A wide range of commercial sound absorbers is based on the Helmholtz type of resonator using perforated panels. The perforations cover almost any geometrical pattern and any shape and size of the individual openings in the panels. The most common types of pattern are the regular perforations by holes of cylindrical shape or by slits of different length. A simple analytical model for calculating the absorption coefficient for the latter type of panel with sub-millimetre wide slits is outlined. Measurements performed in a standing wave tube give results in good agreement with the calculations. The absorption capability and practical performance of such panels is just as good as for the more well-known microperforated panels. Designs are patent pending.

1 Introduction

A wide range of commercial sound absorbers is based on the Helmholtz type of resonator using perforated panels. The perforations cover almost any geometrical pattern and any shape and size of the individual openings in the panels. The most common types of pattern are the regular perforations by holes of cylindrical shape or by slits of different length. In the latter case this length may equal the whole length of the panel, a panel for which we normally will reserve the name “slotted panel” [1]. To obtain a reasonably high absorption coefficient the resonator must include a well-designed resistance component, either in the form of a porous layer in the airspace between the panel and the back wall, which may have the form of a thin fabric glued to the panels, or a combination of a fabric and a thicker porous layer. Using a microperforated panels (with sub-millimetre holes), see e.g. Maa [2], no added resistance component is normally necessary.

Analytical expressions useful in the design of the most common types of resonator panels have been in existence in the literature for a long time. Of special interest in more recent time is the ability to design absorbents where the natural viscous losses in the perforations are utilized to obtain the necessary resistance component excluding the use of extra porous material. The microperforated panel is already mentioned, another idea is the use of a double slit-perforated panel. Here one uses two plates separated by a very small distance, typically 0.1 – 0.3 mm, and the energy dissipation takes place in the gap between the plates [3]. A main feature is to make the absorbent adjustable both in frequency and absorption capability. However, if the latter adjustments are not considered necessary, could a slotted panel be designed to only use the natural viscous losses to obtain a reasonably workable absorbent?

This paper shows that this is indeed possible using what we have coined a micro-slotted panel, being a slotted panel having sub-millimetre slit width. The percentage perforation is again of the same order as used in microperforated panels, i.e. normally less than 1%. The theory is outlined in the next section, and the results substantiated both by measurements in a standing wave tube, see section 3, and in a reverberation room following ISO 354.

Quite recently, the authors have through a reference in a paper by Kang and Brocklesby [4] been aware of similar work performed by Mao and Wang [5] at the University of Tongji in China.

2 Theory

The simple description outlined by Allard [6] to evaluate the effect of viscosity in cylindrical tubes and in slits is used here. We consider one slit in a plate and assume that the input pressure is the same along the whole length l of the slit, the length being long in comparison with the wavelength. Furthermore, the pressure p in the slit varies only in the z-direction, see Figure 1, and the velocity in this direction is only depending on the x-coordinate.

![Figure 1 Slit of width b in a plate of thickness t](image)
The mean velocity \( \langle u_z \rangle \) in the slit may then be expressed as

\[
\langle u_z \rangle = -\frac{\partial p}{j\omega\rho_0\partial z} \left[ 1 - \frac{\tanh(s'\sqrt{j})}{s'\sqrt{j}} \right],
\]

where \( \omega \) and \( \rho_0 \) is the angular frequency and the density of air, respectively. The variable \( s' \) is given by

\[
s' = \left( \frac{\omega\rho_0 b^2}{4\mu} \right)^{\frac{1}{2}}.
\]

Here \( b \) is the width of the slit and \( \mu \) is the viscosity coefficient for air (\( \approx 1.8 \times 10^{-5} \) kg/m/s). This implies that we may rewrite equation (1) as

\[
j\omega\rho \langle u_z \rangle = -\frac{\partial p}{\partial z},
\]

where \( \rho \) is the effective air density in the slit due to the viscosity effects.

\[
\rho = \frac{\rho_0}{1 - \tanh(s'\sqrt{j})/s'\sqrt{j}}.
\]

Alternatively, we may write this as

\[
\rho = \frac{\rho_0}{k' b} \frac{k' \sin(2\pi \epsilon)}{2},
\]

where \( k' \) is given by

\[
k' = \sqrt{\frac{\omega\rho_0}{3\mu}}.
\]

For an infinitely long slit in a plate of thickness \( t \) the specific impedance may then be written as

\[
Z' = j\rho_0\omega t = \frac{j\rho_0\omega t}{\tan\left(\frac{k' b}{2}\right)}. \tag{7}
\]

Using a series expansion in the angular frequency \( \omega \), the first three terms will be

\[
Z' \approx \frac{12\mu t}{b^2} + \frac{1}{700} \frac{t b^2 \rho_0^2 \omega^2}{\mu} + j \frac{6}{5} \omega \rho_0 t,
\]

where the constant term in the real part corresponds to the Poiseuille value \( 8\mu t/a^2 \) found for cylindrical holes with radius \( a \). We may also observe looking at the imaginary part that the viscosity results in an added mass for the air in the slit.

