Description of the acoustic characteristics of ETFE roof structures

Susanne Bron-van der Jagt
Level Acoustics & Vibration, Eindhoven, the Netherlands.

Claire Laudij
Level Acoustics & Vibration, Eindhoven, the Netherlands.

Eddy Gerretsen
Level Acoustics & Vibration, Eindhoven, the Netherlands.

Elma Phaff
Royal HaskoningDHV, Eindhoven, the Netherlands.

Theo Raijmakers
Royal HaskoningDHV, Eindhoven, the Netherlands.

Summary

ETFE structures are increasingly applied in architecture, because of their transparency. It is, however, difficult to realize sufficient sound insulation for these structures, and also to predict the insulation and the sound intensity levels due to rain for example. An ETFE roof is now being realized in a university building with noise-sensitive areas. In order to be able to design an acoustically adequate roof, several tests have been done with mock-ups in the Laboratory for Acoustics. The measurement results have been compared with predictions of the acoustical behavior. The results corresponded well. Some important prediction model have been looked at in more detail. The modal behavior was furthermore investigated with FEM and has been visualized with sound imaging measurements.

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1. Introduction

Among architects, there is a preference for lightweight and transparent envelopes. This can be problematic when they are used as a façade or roof for buildings that have noise-sensitive areas, such as working spaces. ETFE cushions combine transparency with relatively good room acoustical qualities. They are therefore in high demand with architects. Because they are superlight, the realization of sufficient sound insulation for these kind of envelopes, however, is a huge challenge. Describing the expected acoustical behavior of (roof) buildups with ETFE cushions is just as challenging.

This paper contributes to research on ETFE cushions in investigating sound insulation of several buildups of ETFE cushions. Because of our involvement in the design of a university building with working spaces and laboratories under an ETFE roof, we developed several roof solutions aiming at sufficient sound insulation for outdoor noise and rain noise. In order to get a grip on the acoustical behavior of ETFE structures we performed measurements on various buildups in our laboratory. The overall acoustical behavior of the roof has been studied, such as sound insulation and sound intensity level due to rain. Besides, several parameters, like loss factor and radiation efficiency, and the modal behavior have been looked at in detail. The acoustical behavior has also been visualized by sound imaging measurements. Measurement results of the mock-up have been compared with calculations. By fine-tuning the calculations for some less well known aspects to those results the calculation model becomes a practical tool for designing the actual roofs.

2. Methodology

2.1 Sound insulation measurements

Preliminary measurements on a mock-up have been performed in the Laboratory for Acoustics in accordance with ISO 10140. These measurements were performed to investigate the effect of the amount of layers of ETFE, air gaps, sound absorption between cushions/layers and the amount of cushions for the acoustical qualities of the structure. The sample size of this mock-up was 2 x 2 m^2. The height of the mock-up was 0,7 meter. The cavity is filled with 100 mm mineral wool around the sides in all cases with double cushions/layers except for one (to investigate the effect; the absorption resulted in about 5 dB higher sound insulation values). The cavity height of the cushions was 0,45 m in the center.

The preliminary measurements and investigative calculations led to the final design of the ETFE roof. A new mock-up was designed and again tested in the laboratory. The test setup of the new ETFE mock-up is shown in Figure 1.
The mock-up size was 2,55 x 2,55 m^2. The top layer is a reinforced double layer ETFE foil (1,1 kg/m^2), spanned over a steel arc. The bottom part is a four layered ETFE cushion with a thin cushion on the outside (100 µm) and on the inside a thicker cushion (250 µm).
The height of the mock-up is 1 meter and the cavity is filled with 100 mm of mineral wool around the sides. The cavity height of the cushion was 0,6 m, the height of the arc was 0,4 m. This mock-up was used for insulation measurements for both outdoor and rain noise and for the measurement of radiation efficiency.

2.2 Rain noise measurements

Rain measurements were performed in accordance with EN-ISO 140-18. A rain generator was specially developed for these measurements.
The generator has a surface of 1,6 m^2 and rain drops are spread equally over this surface. Rain types are classified in accordance to IEC 60721-2-2. The standard rain type that is recommended to test is heavy. The intense rain type is recommended when requirements for heavy rainfall cannot be met. This was the case for this test setup because of the limited height in the test room. Besides, for the university building in which the roof will be implemented, requirements for rain noise are set for intense rain covering most precipitation situations. The rainfall rate for intense rain is 15 mm/h, the drop diameter 1-2 mm and the fall velocity 2-4 m/s. The rain generator was directly attached to the tap water system and water falling from the roof was drained through a gutter around the roof. All requirements specified in the norm were met. The measurement set-up for the rain measurements is shown in Figure 2.

