# On the sound absorption coefficient of porous asphalt pavements for oblique incident sound waves

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## ABSTRACT

A rolling tyre radiates noise in all directions. Conventional measurement techniques for the sound absorption of road surfaces, however, only give the absorption coefficient for normal incidence. The absorption coefficient for oblique incidence is often computed assuming a locally reacting surface. In this paper, a measurement technique is described with which it is possible to perform in situ sound absorption measurements for oblique incidence. The measurements are performed with a small 3D microphone array. The theory behind the measurement technique is based on the local plane wave assumption. In this paper, an approach is proposed to determine whether a surface behaves as a locally reacting surface or as a non-locally reacting surface, which is an important characteristic for optimising the noise absorption properties of asphalt pavements and for modelling techniques. Preliminary measurements at various angles of incidence are performed to demonstrate this approach as well as measurements of the absorption coefficient at normal incidence to validate the microphone array technique with impedance tube measurements.

Keywords: Sound absorption, Measurement technique, Oblique incidence
I-INCE Classification of Subjects Number(s): 71.1.3, 72.7.1, 72.7.2, 73.4, 76.1.1

## 1. INTRODUCTION

The absorption of sound by porous road surfaces is an important property for reducing tyre road noise. In situ measurements of the sound absorption are characterized by ISO standards, which concentrate on measuring the absorption coefficient for normal incidence (1). However, a rolling tyre will radiate noise in all directions and predominantly as grazing incidence. The angle of incidence and its relation to the absorption of sound is important for modelling purposes, since it shows if a porous road pavement will behave as a locally reacting surface or a non-locally reacting surface.

The in situ absorption coefficient for oblique incidence can be measured with a small 3D microphone array, described by Kuipers et al. (2). This method is based on a local plane wave assumption.

In this paper, we present measurements of the sound absorption coefficient for incoming sound waves at different angles of incidence. The results shown in this paper are preliminary results for in situ measurements of two porous asphalt pavements. The results are compared to predictions of the absorption coefficient for oblique incidence assuming a locally reacting surface. This is a novel measurement technique and the absorption coefficient for normal incident waves can and have been validated with traditional impedance tube measurements.

In the future, the approach presented here can be used to determine the behaviour of porous asphalt pavements, which, in case of non-locally reacting surfaces, should be included in the existing measurements methods used to classify asphalt gradings and in modelling techniques to predict the behaviour of road surfaces.

## 2. MEASUREMENT TECHNIQUES

The in situ sound absorption coefficient is measured with a small microphone array. This method allows measurements of the absorption coefficient for any angle of incidence. Since this is a relatively new method, the results for normal incidence are validated with traditional impedance tube measurements.

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### 2.1 Microphone array for oblique incidence

This method is based on the local (specular) plane wave (LPW or LSPW) method as described by Kuipers (3). Using a microphone array containing 8 pressure sensors, one can find an absorption coefficient for any in situ sound field. Here, this array is used to find the absorption coefficient of porous asphalt pavement for any angle of incidence. This approach is similar as the one described by Kuipers et al. (2), where the sound absorption for oblique incidence is measured and compared to predicted values of the absorption coefficient for a locally reacting surface and an extended reacting surface, as shown in Figure 1.

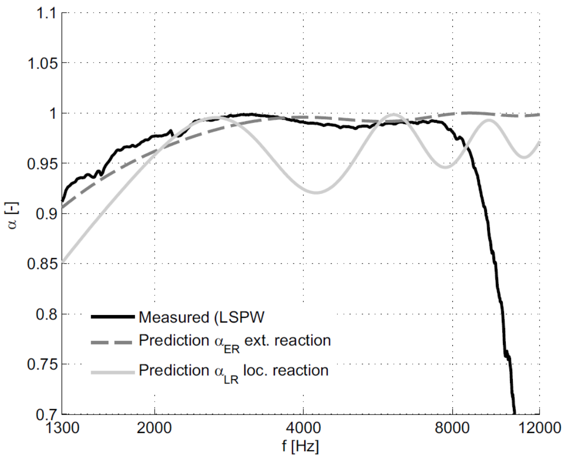


Figure 1 – Figure taken from Kuipers et al. (2). Oblique incidence sound absorption for 45° incidence vs. frequency, measured with LSPW-method, predicted for a locally reacting surface $\alpha_{LR}$, and predicted for an extended reaction surface $\alpha_{ER}$.

