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**In-situ impedance and absorption coefficient measurements using a double-layer
microphone array**

Short title: In-situ array-based material property measurement

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ABSTRACT

Acoustic impedance is typically measured using an impedance tube, which requires a material sample physically fitted to the tube. However, the impedance can vary greatly between the material mounted in the tube and the material located in a real environment, where the mounting conditions are likely to be different. Also, oblique incidence cannot be measured in an impedance tube. In this paper, we investigate the use of a double-layer microphone array for in-situ measurement of surface impedance and absorption coefficient. With the array positioned near the material surface, a source emits broad-band sound towards the array and the material. A measurement is taken, and the sound pressure and the surface-normal particle velocity at the material surface are calculated using Statistically Optimized Near-field Acoustical Holography (SONAH). From the surface pressure and velocity, the impedance across a selected area is calculated, and finally the absorption coefficient is calculated from the impedance. A set of tests has been performed on porous material samples in an anechoic chamber as well as in a fitted room. Different sample sizes and different sound incidence angles have been considered. The results show consistency between the measurements in the anechoic room and the ordinary room as well as good agreement with Miki's model up to large oblique incidence angles.

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Keywords: Absorption coefficient, Surface acoustic impedance, Microphone array, Near-field acoustic holography, In-situ measurement

1. Introduction

Various computer simulation techniques, such as wave-based simulations and geometrical acoustics simulations, have been applied for optimizing the Noise, Vibration and Harshness (NVH) of vehicles for many years. The accuracy of such 3D room acoustic simulations depends heavily on the acoustic properties of materials as well as boundary conditions [1-4]. For that purpose, ISO 10534-2 [5] outlines a method of determining the acoustic absorption coefficient and surface impedance of materials using impedance tubes, while the method of ISO 354 [6] assumes a perfectly diffuse sound field with random incidence of waves. These standardized methods measure material properties under controlled conditions, i.e. free-field normal incidence on a small material sample in a tube or diffuse random-incidence on a single investigated component. None of these conditions represents well the typical application of the materials in a vehicle cabin: The materials are typically mounted in ways very different from that in an impedance tube, and the actual operational sound field will not provide diffuse random incidence. Like other in-situ measurement techniques [7-8], the method of the present paper is applicable to materials mounted for their intended application, for example on the ceiling of a vehicle cabin or on a seat. The incident sound field, however, must locally be close to a single plane wave, and the reflected field must locally be close to the response to the single plane wave. Thus, the method cannot be used with a typical operational sound field in a vehicle cabin. A single-source excitation is needed. But unlike the impedance-tube method, normal incidence is not required, and therefore the dependence of the acoustic properties on the sound incidence angle can be measured. Such information clearly improves the accuracy of acoustic simulations as shown in [9]. The proposed new method, which was first introduced in reference [10], measures the angle-dependent acoustical properties using a double-layer microphone array located near the material surface and a single loudspeaker at a fixed position.

67 An in-situ method using a single microphone was introduced in [11]. The method separates the direct
68 component of an impulse response function from the reflected part for calculation of the impedance. It
69 is simple in terms of instrumentation, but the method suffers from reflections from other surfaces as well
70 as challenging cases in which the reflected part of impulse responses cannot be separated from the
71 incident part, e.g., at near-grazing incidence angles. A more reliable estimation may be achieved by a p-u
72 probe measuring sound pressure as well as surface velocity on a surface directly [12]. However, the
73 method requires a time-consuming calibration procedure and seems to be sensitive to reflections from
74 neighbouring surfaces [13].

75 Several array-based methods for measurement of material surface properties have been published.
76 Tamura [14] introduced a method based on use of a double-layer regular rectangular array in combination
77 with spatial-DFT-based Near-field Acoustical Holography. Using the pressure measured in two parallel
78 planes, the method can resolve the incident and resulting reflected plane waves. For each available
79 incidence direction, the reflection coefficient can be estimated as the ratio between the incident and the
80 corresponding reflected plane wave. Due to the periodicity assumed by the spatial DFT, the method
81 suffers from replicated aperture errors, which can be minimized using large planar panel sections and
82 large arrays, using suitable spatial windowing, and/or by use of a source that focuses the incident field
83 on a limited area. At the lowest frequencies, the method probably also suffers from the errors, which are
84 a main motivation for the method of the present paper, related to the fact that the spacing between the
85 two planar microphone layers must be less than half of the wavelength at the highest frequency of interest.
86 This typically means that the layer spacing is much less than wavelength at the lowest frequency of
87 interest, leading to poor resolution of incident and reflected waves.

