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Airflow Resistivity Measurements of Acoustic Poroelastic Materials and their Influencing Factors

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In the automotive sector, poroelastic materials (PEMs) are used as trim elements to achieve the desired interior acoustics of a vehicle. This study examines the effect of manufacturing as well as measurement techniques on airflow resistivity. This property plays a key role in the acoustic behavior of PEMs. First, the importance of engineering acoustics and poroelastic materials in vehicle industry is reviewed, followed by the introduction of the most important properties and their measurement techniques. Next, the theory and the measurement techniques used to determine resistivity via direct method are detailed. Then the factors influencing the results and their quantified effects are presented. More than 10 influencing factors are identified and examined, from which the inhomogeneity, resulting from the production technology proved to be the most significant. The results obtained with direct and inverse methods are compared for validation purposes and to determine the achievable accuracy of the inverse method. The average difference between the two methods is 4.54%, which means that the inverse method can provide a good approximation. Finally, conclusions are drawn and suggestions are made for the future.

Keywords: Acoustics, Material Characterization, Airflow Resistivity, Medical Industry, Military, Defense Industry

1 Introduction

Nowadays the field of Noise, Vibration and Harshness (NVH) research and development has become increasingly important in vehicle industry and in general engineering due to its wide applicability. Acoustics can be used not only for measuring sound and noise levels, but also in the design of drivetrains and gears [26, 27], or even in the fields of machining [28], military and defense industry or medical industry. Furthermore, NVH deals with predicting and controlling vibroacoustic phenomena, which can cause passenger discomfort in the form of vibrations or noises. Therefore, the automotive industry invests lot of effort in predicting, controlling and eliminating the undesired effects of vibroacoustics, and the goal is to create such vehicle structures, which minimize the sound pressure levels in the passenger compartments as well as the intensity of the vibrations at the contact points between the cars and the passengers, i.e. in case of the steering wheel, the floor, and the seats. In order to meet these complex challenges, modern chassis design involves the combination of strong frame elements, sheet panels as well as so-called trim elements, which role is to absorb or dampen the vibroacoustic phenomena. Trim elements can be characterized as poroelastic materials (PEMs, i.e. a porous elastic solid skeleton saturated by compressible fluid), which acoustic absorption, reflection and transmission characteristics can be quantified by using the so-called Biot-parameters. The theory of deformation and the propagation of elastic waves in poroelastic materials was established by M. A. Biot in 1941 [1] and in 1956 [2, 3], and according to this, poroelastic materials can be described on a "macroscopic" scale by at least 11 parameters (for example, dependent on the used model), which can be grouped into solid phase, fluid phase and transport ("coupling") parameters, as illustrated in Tab. 1. In this sense, the "macroscopic" terminology means that the Biot-parameters do not describe such microscopic data as the pore size or skeleton wall thickness of the PEM material, but rather the parameters related to vibroacoustic behavior of a coupled fluid-structure system, such as porosity, density, tortuosity or airflow resistivity.

Tab. 1 *Grouping of Biot-parameters [4]*

Fluid phase parameters	Fluid phase density, ρ_f
	Celerity (speed of sound), c_f
Solid phase parameters	Solid phase density, ρ_s
	Young's modulus, E
	Poisson ratio, ν
	Structural damping coefficient, η_s
Coupling parameters	Porosity, ϕ
	Resistivity, σ
	Tortuosity, α_∞
	Viscous characteristic length, Λ
	Thermal characteristic length, Λ'

The Biot-parameters not only allow the comparison and selection of various trim materials during vehicle design, but also serve as input parameters to NVH simulations, typically performed by so-called FEM-PEM methods. Therefore, the accurate determination of Biot-parameters is of utmost importance for determining vehicle NVH characteristics.

To date, the full set of Biot-parameters is obtained typically via measurements, which can be classified as direct, indirect, or inverse measurements, as illustrated in Tab. 2. In case of the direct and indirect methods, the Biot-parameters can be measured separately by an equipment dedicated to measure specific Biot-parameters individually. Considering the inverse methods, multiple Biot-parameters can be extracted simultaneously from one single impedance or absorption measurement performed with a Kundt-tube. In this latter case, some of the Biot-parameters, which can be measured directly (such as porosity and airflow resistivity) are used to cross-check the validity or increase the accuracy of the inverse measurement results. In any case, the direct measurement of airflow resistivity plays a key role in determining the Biot-parameters and a major challenge is the uncertainty regarding the accuracy of such measurements. Hence the present study focuses mainly on the influencing factors of the direct method and secondly deals with the inverse method in order to determine its achievable accuracy.

Tab. 2 *Measurement methods for determining Biot-parameters (QMA – Quasi-static Mechanical Analyzer, VBT – Vibrational Beam Testing, DMA – Dynamic Mechanical Analyzer) [5]*

Non-acoustic / Biot-parameters:	"Direct and indirect methods"	"Inverse method"
• Density: ρ_0 • Celerity (sound): c_0 • Temperature: T • Atmospheric pressure: p	Weather station for the measurement of ambient parameters	
• Modulus of elasticity: E	QMA, VBT, Shaker, DMA	
• Poisson's ratio: v	QMA, Shaker, DMA	
• Damping: η	QMA, VBT, Shaker, DMA	
• Density: ρ_1	Porosity & density meter	
• Open porosity: Φ	Porosity & density meter	Impedance tube-based method
• Resistivity: σ	Airflow resistivity meter	
• Tortuosity: α_∞	Tortuosity meter	
• Viscous characteristic length: Λ		
• Thermal characteristic length: Λ'		
• Thermal permeability: k'_0		

Although there are several papers dealing with Biot-parameters measurements [6-11], there are only a handful, which focus on the measurement techniques related to airflow resistivity determination. Hence the most important goals of the present work are to accurately determine the airflow resistivity of PEMs and to quantify the effects resulting from the production and measurement technology (e.g. inhomogeneity of the sample and sample mounting).