#### 2.1.1 Measurement setup

A photo of the microphone array, also called 8p-probe, is shown in Figure 2. The distance between the microphones is 20 mm in all three directions.

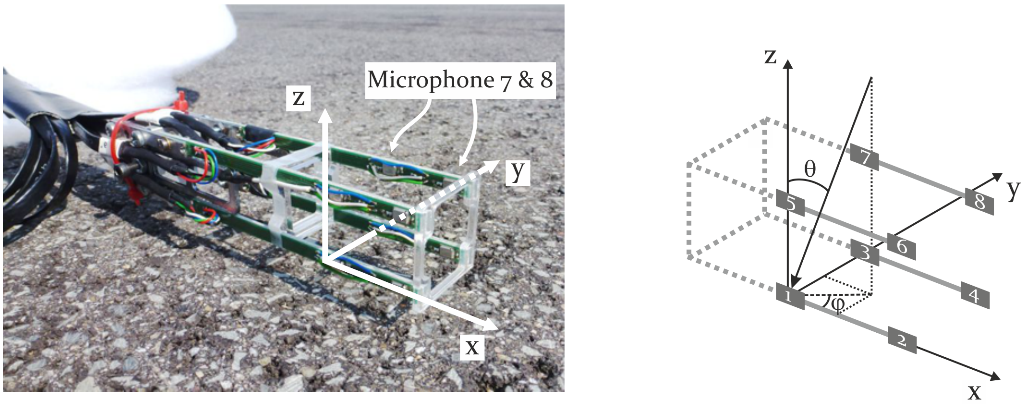


Figure 2 – Photo of the 3D microphone array with 8 equally spaced microphones and schematic view of the array including the numbering of the microphones, the polar angle $\theta$ and the azimuthal angle $\varphi$.

The pressure sensors on the 8p-probe are attached to a data acquisition device to acquire the complete time signal for all microphones. A speaker is added to the setup generating white noise within the desired frequency range. The speaker is attached to a tripod and positioned at a certain height and distance from the probe. Varying this position will vary the angle of incidence of the incoming sound waves. Multiple measurements are performed while varying the position of the speaker. The position of the probe is also varied to minimise the influence of the local surface effects.

#### 2.1.2 Local plane wave assumption

According to the local plane wave assumption, the sound pressure for a microphone with the location defined by $\mathbf{r} = (x, y, z)$ can be written as

$$P(\mathbf{r}, \theta, \varphi, \omega) = A(\mathbf{r}, \omega) e^{-iks(\mathbf{r}, \theta, \varphi)} + B(\mathbf{r}, \omega) e^{iks(\mathbf{r}, \theta, \varphi)} \quad (1)$$

where $A(\mathbf{r},\omega)$ denotes the complex amplitude of the incident plane wave, $B(\mathbf{r},\omega)$ the complex amplitude of the reflected plane wave, $k$ is the wavenumber, $\omega$ the angular frequency and $s$ is a spatial coordinate:

$$s(\mathbf{r},\theta,\varphi) = x\sin(\theta)\sin(\varphi) + y\sin(\theta)\cos(\varphi) - z\cos(\theta) \tag{2}$$

where $\theta$ and $\varphi$ describe the angle of incidence; the polar angle $\theta$ is the angle between the z-axis and the normal of the wave front and the azimuthal angle $\varphi$ is the rotation around the z-axis, as indicated on the right hand side of Figure 2. The law of specular reflection yields that the angle of reflection is equal to the angle of incidence. The direction of the incoming wave is taken positive, since a positive time dependency $e^{i\omega t}$ is assumed.

More details about the local plane wave method and the local specular plane wave method are given by Kuipers (3). In this paper we focus on obtaining the absorption coefficient for any angle of incidence, using the sound pressure from all 8 microphones.

