2010) Spacer fabric supported flat-sheet membranes: A new era of flat-sheet membrane technology. In Desalination, 250(3), p. 1078-1082,

[7] Dias, T., & Monaragala, R. (2006) Sound absorbtion in knitted structures for interior noise reduction in automobiles. In Measurement Science & Technology, 17(9), p. 2499-2505,

[8] Bolton, J. S., Shiau, N. M., & Kang, Y. J. (1996) Sound transmission through multi-panel structures lined with elastic porous materials. In Journal of Sound and Vibration, 191(3), p. 317-347

[9] London, A. (1950) Transmission of Reverberant Sound through Double Walls. In JASA, 22(2), p. 10.

[10] Kiyama, M., Sakagami, K., Tanigawa, M., & Morimoto, M. (1998) A basic study on acoustic properties of double-leaf membranes. In Applied Acoustics, 54(3), p. 239-254,

[11] Sakagami, K., Kiyama, M., Morimoto, M., & Takahashi, D. (1996) Sound absorption of a cavity-backed membrane: A step towards design method for membrane-type absorbers. In Applied Acoustics, 49(3), p. 237-247,

[12] Sakagami, K., Takahashi, D., Gen, H., & Morimoto, M. (1993) Acoustic Properties of an Infinite Elastic Plate with a Back Cavity. In Acustica, 78(5), p. 288-295,

[13] Takahashi, D. (1992) Sound Transmission through Double Plates with Multiple Absorptive Layers. In 14th International Congress on Acoustics, Proceedings, Vols 1-4, p. 1027-1028.

[14] Zhang, X. A. (2008). The vibration sound absorption theory of flexible materials. Paper presented at the Acoustics'08, Paris.

[15] Zhang, Y. G., Wen, J. H., Xiao, Y., Wen, X. S., & Wang, J. W. (2012) Theoretical investigation of the sound attenuation of membrane-type acoustic metamaterials. In Physics Letters A, 376(17), p. 1489-1494,

[16] Hashimoto, N., Katsura, M., Nishikawa, Y., Katagihara, K., Torii, T., & Nakata, M. (1996) Experimental study on sound insulation of membranes with small weights for application to membrane structures. In Applied Acoustics, 48(1), p. 71-84,

[17] Yang, Z., Dai, H. M., Chan, N. H., Ma, G. C., & Sheng, P. (2010) Acoustic metamaterial panels for sound attenuation in the 50-1000 Hz regime. In Applied Physics Letters, 96(4),

[18] Yang, Z., Mei, J., Yang, M., Chan, N. H., & Sheng, P. (2008) Membrane-Type Acoustic Metamaterial with Negative Dynamic Mass. In Physical Review Letters, 101(20),

[19] Pierce, A. D. (1989). Acoustics, An Introduction to Its Physical Principles and Applications: Acoustical Society of America,.

[20] Narang, P. P. (1995) Material Parameter Selection in Polyester Fiber Insulation for Sound-Transmission and Absorption. In Applied Acoustics, 45(4), p. 335-358

[21] Novak, J. (2004). Bending-wave energy propagation in inhomogeneous thin plates and membranes. Paper presented at the Inter-Noise 2004, Prague, Czech Republic

[22] Takahashi, D., Sakagami, K., & Morimoto, M. (1996) Acoustic properties of permeable membranes. In JASA, 99(5), p. 3003-3009

[23] Fahy, F.J., & Gardonio, P. (2007). Sound and Structural Vibration: Radiation, Transmission and Response: Elsevier Science

[24] Novikov, I. I. (1998) Low-frequency sound insulation of thin plates. In Applied Acoustics, 54(1), p. 83-90.

[25] Nute, M. E., & Slater, K. (1973) A study of some factors affecting sound reduction by carpeting. In The Journal of The Textile Institute, 64(11).

[26] Patania, F., Gagliano, A., Nocera, F., & Cascio, G. M. (2014). Acoustic comfort inside tensile membrane structures: experimental investigation and corrective proposals for a lecture room. Paper presented at the The 21st International Congress on Sound and Vibration, Beijing, China.

[27] Zannin, P. H. T., & Zwirtes, D. P. Z. (2009) Evaluation of the acoustic performance of classrooms in public schools. In Applied Acoustics, 70(4), p. 626-635.

[28] Yan Xiang, et. al. (2008). Studies on the relationship between rain noisefrom lightweight roofs and rain

intensity. Paper presented at the Internoise 2008, Shanghai.

[29] Toyoda, M., & Takahashi, D. (2013) Reduction of rain noise from Ethylene/TetraFluoroEthylene membrane structures. In Applied Acoustics, 74(12), p. 1309-1314.

[30] Minarovičová, K. [100 %].Basic Measures of Sustainable Architecture. Advanced Building Construction and Materials 2014. VŠB - Technical University of Ostrava, Faculty of Safety Engineering, 2014. ISBN 978-80-248-3654-6, s. 104-108

[31] Dlhý, D. - Minarovičová, K. Acoustic quality of interior space - options for its improvement. In Akustika, 2014, vol. 21, no. 3, s.27-30

[32] Vargová, A. - Pavčeková, M. Noise Perception in Residential Building Environment. In Advanced Materials Research: enviBUILD Buildings and environment. International conference. Brno, CR, 25.-26.10.2012. Vol. 649 (2013), s.281-284. ISSN 1022-6680(P).

[33] Pavčeková, M. - Ondrušková, T. - Vargová, A. Assessment of Acoustical Properties in Small Rooms used for Speech. In Budovy a prostředí 2012 [elektronický zdroj] : Mezinárodní konference. Sborník. Brno,ČR,25.-26.10.2012. Brno : Vysoké učení technické v Brně, 2012, s.439-442.