Hald et al. [15-16] presented a similar method of estimating material properties by making use of a small double-layer microphone array in combination with a so-called patch-holography method called Statistically Optimized Near-field Acoustical Holography (SONAH) [17-18]. SONAH avoids the use of spatial DFT and therefore does not produce any replicated aperture errors, allowing the use of quite small material samples and arrays. The method separates incident waves from reflected waves, and it maps the incident and reflected sound intensity components, I_{inc} and I_{abs} , on the material surface. Integration over a small surface area provides the incident and reflected sound power, W_{inc} and W_{abs} , from which the average absorption coefficient across the selected area is calculated:

$$\alpha = \frac{W_{\text{abs}}}{W_{\text{inc}}}. \quad (1)$$

This so-called *energy-based method* can be used in-situ and with the incident sound field equal to or close to that of the intended application of the absorbing material. The method cannot provide estimates of the surface acoustic impedance. The study presented in references [17-18] made use of a set of omnidirectional sources behind a microphone array to create an incident sound field similar to that in an aircraft cabin during flight. For practical reasons, such a set-up is challenging to handle inside a small car cabin, where in addition the very low frequencies are of primary importance. At these frequencies, separation of the reflected waves from the incident waves is difficult due to the previously mentioned small physical spacing between the two microphone layers. Experience shows that significant errors may be introduced, typically below 1 kHz for an array like the one used in the present paper. Advantages of the method include that only power quantities are used in the area integration/averaging, avoiding the need for phase information across that area. Thus, it is not critical that the mapping surface follows strictly the panel surface. Also, local reaction is not required after suitable area integration.

109 Another array-based method called the *finite-surface method* was suggested in reference [19] to estimate
110 the acoustic property of a finite-sized absorber for oblique incidence by comparing a sound field model
111 over a finite surface with a measured sound pressure distribution. Good results were obtained with small
112 material samples, which satisfy the original assumption of the finite surface model.

113 Recently, an in-situ spherical-array-based measurement method was proposed based on sparse array
114 processing. The method successfully estimated the acoustic properties of porous materials up to an
115 incidence angle of 60° between 200 and 4000 Hz, [8].

116 The present paper describes a new array-based method similar to the energy-based method, but instead
117 of calculating the incident and reflected sound power data, the sound pressure and particle velocity of
118 the total field are calculated on the material surface and used to calculate the acoustic impedance.
119 Assuming a single incident plane wave with known incidence direction across the measurement area, the
120 absorption coefficient can be calculated from the impedance based on a large-surface approximation.
121 Thus, the method does not directly use measured quantities of the incident and reflected sound field
122 components. If several angles of plane-wave incidence must be covered, one measurement is needed for
123 each angle with a single source in the chosen direction. The paper is organized as follows: Section 2
124 gives a short theoretical description of the proposed method. Section 3 describes a set of simulated
125 measurements in support of the results of actual measurements to be presented in section 4. Both deal
126 with the use of a double-layer array for measurements on a specific type of highly absorbing material.
127 Section 5 presents the results from some further simulated measurements to clarify the influence of array
128 size, microphone phase mismatch and level of absorption. Finally, section 6 contains the conclusions.

129

2. Theory

The proposed method is based on use of SONAH to estimate the sound pressure and the normal component of the particle velocity on the material surface based on measurement with a double-layer array some small distance above the material. SONAH uses a model of the sound field in terms of plane propagating and evanescent waves, one set to represent the incident sound field and another set to represent the reflected field. Based on the sound pressure measured by the microphones, the complex amplitudes of these elementary waves are estimated by the solution of a set of linear equations, and with these amplitudes known, the total (incident plus reflected) pressure and particle velocity on the material surface can be calculated. The system of linear equations is by nature ill-conditioned and needs regularization to limit the amplification of weak components in the measured pressure data. Typically, a Singular Value Decomposition is performed on the coefficient matrix, and the regularization can be specified as an applied dynamic range of singular values used in the solution. Use of a large dynamic range (allowing large amplification) will support the reconstruction of sound field components with a low presence in the measured pressure, but it will also have the effect of heavily amplifying noise and errors in the data. This will become evident in the results to be presented in section 5.