Firstly, there are various methods for airflow resistivity and resistance measurements. The ISO 9053 standard [12] describes two methods one of them is the steady-state/quasi-static airflow measurement technique and the other one is the alternating airflow measurement method, which is described also by Dragonetti et al. [13]. In their paper, the authors suggest an alternating air-flow measurement method based on the ratio of sound pressures measured at frequencies higher than 2 Hz, inside two cavities coupled through a conventional loudspeaker [13].

The method proposed by Naima et al. [14] characterizes the porous material via acoustic reflected waves and there are "inverse" methods using impedance tube, by deriving the airflow resistivity using the fitted curve to the measured absorption coefficient values. Tao et al. [15] present a modified acoustic method, which is based on impedance tube measurements, but in this case an acoustic method based on impedance transfer function is proposed to be used for the measurement of the desired property.

Tang et al. [16] present a review of different resistivity measurement methods, focusing mainly on fibrous materials characterization with the direct airflow method, the alternating airflow method and the so-called acoustical method. It also summarizes the different methods and the current status of the resistivity measurements and as such, is one of the most comprehensive studies, which, however is theory-oriented, and lacks the discussion or analysis of measurement induced practical difficulties.

A study using direct resistivity measurement method and impedance tube method is presented by Joshi et al. [17], which introduces the effects of the density, thickness and positions (locations) on airflow resistivity results. However, in this study the samples examined were made of nearly ideal, homogenous, parallel-sided foam plates. None of the samples were produced from real car components with complicated geometries, where different zones, layers, and crusts are formed, originating from the manufacturing technology. Also, none of the samples were prepared from multi-layered trim materials, where layer separation was necessary. Hence, the preparation of these samples and the measurements from them were less complicated compared to real vehicle trim parts with complex geometry.

It is clear from the above, that although several papers [7, 11-17] have dealt with airflow resistivity measurements, none of them provided a comprehensive sensitivity study on the effect of the velocity selected for the tests, the material inhomogeneity (along the thickness or along the other two dimensions of the components) originating from the manufacturing technology, the mounting of the sample in the measurement device, the orientation of the sample during the measurement, or the repeatability of the tests. Since round robin tests [16, 18, 19] showed that the differences between the measurement results from different laboratories can be as high as 30%, it is rightly presumed that the above effects can have a major role in airflow resistivity measurements.

The present work addresses these issues and therefore, the purposes of this work are:

- To establish that which factors can influence the accuracy of the AFR measurements,
- To quantify the effect of these influencing factors.

This paper is original since - to the knowledge of the authors, - no prior work has addressed the factors influencing the accuracy of AFR measurements before.

2 Direct method

2.1 Theory: Quasi-static airflow resistivity and resistance measurement using direct method

In most cases, there are two parameters related to airflow resistivity, which need to be determined for NVH analysis. One of them is the static airflow resistivity (AFR), which is a material property excluding the geometry (thickness) of the material. The other one is the specific airflow resistance (SAFR), which includes the geometry of the sample by involving a thickness term, which means that this is not a material property, but rather a characteristic of a concrete sample or part. The unit of airflow resistivity, termed as σ, is Ns/m^4, while the unit of the specific airflow resistance, termed as R_S, is Ns/m^3.

These two properties can be calculated according to the following equations [5, 11, 20, 21]:

$$\sigma = \frac{\Delta p}{vL} \tag{1}$$

$$R_s = \frac{\Delta p}{v} \tag{2}$$

$$v = \frac{Q}{A} \tag{3}$$

Where:

Δp…The pressure drop (pressure difference before and after the sample) caused by the sample,

v…The velocity of the airflow,

L…The thickness of the examined sample,

Q…The volumetric flow rate,

A…The cross-section of the sample, perpendicular to the flow direction.

Beside these two parameters, in some cases it is preferred to express the so-called static viscous permeability (or airflow permeability) as well. Static viscous permeability, termed by k and expressed in m^2 units, is essentially the ratio of the dynamic viscosity of air (η) and the airflow resistivity (σ) [5, 20, 21]:

$$k = \frac{\eta}{\sigma} \tag{4}$$

Furthermore, there is an inverse proportionality between permeability and resistivity. Permeability is derived from the Darcy's law [5, 22]:

$$Q = \frac{kA}{\mu L} \Delta p \tag{5}$$

Fig. 1 depicts the schematic representation of the quasi-static airflow resistivity measurement method. It consists of the following main elements: 2 differential pressure sensors, a DAQ (data acquisition) system, current-voltage signal conditioner, electromagnetic valve (to control the flow rate and the airflow velocity), measurement cell (in which the sample is placed) and a calibrated resistance. One of the differential pressure sensors is connected to the measurement cell before and after the sample, the other sensor is connected to the system before and after the calibrated resistance, thus providing 2 output voltage signals, from which the pressure drop caused by the sample can be derived. An air compressor is connected to the inlet side of the resistivity meter through a pressure regulator and an already mentioned valve to control the pressure, and hence the flow rate, on one side of the system. The outlet side of the measuring system is "free" (connected to no further part) providing atmospheric pressure.

