Measurement of airflow resistance by the alternating flow method

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Summary

The airflow resistance is a major acoustic parameter of porous materials. For the use as a damping element in cavities, a certain range of airflow resistances is prescribed by DIN 4109, the major standard for sound insulation in buildings in Germany. The measurement of airflow resistance is standardised in ISO 9053. This standard comprises two different methods, the constant flow method and the alternating airflow method. At PTB, a new measurement device has been set up for the latter method which enables measurements at frequencies between 0.5 and 6.3 Hz. This is a major improvement compared to the majority of today's setups which run at a constant frequency of 2 Hz. In the contribution, the new measurement setup is introduced, the theoretical background of the method is given, the uncertainty is calculated and results of test measurements are reported.

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1. Introduction

The flow resistance of porous media is a major quantity to describe the interaction of the material with acoustic waves. The experimental determination of the airflow resistance is standardised in ISO 9053 [1]. In the current version of this standard, two different methods are described, the alternating flow method and the static flow method. Both methods were proved to give identical results for flow resistances of porous media, e.g. [2], [3].

The alternating flow method was originally developed in [4] and further improved in [5] and [6]. The standardised method is based on [4] and [5]. It is convenient to be used since the measurement equipment is available at building acoustic laboratories and it can easily be included in the regular quality management system.

This paper reports on some work undertaken at PTB which aimed at a thorough investigation of the theoretical background of the method, on the determination of limiting factors and the uncertainty. For that purpose, a new measurement apparatus designed and manufactured at PTB is presented which was used to verify the theoretical findings.

2. Theoretical background

The basic idea of the measurement method is shown in Figure 1. An air cavity is compressed and decompressed by a piston. The sound pressure inside the air cavity is measured once with the mounted specimen and once with an airtight termination which is mounted in the place of the specimen. This sound pressure level difference is used to calculate the airflow resistance. A small sound pressure level difference indicates a small airflow resistivity.

A very simple lumped parameter model is developed from the principles layed down in [7]. Such a model requires that all elements are small compared to the acoustic wavelength and that all elements show a linear behaviour. The model follows from the thought, that the volume flow generated by the piston q is divided into two parts, one for the compression of the air cavity with the compliance N and one for the flow through the test specimen with the airflow resistance R and the acoustic mass of the absorber M. The acoustic compliance of a volume V is

$$N = \frac{V}{\kappa p_s} \quad (1)$$

with the ratio of the specific heats κ and the static pressure p_s. The acoustic mass of a porous absorber can be approximated by [7]

$$M = \frac{p_s\, d}{T\, R_{air}\, \sigma\, A} \qquad (2)$$

with a perfect gas assumption and the density of air ρ, absorber thickness d, porosity σ, absorber cross section A, specific gas constant for air R_{air} and temperature T. The sound pressure p vanishes, when there is no test specimen mounted (shortcut of R and M).

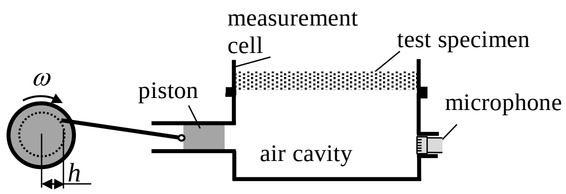

Figure 1. Test setup

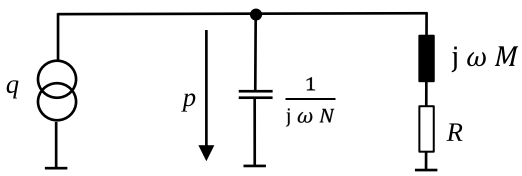

Figure 2. Lumped parameter model of the measurement setup with airflow resistance R, volume flow provided by the source q, acoustic compliance N, acoustic mass M, angular frequency ω and sound pressure p

The ratio of the r.m.s.-values of sound pressure and volume flow follows directly from the lumped parameter model (Figure 2)

$$\frac{p}{q} = \sqrt{\frac{R^2 + (\omega M)^2}{(1 - \omega^2 N M)^2 + (\omega N R)^2}} \; . \qquad (3)$$