The geometry and locations of the microphones are known. The sound pressure for each microphone can be described by Equation 1 and can be written in matrix form:

$$\begin{Bmatrix} P_1(\mathbf{r},\theta,\varphi,\omega) \\ P_2(\mathbf{r},\theta,\varphi,\omega) \\ \vdots \\ P_n(\mathbf{r},\theta,\varphi,\omega) \end{Bmatrix} = \begin{bmatrix} e^{-iks(\mathbf{r_1},\theta,\varphi)} & e^{iks(\mathbf{r_1},\theta,\varphi)} \\ e^{-iks(\mathbf{r_2},\theta,\varphi)} & e^{iks(\mathbf{r_2},\theta,\varphi)} \\ \vdots & \vdots \\ e^{-iks(\mathbf{r_n},\theta,\varphi)} & e^{iks(\mathbf{r_n},\theta,\varphi)} \end{bmatrix} \begin{Bmatrix} A(\mathbf{r},\omega) \\ B(\mathbf{r},\omega) \end{Bmatrix} \tag{3}$$

In short, this system can be written as

$$\{\mathbf{P}\} = [\mathbf{S}]\{\mathbf{a}\} \tag{4}$$

where the vector $\{\mathbf{P}\}$ contains the sound pressure measured by the microphones, the vector $\{\mathbf{a}\}$ contains the unknown complex amplitudes, $A$ and $B$, and the matrix $[\mathbf{S}]$ describes the geometry of the 8p-probe, where the direction of the plane waves is included in the spatial coordinate $s(\mathbf{r},\theta,\varphi)$. The angular frequency $\omega$ is here omitted for readability.

The system is solved using the normal equations, where Equation 4 is solved in a least square sense:

$$\{\mathbf{a}\} = \left([\mathbf{S}]^T[\mathbf{S}]\right)^{-1}[\mathbf{S}]^T\{\mathbf{P}\} \tag{5}$$

where $[\mathbf{S}]^T$ is the conjugate transposed of $[\mathbf{S}]$.

Since the angle of incidence is unknown, the normal equations are solved for a number of possible angles, given by $\theta_j$ and $\varphi_k$, for which the 2-norm of the residue $\varepsilon_{jk} = \mid \mathbf{S}_{jk}\mathbf{x}_{jk} - \mathbf{P} \mid^2$ is minimised, such that the most likely polar and azimuthal angle, denoted by $\hat{\theta}$ and $\hat{\varphi}$, are found.

For these angles $\hat{\theta}$ and $\hat{\varphi}$, the local sound absorption coefficient $\alpha$ is given by

$$\alpha = 1 - |R|^2 = 1 - \frac{B\overline{B}}{A\overline{A}} \tag{6}$$

where $R$ is the reflection coefficient and where $\overline{A}$ and $\overline{B}$ are the complex conjugates of the complex amplitudes, respectively $A$ and $B$.

## 2.2 Impedance tube measurements for normal incidence

The validation of the 8p-probe method is performed with the more traditional impedance tube method. Note that only the measurements for normal incidence can be validated.

### 2.2.1 Measurement setup

The measurement setup for the in situ measurements is shown in Figure 3. The important dimensions of the setup are summarized in Table 1. The setup consists of a PVC tube with 3 microphones. The contact between bottom of the tube and the road surface is sealed with clay. On the topside of the tube, a speaker is attached that can generate a chirp signal within the desired frequency range.

### 2.2.2 Impedance tube measurements using three microphones

The measured signals are analysed in the frequency domain. The approach used here is similar to the approach used for the 8p-probe, described by Equation 1 to Equation 6. The main difference is that the sound field in the impedance tube is assumed to be one-dimensional with the normal of the wavefront perpendicular to the measured surface. Therefore, the spatial coordinate $s(\mathbf{r},\theta,\varphi)$ will be equal to the microphone distances, $s_1$ and $s_2$. Substituting the angle of incidence, $\theta = 0°$, and the microphone distances in Equation 4 results in a fully determined geometry matrix $[\mathbf{S}]$. The complex amplitudes and the absorption coefficient can be determined directly using Equation 5 and 6.

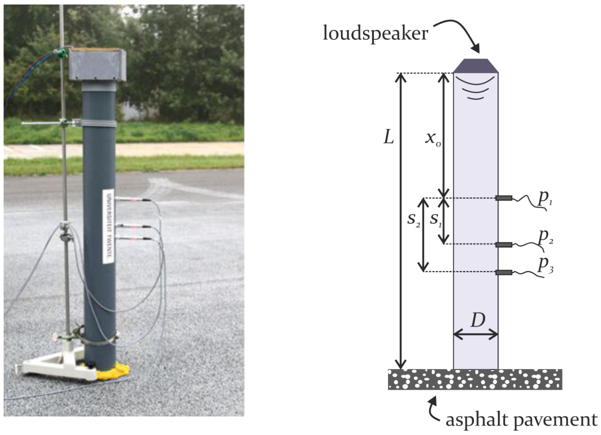


Figure 3 – Photo of the measurement setup using impedance tube and schematic view including the dimensions.