As mentioned already, the new *impedance-based method* uses the same type of double-layer array and the same SONAH holography algorithm for in-situ measurements as the energy-based method [15-16]. For estimation of the absorption coefficient, however, it requires excitation with a single (dominating) incident plane wave with known incidence angle across the measurement area. Experience has shown that the method is much more stable at the lowest frequencies than the energy-based method. An example is included in Fig. 6b in section 4. According to the new method, the complex frequency-domain sound pressure $p(\mathbf{r}_i)$ and the normal component of particle velocity $u_n(\mathbf{r}_i)$ for the total (incident plus

152 scattered/reflected) sound field are calculated at a mesh of points $\mathbf{r}_i$ on the panel surface. The ratio
 153 between these two quantities is the surface impedance. Notice that this calculation involves no plane-
 154 wave or spherical-wave assumption as does for example the two-microphone method of reference [20].
 155 For a locally reacting panel and for a non-locally reacting planar, infinite, homogeneous panel with a
 156 single incident plane wave, this surface impedance is constant across the panel surface, see for example
 157 reference [21]. An area averaging can therefore be performed by requiring the unknown normalized
 158 surface impedance Z_s to fulfil the equation

$$159 \quad p(\mathbf{r}_i) = \rho c Z_s u_n(\mathbf{r}_i) \quad (2)$$

160 for all points $\mathbf{r}_i$ within the considered panel segment, ρ being the density of air and c the sound
 161 propagation speed in air. Arranging the area-related quantities $p(\mathbf{r}_i)$ in a vector $\mathbf{p}$ and the corresponding
 162 quantities $\rho c u_n(\mathbf{r}_i)$ in a vector $\mathbf{u}$, we then estimate the normalized surface impedance Z_s for the selected
 163 segment by solving the over-determined set of linear equations $\mathbf{p} = Z_s \mathbf{u}$ in a least squares sense:

$$164 \quad Z_s = \frac{\mathbf{p}^H \mathbf{p}}{\mathbf{p}^H \mathbf{u}}. \quad (3)$$

165 Here, H represents Hermitian (conjugate) transpose. The method will of course be sensitive to the
 166 complex surface impedance being rather constant across segments of the calculation mesh used for the
 167 least-squares estimation. Use of a single point source at short-to-medium distance will cause the surface
 168 impedance to vary across the surface (see for example reference [22]) and therefore require the use of a
 169 very small averaging area.

170 If the panel is infinite and planar with a plane wave incident at an angle θ from the surface normal, then
 171 the complex pressure reflection coefficient (the “reflection coefficient” in what follows) R_s can be
 172 calculated as, [21]:

$$173 \quad R_s(\theta) = \frac{Z_s \cos(\theta) - 1}{Z_s \cos(\theta) + 1}, \quad (4)$$

174 and the absorption coefficient α is then:

$$175 \quad \alpha(\theta) \equiv 1 - |R_s(\theta)|^2 = \frac{4\text{Re}\{Z_s\} \frac{1}{\cos(\theta)}}{\left|Z_s + \frac{1}{\cos(\theta)}\right|^2}, \quad (5)$$

176 where the operator $\text{Re}\{\}$ returns the real part of a complex number. In connection with practical
 177 measurements, where an (approximate) monopole point source is used at a finite distance, the plane-
 178 wave assumption is replaced by the use of a local plane-wave model/assumption. The errors introduced
 179 by that assumption in Eqs. (4) and (5) could be investigated numerically by use of the *analytical spherical*
 180 *wave-front models* applied in reference [22]. This has not been done, but could be a topic for a future
 181 investigation. The 1.5 m source distance, used in practical measurements in the present paper, will
 182 introduce some errors, mainly at the lowest frequencies.