For the airtight termination of the air cavity, the whole volume flow compresses the air in the cavity and eq. (3) simplifies to

$$\frac{p_{\mathrm{tight}}}{q_{\mathrm{tight}}} = \frac{1}{\omega_{\mathrm{tight}}\, N_{\mathrm{tight}}} \; . \qquad (4)$$

Sometimes, it may be desirable to use a different piston stroke length h for the measurement of the specimen and the airtight termination. The volume flow is then

$$q = q_{\mathrm{tight}} \frac{h}{h_{\mathrm{tight}}} \; . \qquad (5)$$

Eqs. (3), (4) and (5) can be used to determine the airflow resistance

$$R = R\left(\frac{p}{p_{\mathrm{tight}}}, \frac{h}{h_{\mathrm{tight}}}, \kappa, p_s, V, f, \ldots\right) \; . \qquad (6)$$

For negligible absorber mass and volume compliance

$$\omega M << R; \; \frac{1}{\omega N} >> R \qquad (7)$$

the simple expression

$$R \approx \frac{p}{p_{\mathrm{tight}}} \frac{h_{\mathrm{tight}}}{h} \frac{\kappa\, p_{\mathrm{s,tight}}}{2\,\pi\, f_{\mathrm{tight}}\, V_{\mathrm{tight}}} \qquad (8)$$

is yielded. Eq. (8) is practically used in the current version of ISO 9053 [1] even though it is not explicitly formulated this way.

3. Measurementent Device

A new measurement device was set up at PTB to implement the alternating flow method. A piston with a diameter of about 20 mm is driven by an electric motor and an excenter. The piston works on a cavity with a volume of about $1.5 \cdot 10^{-3}$ m³. This volume is either terminated by an airtight plate or by the measurement cell. The latter is made of acrylic glass and has dimensions of 0.2 m X 0.2 m X 0.2 m (Figure 3). This way the same specimen size as for the measurement of dynamic stiffness according to ISO 9052-1 [8] can be used.

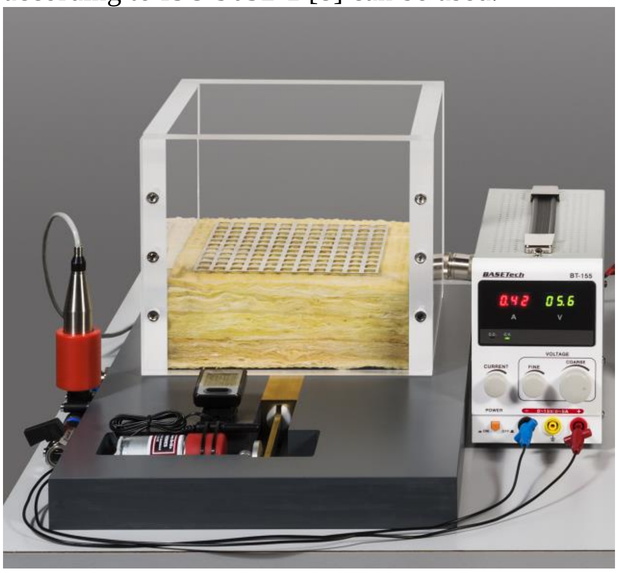

Figure 3. Measurement device

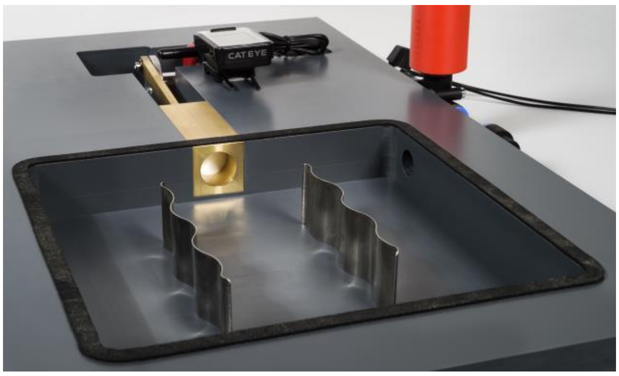

Figure 4. Detail of the measurement device

The sound pressure in the cavity was originally measured with a 1"-microphone as shown in figure 3. Later on, this microphone was replaced by a special low-frequency 1/2"-microphone which is connected to the cavity by a flexible tube. The sound pressure level is measured by a one-third octave band analyser. Only the band level is used that contains the piston frequency. The averaging time is 160 s. To measure the frequency of the piston, an FFT-analysis is additionally performed with a frequency resolution of better than 1 %. The frequency and the sound pressure level are measured simultaneously.