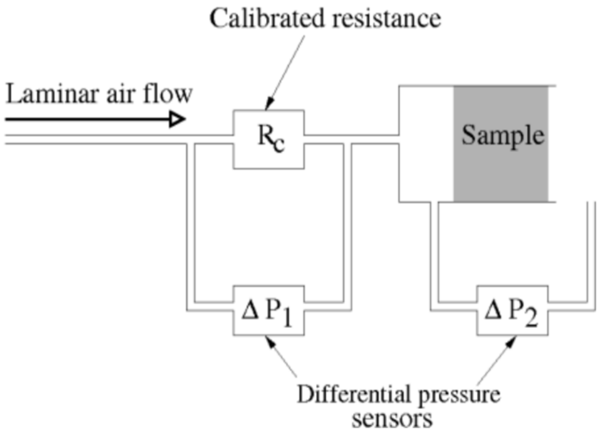

Fig. 1 *The structure of the quasi-static airflow resistivity meter [11, 12]*

In this direct method "steady state flow" is provided, where the pressure and velocity remains constant over time. It requires multiple measurements at different airflow velocities. The pressure drop values can be measured with the help of the 2 differential pressure sensors. After measuring the pressure drop values at different velocities, the resistivity, the resistance and the permeability can be determined.

In the first half of this work only a direct, quasi-static airflow resistivity method was used for the measurements and for the investigation of the influencing factors detailed in later in this paper. (In the second half of this document the inverse method is also mentioned and used for validation purposes. Furthermore the airflow resistivity results generated by the inverse method were also presented in order to confirm the potential and achievable accuracy of the latter acoustical method using impedance tube.)

In the name of the applied direct method, static refers to the low velocity measurements and to the resistivity values calculated and measured at low velocities. According to the literature, and standards, the airflow resistivity values are determined most commonly at 0.5 mm/s and less often extrapolated to 0 mm/s. Static also can refer to the steady-state airflow conditions, which means that the signal acquisition happens at constant airflow velocities. It is true that the pressure drop is measured at different velocities, however, the pressure values during the velocity change are not used. The measurement points recorded at different velocities are used for resistivity determination and for extrapolation, when necessary.

For resistivity values, two types of derivation methods are the most common ones. In the first one, the pressure drop-velocity curve and interpolation are used together. In the second one, the resistivity-velocity curve and extrapolation or interpolation are used together. The standard recommends the former one, which has the advantage that an additional theoretical point helps to determine the resistivity values more precisely. This corresponds to the origin of the x and y axes, meaning that the pressure drop at 0 mm/s flow speed is theoretically zero, as illustrated in Fig. 2.

According to the standard [20] the resistivity is determined most commonly at 0.5 mm/s, however the method provides the possibility to use extrapolation and calculate the airflow resistivity value at 0 mm/s. Furthermore the standard suggests that the desired values shall be determined using the combined use of pressure drop (i.e. pressure difference) - velocity curve and the quadratic polynomial trend line. Depending on the measuring range of the machine and the resistance of the sample, multiple measurement points shall be determined between 0.5 and 1 mm/s to enable as accurate extrapolation as possible (seen in Fig. 2).

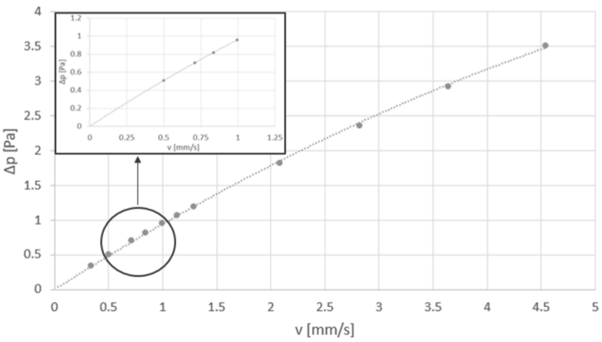

Fig. 2 *An example for pressure drop-velocity curve [5]*

However, for certain materials the resistivity values may fall out of the measuring range of the machine and thus the resistivity cannot be measured at 0.5 mm/s, or in the 0.5-1 mm/s range. In such case, points close to the needed value or range are recorded and used for the extrapolation.

2.2 Materials and samples used for the direct, quasi-static airflow resistivity measurement

For the study presented in the sections of the direct method, cylindrical polyurethane (PU) foam samples of 29 and 44.44 mm diameter were taken from a large automotive trim part.

Six samples were considered for the study of direct measurements, termed as Foam 1-6, with different thicknesses. Ideally, the 6 samples were supposed to be homogeneous, but in reality they were inhomogeneous (Fig. 3) and some of them were featured a very thin, soft film-like layer on the top surface and a thicker crust-like layer on the bottom surface due to the production technology. The foam samples, examined in this work, were cut from the same automotive trim part, the thickness of which, however, was not constant. The different samples and the corresponding descriptions can be seen in Tab. 3.