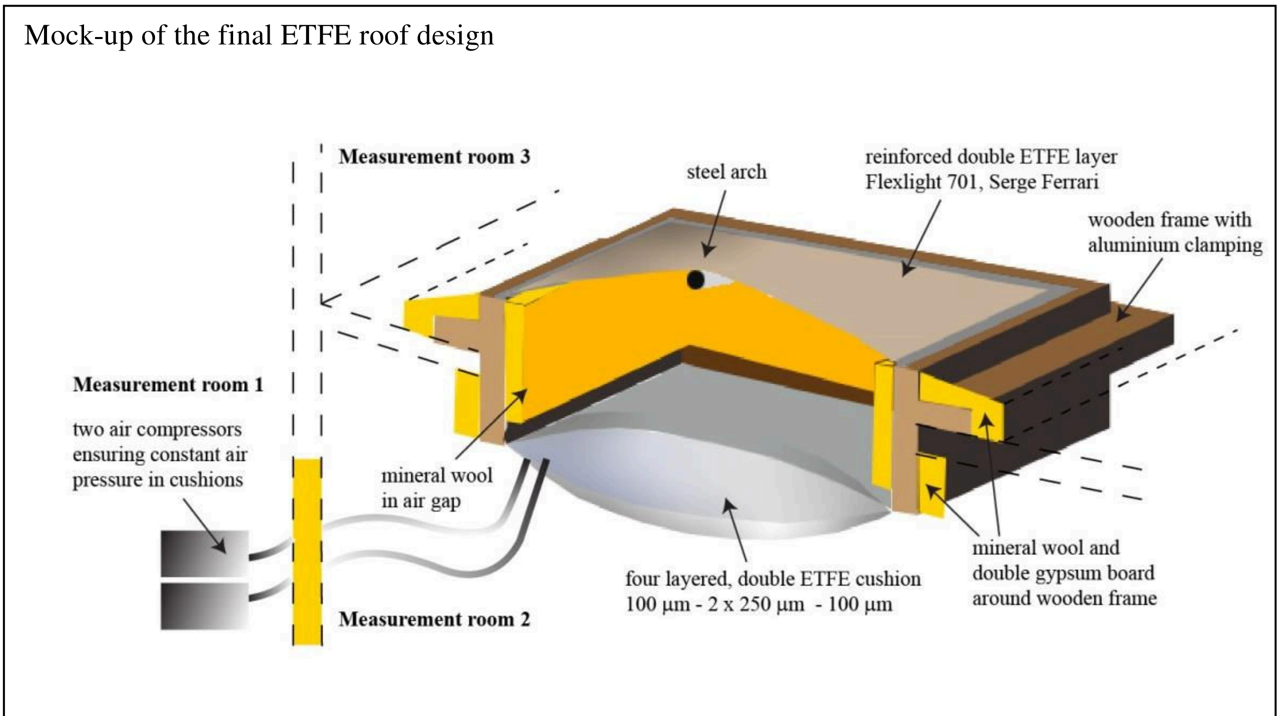

Figure 1. Mock-up of the final ETFE roof design

The rain generator ensured a constant drop diameter. During measurements the fall height and rain flow rate were varied to measure several rain situations, that are representative for the rain situation at the location of the building [1]. The rainfall rate was adjusted by varying the water pressure. The height and thus the fall velocity could be adjusted by means of the hoist. The fall velocities used were in the range that is required for the intense rain (2-4 m/s). The rain flow rate that was measured (11-18 mm/h) was around what is required for intense rain (15 mm/h). The position of the rain generator was altered between above center or above the side.

Rain measurement set-up

Figure 2. Rain measurement set-up

2.3 Radiation efficiency

The radiation efficiency and loss factor were derived from measurements using a Polytec laser-vibrometer. The vibrometer measured the velocity of the surface. This value was then related to the measured sound level in the diffuse field, measured with a calibrated ICP microphone in swing arm, to derive the radiation efficiency.

2.3.1 Sound imaging

Sound imaging results were acquired using a Sorama scanner making use of a MEMS microphone array containing 1024 microphones. Eigenfrequencies, mode shapes, particle velocities near the roof and sound pressure levels were derived.

2.4 Calculations

Prior to the measurements for radiation efficiency and loss factor, the modal behavior was examined using FEM. Sound insulation values were predicted using BASlab [2]. Sound intensity levels due to rain were predicted based on a combination of an existing rain noise model [3, 4] and the sound insulation values predicted with BASlab.