Table 1 – Dimensions of impedance tube.

| Setup | Dimensions, mm |
|---|---|
| Diameter tube (*D*) | 100 |
| Length (*L*) | 1000 |
| Distance to first microphone ($x_0$) | 380 |
| Microphone distance ($s_1$) | 90 |
| Microphone distance ($s_2$) | 130 |

## 3. ABSORPTION COEFFICIENT FOR LOCALLY REACTING SURFACE

Porous asphalt pavements are assumed to behave as extended reacting surfaces or non-locally reacting surfaces ((4), Section 2.4). It is difficult to model or predict the impedance and absorption coefficient of such surfaces. When a locally reacting surface is assumed, the absorption coefficient for oblique incidence can be determined using the measurements for normal incidence. This approach is based on the relation between the reflection coefficient $R$ and surface impedance for normal incident sound waves $Z_n$:

$$R = \frac{Z_n - Z_0}{Z_n + Z_0} \tag{7}$$

where $Z_0 = \rho_0 c_0$ is the characteristic impedance of air. The reflection coefficient and the impedance both depend on the angular frequency, $\omega$, which is omitted here for readability. The reflection coefficient can be derived from Equation 6 once the complex amplitudes are known. Rewriting Equation 7 will give the surface impedance for normal incidence.

For a locally reacting surface, the reflection coefficient for oblique incidence is given by ((5), Chapter 5):

$$R(\theta) = \frac{Z_n \cos\theta - Z_0}{Z_n \cos\theta + Z_0} \tag{8}$$

Here, the reflection coefficient depends only on the angle of incidence $\theta$ of the incoming sound waves. Therefore, the sound absorption coefficient as function of the angle of incidence can be computed using the complex amplitudes or reflection coefficient for normal incidence.

## 4. RESULTS AND DISCUSSION

The described measurement techniques are used for indoor measurements of a sheet of 50 mm thick melamine resin foam with hard backing and in situ measurements for two types of porous asphalt pavements. The asphalt gradings have different porosity, stone sizes and layer height, which are listed in Table 2.

### 4.1 Normal incidence

The absorption measurements with the impedance tube are used to validate the 8p-probe technique for normal incidence. The averaged absorption coefficient for all three situations is shown in Figure 4. For the measurements with the 8p-probe, the speaker was attached to a tripod and positioned such that the angle

Table 2 – Properties of porous asphalt concrete.

| Road | Porosity, % | Stone sizes, mm | Layer height, mm |
|---|---|---|---|
| Deciville ES | 15 | 2/5 | 30 |
| DAB | 4 | 4/8, 8/11, 11/16 | 40 |

of incidence was close to normal incidence. The angle of incidence is later determined as described in Section 2.1.2. The computed angle of incidence is $\theta \leq 10°$ for all measurements.

In Figure 4, it can be seen that the standard deviation for the absorption coefficient measured by the 8p-probe technique is larger than for the impedance tube, especially for the lower frequencies of the in situ measurements. A possible explanation is the small distance between the microphones, since a 20 mm distance equals about 3% of the wavelength at 500 Hz, which is 10.5°. Note that for the indoor measurements of the foam sheet, the standard deviation is smaller, especially for frequencies above 1000 Hz.