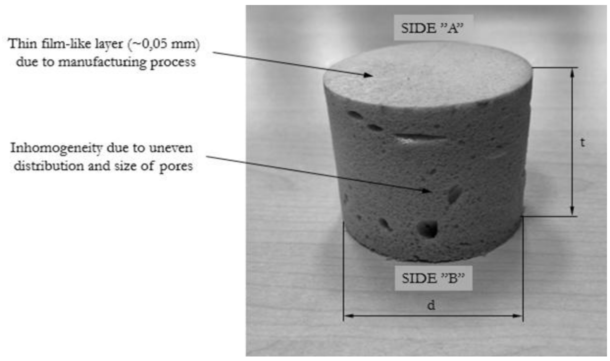

Fig. 3 *Inhomogeneity of a foam sample*

Tab. 3 *The different samples (and their descriptions) used for the direct measurements*

Sample name	Nominal diameter d [mm]	Thickness t [mm]	Thin film-like layer on top	Thicker curst-like layer on bottom
Foam 1	44.44	14	No	No
Foam 2	44.44	13.4	No	No
Foam 3	29	~12	Yes	Yes
Foam 4	29	~11.95	No	Yes
Foam 5	29	~9.6	No	No
Foam 6	44.44	17	No	No

Foam 4 and Foam 5 were also prepared from the original Foam 3 sample. The only difference between these was, that for Foam 4 a very thin, soft film-like layer was removed from one side of the sample while in case of the Foam 5 another layer, which was thicker, was removed from the other side (Fig. 4). These layers were the peculiarities of the applied production technology.

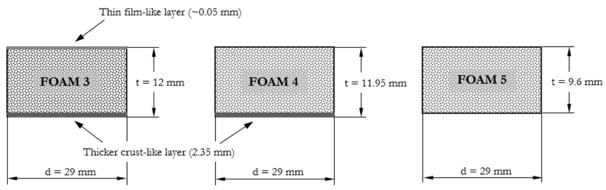

Fig. 4 *Top film-like, bottom crust-like and middle core layers of foam samples due to the production technology*

2.3 Experimental method: Quasi-static airflow resistivity measurement

The measurements performed in this study were done using an in-house designed and built quasi-static airflow resistivity meter. The measurement setup can be seen in Fig. 5. The schematic representation of this system is identical with the one described in Fig. 1.

Fig. 5 *In-house designed and built quasi-static airflow resistivity meter [5]*

As mentioned earlier, this measuring system consists of the following main elements: 2 differential pressure sensors, a DAQ (data acquisition) system, current-voltage signal conditioner, electromagnetic valve, measurement cell and a calibrated resistance. The differential pressure sensor had the following parameters [23, 24]:

- Measuring range: 0-25 Pa,
- Linearity: 0.3% FS (BFSL),
- Hysteresis: 0.02% FS,
- Repeatability: 0.05% FS,
- Accuracy: 75 mPa.

One of the 2 differential pressure sensors is connected to the measurement cell before and after the sample, the other sensor is connected to the system before and after the calibrated resistance, thus providing 2 output voltage signals, from which the pressure drop caused by the sample can be derived. The two output voltage signals can be seen in Fig. 6. The pressure differences are measured at different airflow velocities from which the pressure drop-velocity curve and the desired resistivity can be determined. The airflow velocity is controlled by an electromagnetic valve.

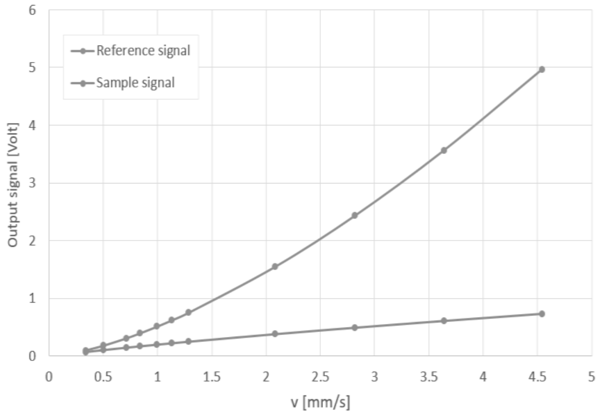

Fig. 6 *Reference and sample signals measured by the two differential pressure sensors [5]*

During the measurements, it is important to consider the error resulting from the offset error, which is represented by the output voltage signal from the differential pressure sensors when the electromagnetic valve is closed. Furthermore, in order to ensure the accuracy of the measurements, it is also worth considering the strength/magnitude of the signals. By selecting various sample diameters and by using various calibrated reference resistances, the reliability of the output voltage signals, and thus the quality of the results can be improved. Ideally, the entire measurement range (0-5 Volts) should be used, or at least taken into account when evaluating and determining resistivity values.

2.4 Research methodology for the direct measurement method

As mentioned above, the effects of various influencing factors on airflow resistivity results (determined by direct method) are investigated and quantified in following sections, which are the followings:

- Selected airflow velocity and velocity range,
- Repeatability, orientation and reinstallation,
- Sample mounting (gap, sealant and tighter fit / extra radial compression),
- Inhomogeneity along the thickness,
- Inhomogeneity due to the location of the sample taking.