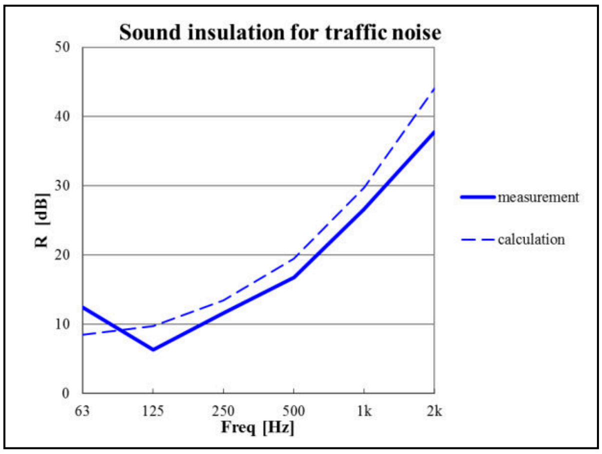

Figure 3. Sound insulation $R_{A;tr}$ for outdoor noise

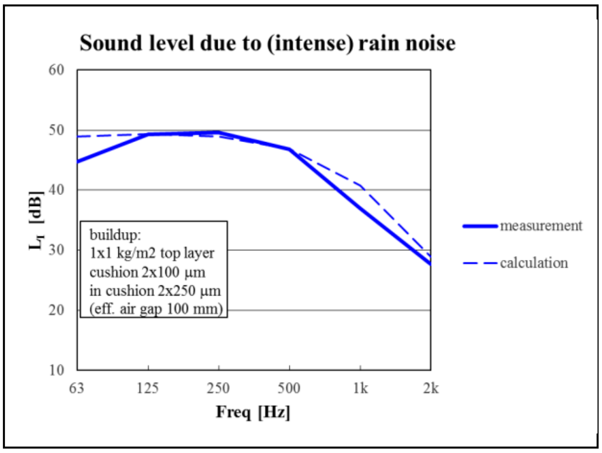

Figure 4. Sound intensity level L_I of rain noise

3. Results and discussion

3.1 Insulation for outdoor noise

The first mock-up tests resulted in a comparative overview of ETFE buildups and their relative improvement of the sound insulation, of which Table 1 shows some results.

Table I. Relative improvement on insulation of ETFE buildups

Configuration	*Improvement* $\Delta R_{A,tr}$
One pillow	0
Two pillows on air gap without sound absorption in cavity [1]	3
One pillow with an ETFE layer on air gap	6
Two pillows on air gap	9
One pillow with an additional PVC layer on air gap	11
Two pillows with an additional layer of ETFE on one pillow	11
Two pillows with additional ETFE layer in between	11
One pillow with two ETFE layers on two air gaps	12
Two pillows with additional layer of PVC on one pillow	14
Two pillows with an additional PVC layer in between	15

[1] In all other configurations in this table sound absorption, i.e. 100 mm mineral wool around the edges, in the air cavity between cushions/layers was applied

Table 1 shows that the best results were found when a buildup with two pillows was used with an additional PVC layer on the pillow or on an air gap. Because of fire safety and structural reasons (e.g. wind loads) a combination of a double cushion with one laminated and stiffened ETFE top layer (basically consisting of two ETFE layers glued on top of each other and stiffened by a grid of threads) was chosen for the final design, which also shows a large relative improvement for insulation.

The sound insulation $R_{A;tr}$ for outdoor noise of the final ETFE roof design is measured to be 19 dB (Figure 3). Measurements performed with the sound source in the air cavity showed that the sound insulation $R_{A;tr}$ for outdoor noise for the double cushion is 8 dB. The reinforced ETFE foil above the air gap and the sound absorption in the air gap seem to have a big influence on the total sound insulation.

Through calculations with BASlab [2] it was determined that the effective value of the thickness of a planar cavity in the calculations is 1/6th of the height of the cushion at the center.

3.2 Rain noise levels

Figure 4 shows the sound intensity level of the ETFE roof due to rain. For intense rain the sound intensity level is 46 dB(A). The resulting sound level in the building was calculated to be 55-60 dB(A), which was deemed acceptable by the client for open meeting points, circulation zones and restaurant under the roof. Variations occurred for different position of the rain generator above the roof. With same fall velocity, and with same rain flow rate, the intensity level L_{IA} was higher when the rain was falling in the center of the roof. The roof top layer might be stiffer locally because of the arc that is stretched underneath it.