183 The infinite panel assumption implicit in Eqs. (4) and (5) could be generalized as described in reference
 184 [19] using a finite-surface model:

$$185 \quad \alpha(\theta) = \frac{4\text{Re}\{Z_s\} \frac{1}{\cos(\theta)}}{|Z_s + Z_F|^2}, \quad (6)$$

186 where Z_F is the normalized specific radiation impedance. For an infinite planar area, $Z_F = \frac{1}{\cos(\theta)}$. This
 187 finite-surface extension covers only planar material surfaces, and it will not be investigated further in the

188 present paper. Other investigations of the challenges associated with finite-sized material samples can be
 189 found for example in references [23-26].

190

191 **3. Simulated measurements**

192 The present section will describe some simulated measurements in support of the real tests to be presented
 193 in section 4. The material is an infinite sheet of 100 mm thick ceiling absorber of type Industry Modus
 194 (manufactured by Ecophon) mounted on a rigid backing and with a specific air-flow resistivity σ of
 195 10900 Nm⁻⁴s (provided by Ecophon). Sound propagation inside the material was simulated using an
 196 isotropic, equivalent-fluid model with the complex wavenumber k_c and the normalized characteristic
 197 impedance Z_c obtained from the single-parameter Miki model, [27], requiring only the flow resistivity
 198 as input. For the simulated measurements, we assumed an infinite planar sheet of material and a single
 199 plane wave incident at an angle θ from the surface normal, while for the practical tests a finite sample
 200 was of course used with a single source at a finite distance.

201 Following reference [21], the simulated-measurement model (infinite material with plane-wave
 202 incidence) predicts the following normalized material-surface impedance:

$$203 \quad Z_s = -j Z_{c \frac{k_c}{k_{c,n}}} \cotg(k_{c,n} d), \quad (7)$$

204 where $d = 0.1$ m is the material thickness, j is the imaginary unit and $k_{c,n}$ is the component of the
 205 wavenumber vector in the material in the direction normal to the surface. That wavenumber component
 206 is obtained from the requirement $k_c^2 = k_{c,n}^2 + k_{c,t}^2$, where $k_{c,t}$ is the tangential component in the material,
 207 which must equal the tangential wavenumber component $k \sin(\theta)$ in air. This leads to:

$$k_{c,n} = \sqrt{k_c^2 - (k \sin(\theta))^2}, \quad (8)$$

where $k = \omega/c$ is the wavenumber in air, $\omega = 2\pi f$ is the angular frequency, and f is the frequency. In the above, the implicit time dependence has been assumed to be $e^{j\omega t}$. The “true” plane-wave reflection coefficient R_s at the material surface and the “true” absorption coefficient α can then be calculated by use of equations (4) and (5), respectively.

Once the reflection coefficient has been calculated, the reflected pressure resulting from a given incident plane wave can be reconstructed, and the complex sound pressure can be calculated at all microphone positions of a simulated array. A SONAH calculation can then be performed to estimate the sound pressure and particle velocity on the material surface, and based on that information, an estimate of the surface impedance, $\tilde{Z}_s$, can be obtained using Eq. (3). For this, a calculation mesh identical to the array mesh was used, but with one row/column removed at all four edges, because reconstruction errors will be largest near the edges. Thus, with an 8×8 -element regular quadratic array we get a 6×6 -point calculation mesh, and with a 3×3 array we get only a single calculation point, which implies no area averaging. Finally, $\tilde{Z}_s$ can be used in equations (4) and (5) to get an estimate $\tilde{\alpha}$ of the absorption coefficient. By comparing $\tilde{Z}_s$ against Z_s and $\tilde{\alpha}$ against α it is possible to get an indication of the level of uncertainty added by the array processing under ideal conditions, i.e. with no measurement errors and no added noise. For the single calculation points on the material surface, the errors in the reconstructed pressure and particle velocity will depend on the array geometry (number of rows, number of columns and element spacing), the measurement distance and the parameters used for the SONAH calculation. In general, a large array with a small microphone spacing (many channels) used at a small distance will minimize the errors - see reference [17] for a description of these so-called Inherent Errors of SONAH

sound field reconstructions. These errors are due to SONAH not making any assumptions about the sound field, requiring many measurement points to be able to accurately reconstruct all types of sound field. Section 5 presents an investigation on the reconstruction errors, when in addition input data are noisy. The investigation shows that area averaging is effective at suppressing the impact of the point-wise errors on impedance and absorption-coefficient estimates (provided that the true surface impedance is constant across the averaging area).