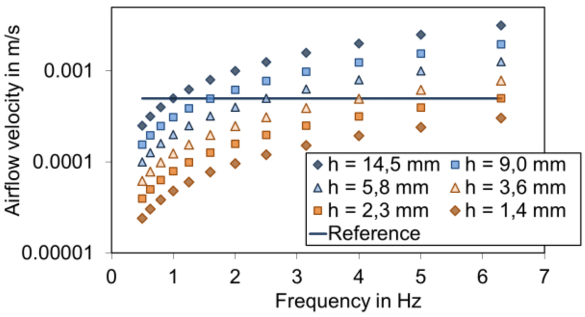

Figure 5. r.m.s.-values of the flow velocities

To avoid structural vibration of light material with a high airflow resistivity, the material can be put on two pieces of corrugated metal (Figure 4) and a metal grid may serve as a static load (Figure 3) on the specimen.
The piston stroke length can be varied in steps between 1.4 and 14.5 mm. In combination with the rotational frequencies between 0.5 and 6.3 Hz and the specimen cross section of 0.04 m², different airflow velocities can be realised (Figure 5) which also comprise the reference value of 0.0005 m/s.

4. Uncertainty estimate

Assuming validity of approximation (7), eq. (8) is used to estimate the measurement uncertainty. For a constant piston stroke length between measurements with specimen and with airtight termination, the uncertainty of measured airflow resistance is

$$\left[\frac{u(R)}{R}\right]^2 = \left[\frac{u\left(p_{\mathrm{s,tight}}\right)}{p_{\mathrm{s,tight}}}\right]^2 + \left[\frac{u(f_{\mathrm{tight}})}{f_{\mathrm{tight}}}\right]^2 + \left[\frac{u(V_{\mathrm{tight}})}{V_{\mathrm{tight}}}\right]^2 + \left[\frac{u(\kappa)}{\kappa}\right]^2 + \left[\frac{u\left(p/p_{\mathrm{tight}}\right)}{p/p_{\mathrm{tight}}}\right]^2 \quad . \tag{9}$$

When measured as a sound pressure level difference, the relative uncertainty of the sound pressure ratio turns out to be

$$\frac{u\left(p/p_{\mathrm{tight}}\right)}{p/p_{\mathrm{tight}}} = \frac{\ln 10}{20\ \mathrm{dB}}\, u\left(L_p - L_{p,\mathrm{tight}}\right) \quad . \tag{10}$$

With reasonable assumptions for the uncertainty of frequency, volume, static pressure and ratio of specific heats, the uncertainty of the sound pressure level difference is the dominant uncertainty contribution (Figure 6). So, for a realistic uncertainty of the sound pressure level difference of 0.5 dB, the relative uncertainty of the airflow resistance is 7 %.

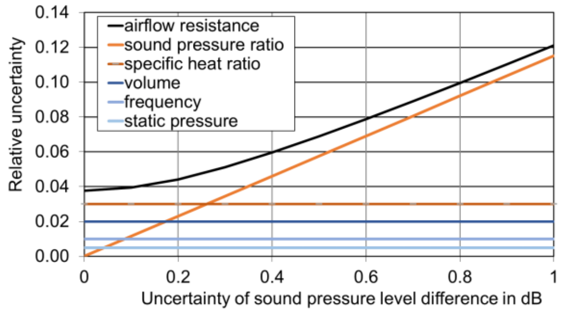

Figure 6. Relative uncertainty of the airflow resistance according to eq. (9) and relative uncertainties of the input quantities

For many applications, the airflow resistivity r is required. It is calculated from airflow resistance R, specimen thickness d and cross section A according to

$$r = R\,\frac{A}{d} \tag{11}$$

The relative uncertainty of airflow resistivity is then simply

$$\left[\frac{u(r)}{r}\right]^2 = \left[\frac{u(R)}{R}\right]^2 + \left[\frac{u(A)}{A}\right]^2 + \left[\frac{u(d)}{d}\right]^2 \tag{12}$$

with relative uncertainties of 7 % for airflow resistance, 3 % for the cross section area and 5 % for the specimen thickness