These measurements in combination with an existing rain model made it possible to attribute more precise characteristics to the materials as used in the new structure. The E-modulus of ETFE when used as a foil was roughly known. When ETFE is used as a cushion, the material will have a different stiffness, because it is stretched. By comparing measurements with calculations in BASlab it was estimated that that E-modulus for stretched ETFE is approximately 16 times higher than non-stretched foil.

3.3 Radiation efficiency

Studies with FEM of the bottom layer of the cushion and the top layer of the structure show that these surfaces have rather pronounced modes in the low frequency range. The modal density is 1 or larger from the 160 Hz 1/3 octave band on. However, due to low loss factors, the modal overlap is small, around 0,1 for the first 200 Hz, while ideally the modal overlap should be reaching 1 for the spectrum area that is being researched. When modal overlap is low, the amount of measurement points has to be chosen carefully. In this mock-up twenty-five points were chosen, in a grid of 0,4x0,4 m (with the central point at the center of the cushion). Figure 5 shows that the radiation efficiency for different zones are

comparable. This means that the measurements together give an adequate idea of the performance of the surface as a whole.
To calculate the radiation efficiency, noise was played in the top chamber, and the radiated power was measured with the vibrometer for the bottom layer. Because the structure is excited by airborne noise, the expectation is that the radiation efficiency lies in between the calculated graphs for forced waves and resonant waves. Measurements showed that this is the case.

Additionally the radiation efficiency was measured with excitation by hand (imitating rain) and hammer. Both excitation and measurement were on the bottom layer in order to investigate the radiation efficiency of the cushion itself and reduce the influence of the acoustics of the structure. A peak around the 200 Hz can be seen in Figure 6 for excitation by hammer. This peak derives from the radiated sound power, and not from the vibration levels of the cushion. A possible explanation for this is cavity resonance. The peak is not seen in the intensity levels for rain, so it has no effect on sound insulation for rain noise. Figure 6 confirms furthermore that the higher stiffness was rightly assumed.

The loss factor of the cushion is determined by the decay time of the hammer measurements. The calculated graph is fitted, because it is not possible to theoretically determine its boundary losses. The very low assumed internal loss factor of 0,0005, needed to fit calculation results to measurements from literature [5], seems to be confirmed. The value of the loss factor will move towards this value for high frequencies.