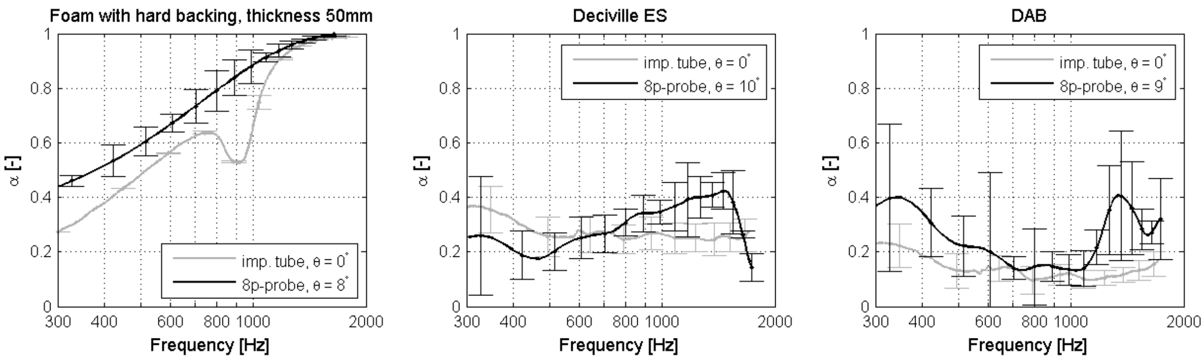


Figure 4 – Averaged absorption coefficient measured with impedance tube and with 8p-probe. The error bars indicate the 68.3% confidence limits (±1 S.D.).

Figure 5 shows the difference between the absorption coefficient determined with the impedance tube measurements and the 8p-probe technique, where

$$\Delta(\omega) = \alpha_{\text{probe}}(\omega) - \alpha_{\text{imp. tube}}(\omega) \tag{9}$$

This figure shows that the differences for the foam sheet between the measurements with the impedance tube and 8p-probe is large around 900 Hz. Above 1100 Hz, the agreement between both methods is fairly well. For the two in situ measurements, the differences are large for frequencies around 1300 Hz. It is possible that this is introduced by the distance between the probe and the pavement ((3), Section 3.3), but more measurements should be performed to determine the cause. The difference between both methods is smallest between 600 Hz and 1200 Hz for the in-situ measurements, which is the most interesting frequency range for tyre road noise.

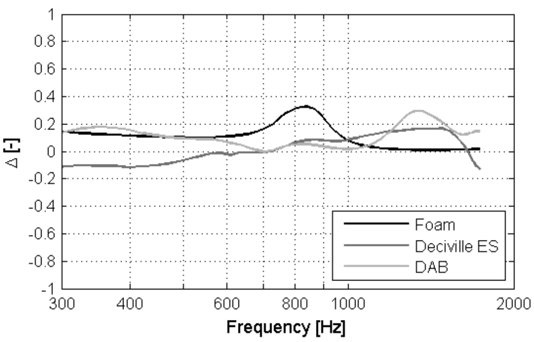


Figure 5 – Difference between averaged absorption coefficient measured with impedance tube and 8p-probe for the indoor (foam) and in situ (both road surfaces) measurements.

### 4.2 Oblique incidence

The sound absorption coefficient for oblique incidence is measured with the 8p-probe. The preliminary results for measurements where the angle of incidence is varied, are shown in Figure 6. It can be seen that the absorption coefficient for the DAB road surface is very low for a large angle of incidence, $\theta = 71^\circ$. The sound absorption of the first road, Deciville ES, is larger than for the DAB road surface, which corresponds with the larger porosity of this pavement.

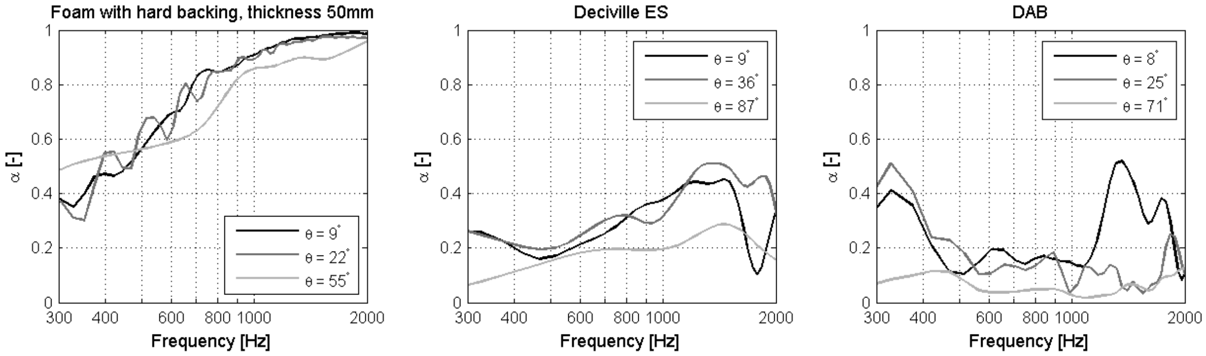


Figure 6 – Absorption coefficient for oblique incidence measured with the 8p-probe.