2.5 Measurement results of direct method

2.5.1 Effect of the selected airflow velocity range

If one is interested in determining the airflow resistivity at 0 mm/s, the velocity range selected for the tests can make a difference. Therefore, two velocity ranges have been selected for comparison: 0.5 – 1 mm/s and 0 – 4.6 mm/s. The resistivity extrapolation to 0 mm/s and the determination at 0.5 mm/s were then made from these ranges. This test was performed on Foam 1, which results are shown in Fig. 7.

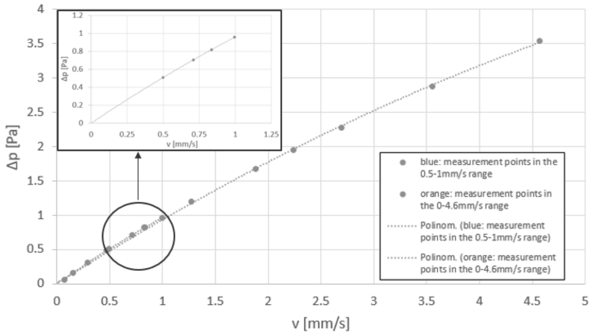

Fig. 7 *Pressure drop-velocity curves (using two different ranges: blue: 0.5-1 mm/s, orange: 0-4.6 mm/s) [5]*

The differently selected ranges resulted in about 10% deviation at 0 mm/s, and about 6-7% at 0.5 mm/s, when using the recommended quadratic polynomic equation for the pressure difference calculation and Equation 1 for the resistivity determination. The differently selected velocity ranges and measurement points can be seen in Fig. 2 and in Fig. 7. Note that these values are true for the present material, and could differ for other materials.

2.5.2 Repeatability and the effect of sample orientation and reinstallation

From now on, the directly measured resistivity values of all samples were determined based on the recommendations of the ISO 9053 standard [20] for better impact analysis and comparability. The following recommendations were considered: the design of the measuring system, the mounting of the samples, the used theory and the equations, the interpolation/extrapolation method, the velocities and velocity ranges, etc.

In this section the following effects were investigated (as shown in Tab. 4):

- The effect of the repeatability without reinstallation,
- The effect of the applied, slightly different velocities/measurement points in the same recommended velocity range (0.5-1 mm/s), since the measurement points are selected manually by an electromagnetic valve, and hence in the case of consecutive measurements, the measurement points do not match 100%,
- The effect of the sample orientation, i.e. the direction of the airflow through the samples, thickness, and
- The effect of reinstalling the sample.

During the repeatability, orientation and reinstallation test multiple samples were examined (the differences considering the resistivity values were usually below 1%), but here only the results for Foam 1 are presented. This sample was measured 3 times (see in Tab. 4), the results are shown in Tab. 5. The first measurement was the reference measurement. The second measurement was a repeat of the first measurement, without reinstallation of the sample. The second measurement differs from the first one only in the measured velocities/measurement points, since as it was explained above, the velocity values/measurement points were defined manually, depending on the position of the electromagnetic valve. There were only slight differences considering the velocities/measurement points (on which the quadratic polynomial curve is fitted and used for the resistivity determination), which were determined still in the same recommended range. The third measurement differed in the sample orientation from the first two measurements, hence the sample was reinstalled here.

Tab. 4 *Schematic of the foam sample setup in the 3 measurements*

Measurement no.	Sample name	Flow direction		Sample removed and reinstalled	Measurement repeated without intentional change
		From SIDE „A"	From SIDE „B"		
1	Foam 1	x	-	-	-
2	Foam 1	x	-	-	x
3	Foam 1	-	x	x	-

Tab. 5 *Effect of repeatability, sample orientation and repositioning [5]*

Sample name:	Measurement:	Measurement details / Differences compared to 1st measurement:	Resistivity [Ns/m^4]			
			(at 0 mm/s)	Relative difference	(at 0.5 mm/s)	Relative difference
Foam 1	1st	reference measurement	76 864	-	72 996	-
Foam 1	2nd	sampling / measured velocities	76 724	-0.18%	72 705	-0.40%
Foam 1	3rd	orientation, reinstallation, sampling / measured velocities	77 368	0.66%	73 241	0.34%

As can be seen from Tab. 5, any such change of the measurement conditions leads to less than 1% difference overall, allowing to conclude that none of these factors have a significant influence on the results.

5.2.3 Effect of sample mounting

In this section, the effect of the leakage around the sample, the use of sealant, the tightness of sample fitting, or in other words, the contact quality between the sample and the measurement cell are examined. Foam 2, 3, 4 and 5 were used for the comparison, with the results for Foam 2 shown in Tab. 6, and for the others in Tab. 7.