For a slotted panel, see Figure 2, making up our distributed Helmholtz resonator we have slits of width \( b \) regularly placed at a distance \( B \), i.e. the percentage open area \( \epsilon \) of the panel is \( b/B \). To calculate the specific impedance of the panel we have to correct the expression (7) by this perforation ratio. Furthermore, we will use the classical expression by Smits and Kosten [7] to add a term for the end correction being

\[
\Delta t = -\frac{b}{\pi} \ln \left( \sin \frac{\pi}{2} \epsilon \right).
\]

Finally adding the specific impedance for the airspace behind the panel the input impedance for the absorber yields

\[
Z = \frac{1}{\epsilon} \left[ Z' + j\rho_0\omega(2\Delta t) \right] - jZ_0 \cot \left( \frac{d \omega}{c_0} \right), \tag{10}
\]

where \( Z_0 \) is the characteristic impedance of air. It is also assumed that the end correction is equal on both sides of the panel. For normal incidence the absorption coefficient may then be calculated by the well-known formula

\[
\alpha = \frac{4 \text{Re} \left( \frac{Z'}{Z_0} \right)}{\left( \frac{Z'}{Z_0} \right)^2 + 2 \text{Re} \left( \frac{Z'}{Z_0} \right) + 1}, \tag{11}
\]

where Re signify ‘the real part of’.

3 Measurements

Measurements in a standing wave tube are conducted to verify the predictions above. The tube had a square cross section with side length 200 mm, which limit the measurement range upwards to approximately 850 Hz. The first set of samples were made of strips of aluminium, 50 mm wide and with thickness varying between 2 and 6 mm, which were mounted on a frame fitted within the tube. The slit width between the strips was varied between 0.3 and 0.5 mm. Results from further measurements on thinner panels where the slits
are made by laser will be shown at the conference, likewise results from reverberation room tests.

The airspace behind the specimen was also varied in the experiments that closely followed the procedure given in ISO 10534-2 [8]. The transfer function of sound pressure between the two microphones was deduced from impulse response measurements using the WinMLS™ software, i.e. the impulse responses for the loudspeaker detected at each microphone when feeding the loudspeaker with a Maximum Length Sequence (MLS) type of signal.

![Figure 3 Absorption coefficients with 4 mm plate thickness and airspace 100 mm. The slit width b is indicated in the diagram. Solid lines; measured. Broken lines; calculated.](image)

Examples of results from the measurements and the calculations are shown in Figure 3 and Figure 4. In the first one the thickness of the strips are 4 mm and results are shown for slit width 0.3 and 0.4 mm. The depth of the air space is 100 mm. As seen the fit between measured and calculated data is satisfactory except for a local peak around 300 Hz. This is caused by mechanical resonance in the individual strips. The exact frequency is of course difficult to predict, as it will depend on the boundary conditions. However, if we assume that the strips are simply supported at the frame the frequency should be \( \approx 250 \) Hz, whereas for clamped conditions it should be \( \approx 320 \) Hz.

In Figure 4 the plate thickness is 6 mm and the depth of the air space is reduced to 50 mm. Again, the fit between measured and calculated values is satisfactory. As expected the fundamental mechanical resonance of the strips moved upwards as compared with 4 mm plate thickness and also being a little less pronounced.

![Figure 4 Absorption coefficients with 6 mm plate thickness and airspace 50 mm. The slit width b is indicated in the diagram. Solid lines; measured. Broken lines; calculated.](image)

**4 Conclusions**

Experiments with specimens of micro-slotted panels, panels with slits of width in the sub millimetre range, indicate that the absorption capability can be made just as good as for the more well-known microperforated panels. The agreement between measured and calculated values for the absorption coefficient in a standing wave tube is satisfactory. Designs are patent pending.

**Acknowledgement**

The authors are grateful to stud. techn. André Bergan who performed the first measurements as part of a project work at NTNU.

**References**