The same array geometry was used in the simulations as in the practical measurements: A planar double-layer array with 8×8 microphones in each one of the two identical parallel layers. The quadratic regular grid array in each plane had a pitch equal to 25 mm, the separation between the layers was 29 mm, and the distance from the material surface to the nearest parallel array plane was 13 mm. With these microphone spacings, the upper limiting frequency for SONAH calculations will be around 5 kHz, while the lower limiting frequency will be around 200 Hz. Neither measurement errors (e.g. microphone phase mismatch) nor noise were added. The SONAH calculation parameters were chosen to be equal to those used for the real measurements.

Fig. 1. Relative error on the estimated surface impedance in percent for four different plane wave incidence angles: 0° , 30° , 60° and 75° .

Figure 1 shows the relative error on the estimated surface impedance in percent, $100\% \cdot |\tilde{Z}_s - Z_s|/|Z_s|$, for four different values of the plane-wave incidence angle: 0° , 30° , 60° and 75° . The error added by the array processing is seen to be small for frequencies up to around 5 kHz, typically within 5%, when area averaging is applied. Above 5 kHz, the error increases steeply. The errors shown in Fig. 1 are the minimum errors introduced by the array processing, i.e. with no measurement errors and no noise. They are the inherent errors of SONAH sound-field reconstructions mentioned earlier, but with an error reduction obtained by the area averaging in the impedance estimation. Other simulations have been performed with random microphone phase errors within $\pm 0.25^\circ$ added to the simulated measurements. The only effect was some fluctuations added to the curves of Fig. 1, concentrated at the low frequencies. Examples will be given in section 5.

Fig. 2. True absorption coefficient from Miki model α (solid) and from array calculation $\tilde{\alpha}$ (dashed) for four different plane-wave incidence angles: 0° , 30° , 60° and 75° .

Figure 2 shows the true and estimated absorption coefficient spectra, α and $\tilde{\alpha}$, for plane-wave incidence angles 0° , 30° , 60° and 75° . In general, the deviations are small, but slightly increasing with increasing off-normal incidence angle. The frequency averaged percentage errors, $100\% \cdot \sum |\tilde{\alpha} - \alpha| / \sum \alpha$, where

summation is over frequencies, are 0.2%, 0.2%, 0.2%, 0.3%, 0.6% and 1.4% for incidence angles 0° , 15° , 30° , 45° , 60° and 75° , respectively. The frequency lines used in the summations were equidistant on the logarithmic frequency axis of Fig. 2.

The errors introduced by the array processing are clearly very small under ideal conditions. In realistic in-situ measurements, the material sample will probably not be perfectly planar, be inhomogeneous, have finite extent, be subject to a complicated incident field etc. Some of these factors will be investigated through the real measurements to be presented subsequently.

4. Measurements

A measurement campaign has been carried out using a double-layer $8 \times 8 \times 2$ -element microphone array with the same geometry as defined above and an omni-directional sound source (B&K type 4295) excited by white noise to generate the sound field impinging on a material. To investigate the capabilities of the proposed method, different factors are considered in the tests: type of room, incidence angle of the sound wave and sample size.

Reflections from different surfaces in a room will introduce errors in the estimation of impedance and absorption coefficient, since basically a single incident plane wave is assumed with known incidence angle, ref. Eq. (4). To examine this influence on the estimation, measurements have been performed in two very different rooms: 1) an anechoic chamber with dimensions $12 \times 10 \times 9 \text{ m}^3$ and 2) a fitted room with dimensions $6.3 \times 6.8 \times 3.1 \text{ m}^3$ and with T30 reverberation times 0.67, 0.45, 0.48, 0.48, 0.50 and 0.50 seconds in the octave bands from 125 Hz to 4 kHz. In the anechoic condition, reflections are minimized, and the results can be used as a reference. In the fitted room, floor, ceiling, walls and different objects create reflections.