Tab. 6 *The effect of the sample mounting on airflow resistivity [5]*

Sample name:	Measurement:	Measurement details:	Resistivity [Ns/m^4]			
			(at 0 mm/s)	Relative difference	(at 0.5 mm/s)	Relative difference
Foam 2	1st	reference measurement, using silicone grease as sealant	177 149	-	167 591	-
Foam 2	2nd	small gap between the sample and the wall	123 971	-30.02%	117 237	-30.05%

Although all samples (Foam 1-5) were cut out from the same trim part with the same technique, due to the inhomogeneity and the different material properties (such as stiffness) within a part, and because of practical discrepancies the sample sizes were differing slightly from each other. For example. Foam 1 yielded no noticeable gap between the measurement cell and the sample, i.e. developed a perfect fit. However, for Foam 2 there was a small gap between the sample and the measurement cell, which could originate from a slight ovality, surface unevenness or deviation from the nominal sample diameter. In order to improve the results, silicone grease was added to the edges to prevent the leakage. One of the disadvantage of using silicone grease is that the sample cannot be used for certain further characterization methods later, such as for the open-cell porosity and bulk density measurement due to clogging some of the pores and because of the added mass. Care must be taken during the application of sealant, for which silicone grease was used, since it should not penetrate into the sample nor cover the top and bottom surface of the sample. It is clear from the results shown in Tab. 6, that the application of the sealant has a huge effect on the results, yielding as much as ~30% difference.

An alternative solution to avoid leakage would be to use adapters with smaller internal diameters for a better fit, or just simply making larger samples, fitting tightly into the measurement cell. However, a too tight "radial" fit can result in longitudinal compression on the samples during the process of inserting the sample into the measurement cell, which may cause even higher effect on the resistivity values than the radial compression itself. On the other hand, the advantage of using a smaller diameter adapter (hence using extra radial compression) is that the sample remains usable for other characterization methods. Thus the sample will be not be damaged and this solution is much more sophisticated and faster if the adapter is readily available. Such adapters were manufactured and tested for Foams 3, 4, and 5, which results are shown in Tab. 7.

Tab. 7 *The effect of the gap and the proper, tighter fit using extra adapter on resistivity results [5]*

Sample name:	Measurement:	Measurement details:	Resistivity [Ns/m^4]			
			(at 0 mm/s)	Relative difference	(at 0.5 mm/s)	Relative difference
Foam 3	1st	reference measurement; proper, tighter fit using extra adapter	248 005	-	242 307	-
Foam 3	2nd	small gap between the sample and the wall	205 241	-17.24%	200 482	-17.26%
Foam 4	3rd	reference measurement; proper, tighter fit using extra adapter	207 710	-	203 621	-
Foam 4	4th	small gap between the sample and the wall	161 999	-22.01%	158 792	-22.02%
Foam 5	5th	reference measurement; proper, tighter fit using extra adapter	138 965	-	135 811	-
Foam 5	6th	small gap between the sample and the wall	115 710	-16.73%	113 081	-16.74%

Note that the lines with gray background in Tab. 7 correspond always to the reference measurement with no leakage, where an adapter was used to achieve the proper fit, while the lines with white background correspond to the setup without the adapter, i.e. with a slight gap between the sample and the measurement cell. The results show, that the effect of the adapter is on a similar scale than that of the silicone sealant, resulting in ~17-22% difference. The extra radial compression in this study was a few tenths of a millimeter in the in case of a 29 mm sample diameter.

5.2.4 The effect of material inhomogeneity along the thickness

The literature review showed that no prior study was dedicated to the detailed sensitivity analysis of the resistivity properties of poroelastic foams to the inhomogeneity along the thickness of the sample caused by the manufacturing technologies. Since NVH simulations require the properties of an ideal, average sample, but in reality the samples are inhomogeneous, therefore the sensitivity of the airflow resistivity to inhomogeneity is investigated in this section.

Samples Foam 3, 4 and 5 were prepared from the very same 29 mm diameter sample, as shown in Tab. 3 and in Fig. 4. Recall, that the only difference was that for Foam 4 a very thin, soft film-like layer was removed from one side of the original sample (Foam 3) while for Foam 5 another layer, which was thicker, was also removed from the other side. The thin layer was less than a tenth of a millimeter (~0.05 mm) and this film was created on the side of the production tool due to manufacturing technology reasons. The thicker layer was detached from the other side, which was around 2.35 mm thick and originally this side was attached to another type of acoustic material. Unlike the thin soft layer, the thicker layer was not a film-like layer but a rind / crust-like layer with higher stiffness. Please note that the thickness change itself did not have influence on the resistivity results since the resistivity is a material property. The resistivity results of samples Foam 3, 4 and 5 can be seen in Tab. 8.

Tab. 8 *The effect of the material inhomogeneity along the thickness on airflow resistivity [5]*

Sample name:	Measurement:	Measurement details:	Resistivity [Ns/m^4]			
			(at 0 mm/s)	Relative difference	(at 0.5 mm/s)	Relative difference
Foam 3	1st	none of the layers originated from manufacturing technology were removed from the two sides	248 005	78.47%	242 307	78.41%
Foam 4	2nd	a very thin, soft film-like layer was removed from one side of the sample	207 710	49.47%	203 621	49.93%
Foam 5	3rd	reference measurement; both the thin and thicker layers from the two sides were cut off	138 965	-	135 811	-

Looking at the results, it is obvious that the effect of the layers and so the effect of the inhomogeneity along the thickness are the most significant influencing factors discussed so far. Resulting in as much as ~50% difference between Foam 4 and Foam 5 and more than 78% difference between Foams 3 and 5.