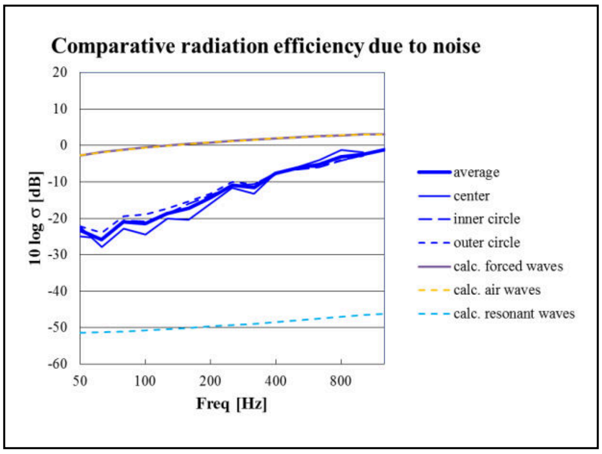

Figure 5. Radiation efficiency for noise excitation on bottom layer

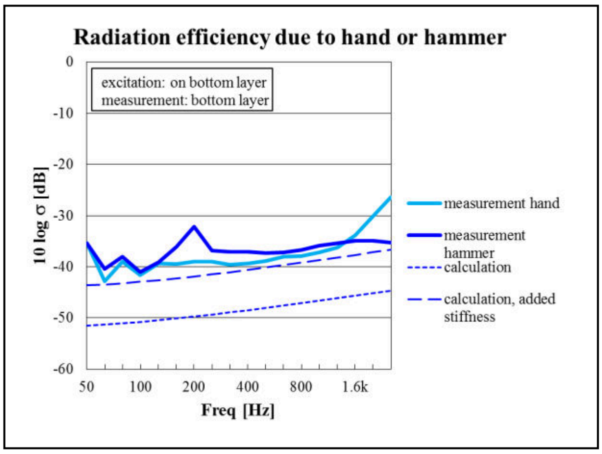

Figure 6. Radiation efficiency for direct excitation on bottom layer

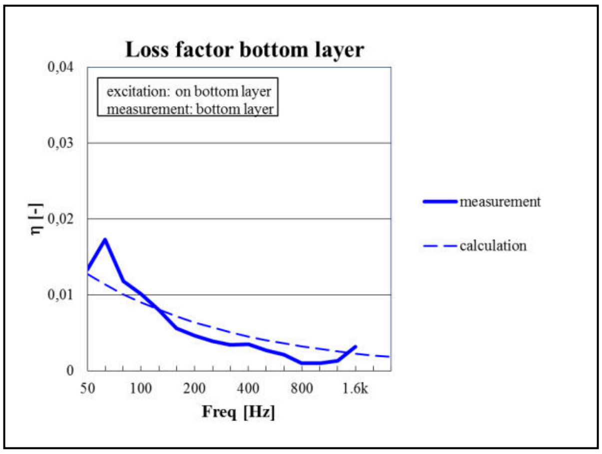

Figure 7. Loss factor bottom layer

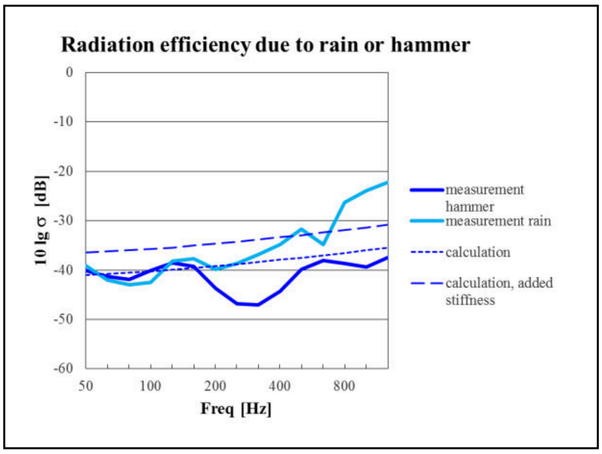

Figure 8. Radiation efficiency for direct excitation on top layer

The radiation efficiency and loss factor was also determined for the top ETFE layer. This was done for rain and excitation by hammer. The results for radiation efficiency are shown in Figure 8. The results are in the same order as for the bottom layer. For the higher frequencies the radiation efficiency for rain noise increases strongly. This might be due to the fact that the microphone also records the direct rain noise, showing the difficulties of measuring the radiation efficiency for a multilayered structure like this. More interesting is a dip around 300 Hz that can be seen for the radiation efficiency due to excitation by hammer. The main difference between the bottom layer and top layer is the arc over which the ETFE layer is stretched. It has been shown earlier in this paper how the arc might be responsible for other frequency tops or dips. Energy loss around this frequency through the arc might be dominant here. The loss factor, that is related to the measurements with the hammer, shows an increase around 300 Hz.

3.3.1 Sound imaging results

Figures 9 to 11 show some of the generated sound images. Currently the sound imaging results, specifically eigenfrequencies and sound radiation data, are compared with the results from the calculations described in this paper. A wrap up will be given during our presentation.

Figure 9. Sound image at 46 Hz

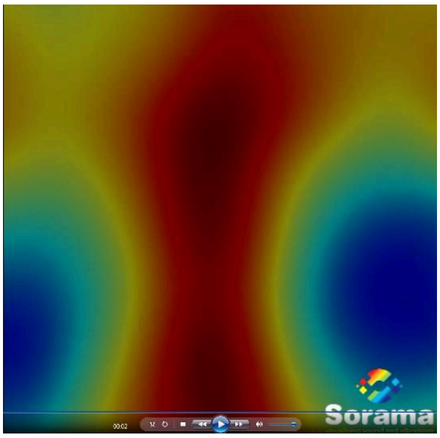

Figure 10. Sound image at 64 Hz

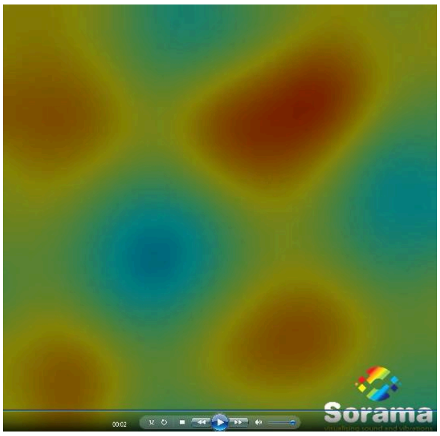

Figure 11. Sound image at 90 Hz

4. Conclusions

The relatively high sound insulation of this ETFE structure for traffic and rain noise makes it possible to use ETFE roofs in buildings with noise sensitive areas such as the considered one.

By comparing calculations with measurement results generated in mock-ups in the lab and by fine-tuning the calculations for some less well known aspects, our calculation model becomes a practical tool for designing actual ETFE roofs.

References

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