5. Test measurements

At first, test measurements with the airtight termination were performed to check whether sound pressures calculated according to eq. (4) are observed in practice. The r.m.s. value of the volume flow is

$$q = \sqrt{2}\,\pi\, f\, A_P\, h \tag{13}$$

with the piston face area A_P and the piston stroke length h. With eq. (1), the sound pressure in the cavity is simply

$$p_{\text{tight}} = \frac{A_P\, h\, \kappa p_s}{\sqrt{2}\; V} \quad . \tag{14}$$

This value is well measured with both different microphones at higher frequencies (Figure 7). At lower frequencies, the influence of the frequency response of the microphones and the measurement system is observed. The background noise turned out to depend on the wind outside the laboratory building. The values shown are relatively large values and are nearly identical for both microphone types. Further test measurements were performed with varying piston strokes and cavity volumes. The results are in line with theoretical prediction (Figure 8). Remaining deviations are attributed to the frequency response of the measurement system.

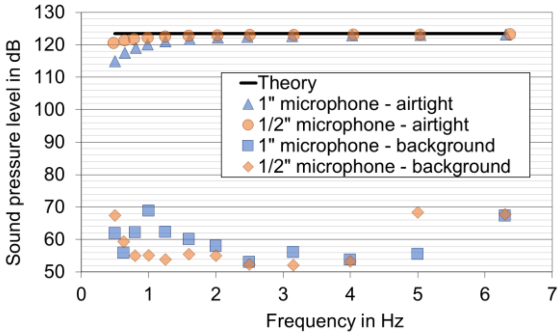

Figure 7. Sound pressure level measured with airtight termination, theoretical value according to eq. (13) and background noise

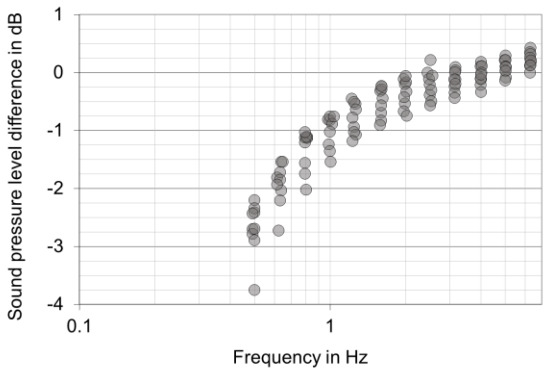

Figure 8. Differences between measured and calculated sound pressure levels for the airtight termination, 1/2" low frequency microphone

An interesting result of the theoretical consideration is that the measured flow resistivity is independent of the volume size (see eq. (8)) as long as approximation (7) holds. This has been checked by measuring the airflow resistance of different materials mounted at different heights in the measurement cell. This way, the volume was varied between $1.5\cdot10^{-3}$ m³ and $7.5\cdot10^{-3}$ m³. Measured sound pressure levels turned out to be reasonably constant (Figure 9) when the sound pressure level remains at least 10 dB below the level which is calculated for the airtight termination of the same volume. From the measured sound pressure levels, airflow resistances were calculated according to eq. (8). They are constant within the expanded uncertainty (k = 2) of 14% independent of the volume (Figure 10). Only the high resistance material shows larger deviations for the three largest volumes. This is caused by an insufficient sound pressure level difference between airtight termination and mounted specimen (see Figure 9).

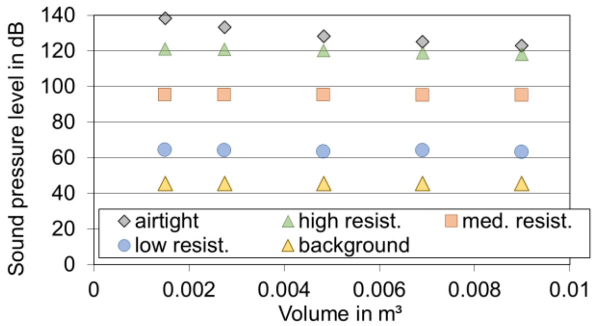

Figure 9. Measured sound pressure levels for specimens at different mounting heights in the measurement cell and calculated sound pressure level for the airtight termination of the same volume and background noise level