Note that for Foams 3, 4 and 5 only the equivalent resistivity results were determined, including different set of "layers" (thin film-like, thicker crust-like, "more homogeneous" middle core). So the basis, the "more homogeneous middle core" was the same in case of these foam samples. This means that the difference could be even higher by measuring the different type of layers along the thickness separately (e.g. comparing the film-like layer to the middle core or to the crust-like layer etc.).

5.2.5 Effect of inhomogeneity due to sample taking location

The material inhomogeneity due to the location of the sample taking, i.e. along the two largest dimensions of the entire trim part can have an effect on the measured airflow resistivity, which investigation is discussed in this section. Tab. 9 shows the airflow resistivity for samples taken from different locations along the trim part.

Tab. 9 *The effect of inhomogeneity along the component, i.e. due to the location where the samples were taken (Locations 1-4) on airflow resistivity [5]*

Sample name:	Measurement:	Measurement details:	Resistivity [Ns/m^4]			
			(at 0 mm/s)	Relative difference	(at 0.5 mm/s)	Relative difference
Foam 1	1st	Location 1	76 724	-34.46%	72 705	-35.02%
Foam 2	2nd	Location 2	177 149	51.33%	167 591	49.78%
Foam 5	3rd	Location 3	138 965	18.71%	135 811	21.38%
Foam 6	4th	Location 4	75 404	-35.59%	71 452	-36.14%
Average of the 4 measurements:		Reference	117 060	-	111 890	-

As can be seen, the locations of the samples – excluding the inhomogeneity along the thickness – can alone lead to differences as high as +51% and -36% compared to the average resistivity values. Thus, in addition to the inhomogeneity along the thickness, the inhomogeneity along the component has the most significant effect on the resistivity results.

5.2.6 Summary of those influencing factors considered during direct measurements prescribed by the standard

The most important goal of the present study was to accurately determine the static airflow resistivity of acoustic porous materials (which were determined by direct measurements prescribed by the standard), and to quantify the effects and phenomena resulting from the production and measurement technology.

Furthermore, this study aimed to quantify the effects of further influencing factors (such as repeatability, orientation, velocities etc.) in case of airflow resistivity measurements of acoustic porous materials. The novelty of this article is the comprehensive sensitivity analysis and quantified evaluation of the influencing factors of resistivity results. Altogether more than 10 influencing factors were examined (including repeatability, orientation, reinstallation, different sampling, different velocities: 0.5 and 1 mm/s, different velocity ranges, gap, application of sealant and extra adapter providing tighter fit, different extrapolation and interpolation methods using different curves, inhomogeneity along the thickness and along the component).

Tab. 10 shows the absolute values of the maxima of the quantified effects, as well as the typical differences in the last column. As can be seen, the most significant effects were the inhomogeneity as well as the gap between the sample and the wall. These were followed by the selected airflow velocity range, while of the effect of repeatability, orientation, reinstallation and different samplings had the least influence.

Tab. 10 *The effect of influencing factors on resistivity values in case of the examined samples [5]*

Influencing factors	Measurement details:	Sample:	Effect on resistivity Absolute value of relative difference	
			Maximum	Typical
Repeatability, orientation, reinstallation and different sampling together	Different sampling means: slightly different velocities defined manually, still in the recommended range; compared to reference measurement	In case of the presented foam samples	<1%	<1%
Differently selected airflow velocity range	Range 1: 0.5-1 mm/s; Range 2: 0-4.6 mm/s; compared to reference range: 0.5-1 mm/s	In case of the presented foam samples	10%	8%
Slight gap vs. proper, tighter fit using extra adapter	Proper / Tigher fit means: extra radial compression using an adapter with smaller inner diameter; compared to reference measurement	In case of the presented foam samples	22%	20%
Slight gap vs. proper fit using sealant	Gap / sealant between the sample and wall; compared to reference measurement	In case of the presented foam samples	30%	30%
Location / inhomogeneity along the part	Considering just the locations of the samples – excluding the inhomogeneity along the thickness by having just the "homogeneous core"; compared to reference measurement	In case of the presented foam samples	51%	35%
Inhomogeneity along the thickness	Considering only equivalent resistivity results having the same "homogeneous core"; compared to reference measurement	In case of the presented foam samples	78%	64%

It should be noted that the examined samples were cut from the very best quality areas of the part in order to obtain high quality samples, which means that the properties may show even greater deviation in reality.

5.2.7 Effect of selected velocity at which the resistivity is determined

So far the measurements were conducted according to the standard [20], detailed above. As it was mentioned earlier, the standard [20] recommends to determine the airflow resistivity at 0.5 mm/s in case of the direct, quasi-static airflow resistivity measurement – because of practical reasons. However, for the sake of completeness the resistivity values were also determined at 0 mm/s in this study, since according to the theory the resistivity supposed to be measured as close to 0 mm/s velocity as possible and the in-house built measurement setup provides the possibility to derive it by extrapolation. In this section the effects of the differently selected velocities (0 mm/s and 0.5 mm/s) are presented, which results can be seen in Tab. 11. The comparison were executed by using 4 different 29 mm diameter cylindrical samples, 2 foam and 2 fibrous samples (Foam 7, Foam 8, Fibrous 1 and Fibrous 2).