### 4.3 Locally reacting surface assumption

The absorption measurements with the 8p-probe can be used to determine whether the measured porous asphalt pavements behave as a locally reacting surface or as a non-locally reacting surface. The method described in Section 3 is demonstrated here.

The predictions of the absorption coefficient for oblique incidence are based on the measurement results of the 8p-probe for normal incidence. The predicted sound absorption is shown in Figure 7, where the solid lines represent the predicted absorption coefficient and the dashed lines the measured absorption coefficient. For the indoor measurements of the foam sheet, the predicted absorption coefficient assuming a locally reacting surface is lower than the measured values, which is an indication that the surface should not be assumed to be a locally reacting surface.

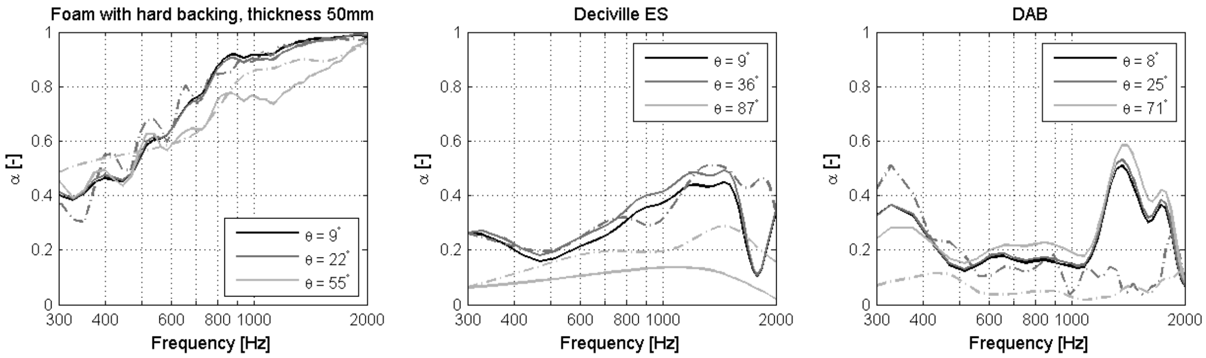


Figure 7 – Absorption coefficient for foam and porous asphalt pavement. Measurement results are given by the dashed lines. Predictions assuming a locally reacting surface are shown by solid lines, which are based on the measurement results for $\theta \leq 10^\circ$.

Due the measurement uncertainty, the results for the two in situ measurements for frequencies above 1200 Hz are not discussed here. The absorption coefficient of the Deciville ES pavement for the second angle of incidence, $\theta = 36^\circ$, is predicted fairly well. The measurements performed at the third angle of incidence, $\theta = 87^\circ$, are at grazing incidence. For such a large angle of incidence, the absolute value of the reflection coefficient according to Equation 8 will be close to 1, which gives an absorption coefficient close to zero. The measured value of the absorption coefficient for grazing incidence is low, but not as low as the predicted values. The predicted sound absorption coefficients for the DAB road surface at oblique incidence, $\theta = 25^\circ$ and $\theta = 71^\circ$, are larger than the measured absorption coefficient, especially for the largest angle of incidence.

The differences between the predicted values and the measured absorption coefficient are an indication that porous asphalt pavements indeed behave as a non-locally reacting surface. However, more measurements are needed before a conclusion can be drawn.

## 5. CONCLUSIONS

The measurement technique described in this paper can be used to determine the sound absorption coefficient of a surface for oblique incidence. Using this technique for porous asphalt pavements, the absorption coefficient as function of the angle of incidence can be determined, which can be used to optimise the design of asphalt gradings and to validate numerical models of porous surfaces.

Measurements are performed to validate this technique for in situ absorption measurements. Also, a first indication is shown that porous asphalt concrete does not behave as a locally reacting surface. However, these measurements have a large standard deviation which indicate that some improvements of the setup are needed. In the future more research will be performed to find the influence of the distance of the probe to the measurement surface, to research the use of a scanning motion during the measurements and to find the influence of the dimensions of the area that is scanned. Also the method to estimate the angle of incidence has to be validated, since the measurements performed at normal incidence indicate an uncertainty of about 10°. Another effect that has to be researched is the influence of leakage of acoustical energy through the edges of the measured surface, since the incoming sound will not only be absorbed, but will also flow along the surface, especially in case of acoustical hard surfaces. Therefore, more measurements with an improved setup have to be performed.

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