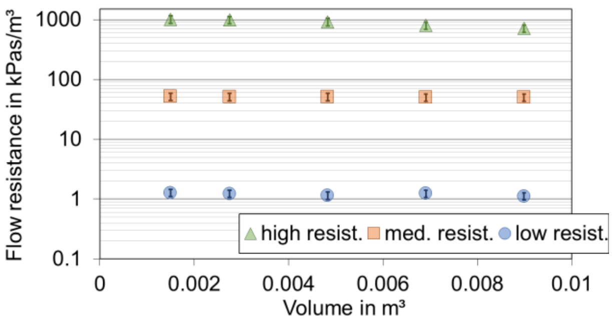

Figure 10. Airflow resistances calculated by eq. (8) for different mounting heights and expanded uncertainties (k = 2)

The method was then applied to different materials. Examples are given in Figures 11, 12 and 13. There, the airflow resistivity of porous media is shown in different directions. For the very low resistivities, the low frequency results show a scatter larger than the indicated expanded uncertainties. It is suspected that the unsteady background noise causes this scatter. Whereas the first two specimens show only minor influences of the flow direction, the material shown in Figure 13 clearly has a different flow resistivity in the different directions.

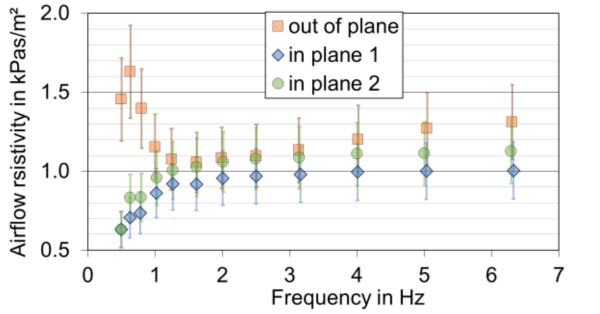

Figure 11. Airflow resistivity for a fibrous material in different flow directions

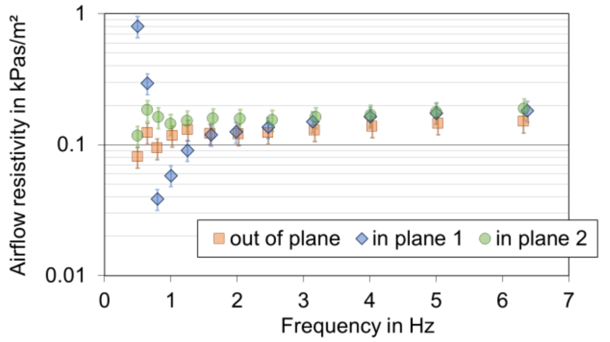

Figure 12. Airflow resistivity of an open cell foam in different flow directions

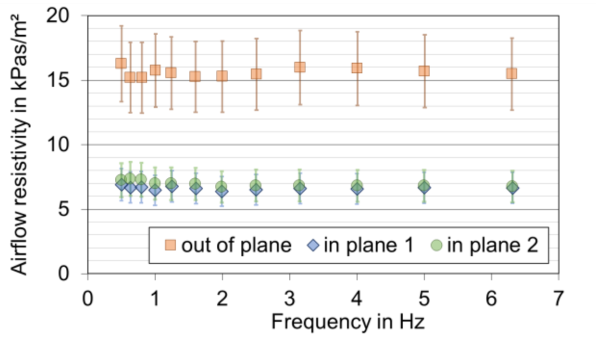

Figure 13. Airflow resistivity of a fibrous absorber in different flow directions

6. Conclusion

The theoretical background for the measurement of airflow resistances or resistivities by the alternating flow method was briefly discussed. A new measurement device was set up at PTB to perform such measurements under variation of the major governing parameters. The standard uncertainty was estimated to be 7 % for the measured airflow resistance and 9 % for the airflow resistivity. Test measurements confirmed the results of the theoretical considerations including the uncertainty estimate.

7. Future work

Future work will involve further investigations on the method especially on the influence of the airflow velocity on measured resistivities. Furthermore, comparative measurements with the static flow method are planned.

Acknowledgement

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