Tab. 11 *Airflow resistivity results determined at different velocities (0 mm/s and 0.5 mm/s) using direct measurement method and 4 different cylindrical samples*

Sample name and material type	Nominal diameter d [mm]	Thickness t [mm]	Airflow resistivity [Ns/m^4] (at 0 mm/s)	Airflow resistivity [Ns/m^4] (at 0.5 mm/s) Reference measurements	Relative difference
Foam 7	29	10	115710	113081	2.33%
Foam 8	29	12	161999	158792	2.02%
Fibrous 1	29	26	14447	14183	1.86%
Fibrous 2	29	27.1	12546	12308	1.94%

As it can be seen in Tab. 11, even though the differences are not as significant as in case of most of the previously discussed influencing factors, there is an average ~2% difference due to the differently selected velocities. Further future development opportunity would be to investigate and determine the reason of this difference.

3 Inverse method and its results

For the completeness, another effective alternative method for the measurement of airflow resistivity is also mentioned here, which is the combined use of impedance tube and inverse method. This method was used on one hand for validation purposes, in order to validate the directly measured (previous) results, on the other hand the goal of the investigation of inverse method was to confirm the potential and achievable accuracy of this acoustical method using impedance tube. This impedance tube-based method can be used not only to determine Biot-parameters, but also to determine other acoustic properties such as absorption, NRC (Noise Reduction Coefficient), and TL (Transmission Loss) [29, 30].

In Fig. 8 a traditional, widely used impedance tube can be seen, such a device was used during the present work as well. As it can be seen there is a sound source on the left side of the tube and there is an adjustable piston – which functions as a rigid wall – on the right side of it. In the middle 3 microphone holders can be seen, pointing upwards. The samples have to be positioned between the microphones (microphone holders) and the adjustable piston. First the pressure fluctuations are measured by the microphones. The pressure data measured over time are converted into the frequency domain by Fourier transformation. From the pressure fluctuations the absorption of the material is derived, and with the help of it the desired resistivity can be calculated.

Fig. 8 *Impedance tube used for the inverse method [25]*

The advantage of this method is that it is possible to determine multiple material poperties with only a single impedance or absorption measurement, hence it can be a productive, effective and cost-efficient solution. On the other hand, if the user is inexperienced and unaware of the ranges within each Biot-parameter can vary, then the poorly chosen parameters and settings can easily result in significant errors. With more complex materials, even an experienced user can easily make mistakes, which can also lead to significant errors. Despite all this, in the present study, the resistivity values obtained with different measurement methods showed good agreement (Tab. 12), although in case of some samples the difference reached ~8-10%, but on average the difference was 4.54%, which means that even the inverse method using imedance tube can provide a good approximation for the airflow resistivity. The comparison were executed by using 6 different – 44.44 mm diameter cylindrical – fibrous samples (termed as Fibrous 3-8).

Tab. 12 *Comparison of resistivity results determined by direct, quasi-static airflow resistivity measurement and inverse method using impedance tube*

Sample name and material type	Nominal diameter d [mm]	Thickness t [mm]	Direct method Airflow resistivity [Ns/m^4] (at 0.5 mm/s) Reference measurements	Inverse method Airflow resistivity [Ns/m^4]	Absolute value of relative difference
Fibrous 3	44.44	5.4	303943	291118	4.22%
Fibrous 4	44.44	5.4	233098	232325	0.33%
Fibrous 5	44.44	4	68432	68306	0.18%
Fibrous 6	44.44	4	53237	55484	4.22%
Fibrous 7	44.44	4.5	465964	429134	7.90%
Fibrous 8	44.44	4.5	519175	465331	10.37%

4 Conclusions and future work

Accurate measurement of airflow resistivity during the determination of Biot-parameters is challenging and therefore the aim of this paper was to examine and quantify the effect of the measurement technique on airflow resistivity. Several measurement steps were systematically considered during the quasi-static airflow resistivity measurements and it was found that:

- The repeatability of the presented direct method with the used system is good (error is less than 1%), therefore no repetition is necessary.

- It has been proven that the selected airflow velocities and velocity ranges have significant effect on the results, therefore it is important to select them carefully, according to the standard.
- It has been proven that the proper fit of the sample in the measurement cell is one of the most important influencing factors and the use of an appropriate adapter is the best way to ensure it; in the absence of this, the use of sealant is recommended.
- It has been proven that the inhomogeneity of the material and the effects of the layers originated from manufacturing technology have to be considered during the material characterization and in simulations, since these factors have the largest impact on the results.
- If it is necessary to cut the sample along the thickness in order to have parallel sides, and to ensure the proper geometry for the measurements, that can result in different material properties in some cases.

Future work shall focus on examining the correlation between thickness and the resulting material properties, as well as defining a best practice on how to implement thickness-dependent properties into the simulation models. Further future development opportunity would be to investigate and determine the reason of the difference between the resistivity results defined at 0 mm/s and at 0.5 mm/s.

An alternative method for the measurement of airflow resistivity was also mentioned, which was the combined use of impedance tube and inverse method. This method was used to validate the correctness of the detailed direct measurement technique and to confirm the potential and achievable accuracy of inverse method. It was found that this method itself can lead to significant errors in case of lack of experience and without adequate theoretical background. Despite this, the resistivity values obtained with different measurement methods showed good agreement. Although in case of some samples the difference reached ~8-10%, but on average the difference was 4.54%, which means that with the inverse method one can achieve a good approximation for the airflow resistivity.

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