A single source has been used at different incidence angles: 0° (normal incidence), 30° , 60° and 75° (75° was applied only in the anechoic chamber). To precisely explain the geometry, we define the point on the material surface under the array center as the *reference point*. The incidence angle is defined as the angle between the material surface normal at that point and the line from the reference point to the source. The distance of the source from the reference point was always approximately 1.5 meter. This guaranteed a dominating direct spherical sound wave (in comparison with reflections), while keeping the direct wave close to a plane wave across the averaging area used in Eq. (3): The variation in spherical wave propagation direction is within a 6.7° wide interval around the angle at the reference point.

Finally, three different quadratic panel sizes have been tested: small sample (0.1 m^2), medium sample (1.4 m^2) and large sample (4.3 m^2). All the panels contain the same type and thickness of porous material mounted in a wooden frame, and all panels were placed on a larger rigid surface. Some of these configurations are shown in Figs. 3 and 4. The approximate 13 mm distance between the array and the material surface was ensured by 4 small “feet” mounted in the corners of the array.

Fig. 3. Examples of setup in the anechoic chamber. a) Small panel, source at 0° . b) Medium panel, source at 45° . c) Large panel, source at 60° .

Fig. 4. Examples of setup in the fitted room. a) Small panel, source at 60° . b) Medium panel. c) Large panel, source at 0° .

The two graphs in Fig. 5 show (with solid line) the real and imaginary parts, respectively, of the measured impedance for different angles of incidence in the case of the measurements on the medium-size panel in the anechoic chamber. The theoretical values directly from the Miki model are shown dash-dotted for comparison. The measured real parts of the impedance show some significant deviations from the theoretical curves, especially at high frequencies and large incidence angles. When comparing measured and theoretical values one must be aware of the fact that the theoretical predictions assume an infinite material surface, while measurements were taken on a 1.4 m² sample in a frame. The finite sample size will introduce some errors (ripples), mostly at low frequencies, where also the spherical form of the incident wave will introduce errors. Other important causes for the differences are errors associated with the Miki model:

- 1) The parameters of the isotropic, equivalent-fluid Miki model were derived from only normal-incidence (impedance tube) measurements.
- 2) The test samples were made from glass wool, which can be quite far from isotropic, see for example reference [28].

Despite the significant differences between measured and theoretical impedances, the absorption coefficients in Fig. 6 show good agreement between measurement and theory, except for the extreme angle of 75°. For all incidence angles except 75°, the absorption coefficient spectra are very similar, both the theoretical and the measured spectra. At 75° incidence, both the measurement and the Miki model show a strongly reduced absorption coefficient when comparing with the smaller incidence angles. In the second graph of Fig. 6, only the normal-incidence data are included, but the result of applying the energy-based method to the array measurement has been added. That result shows an example of the instability of the energy-based method at low frequencies (below approximately 1 kHz for the array used

here): The estimated absorption coefficient sometimes exceeds 1.0 in some frequency bands. In general, the method has been found to produce sometimes poor results at the low frequencies.

Fig. 5. Effect of the sound incidence angle on the measured impedance for the medium-size sample in the anechoic chamber. The two graphs show the real and imaginary parts separately. The dash-dotted lines show the values directly from the Miki model.

Fig. 6. Effect of incidence angle on the measured absorption coefficient for the medium-size sample in the anechoic chamber. Solid lines: Impedance method applied to measurement. Dash-dotted lines: Values directly from the Miki model. Dotted line: Energy-based method applied to measurement.

Fig. 7. Effect of the angle of incidence on the medium sample in the fitted room. The upper curves in the impedance plot are real values, and the lower ones are imaginary values.

Figure 7 shows impedances and absorption coefficients measured in the fitted room. These can be compared against the anechoic-room results in Figs. 5 and 6. Similar tendencies are observed, although some fluctuations have been added in the fitted-room results. To get a clearer picture of the influence of the reflections in the fitted room, Fig. 8 compares the results from the two rooms directly for normal incidence and for the different panel sizes. These graphs confirm that the impedance and absorption estimations are very similar between the two different rooms. We notice that the estimations from the anechoic chamber are smoother than the ones from the fitted room. The ripples added in the fitted-room results are probably due to reflections from the surroundings. We notice also a slightly over-estimated absorption coefficient at low frequencies for all the panels when measured in the fitted room. This may be because of relatively strong low-frequency reflections impinging from oblique angles. An observation to justify this is that the results of simulated tests to be presented in Figs. 10 and 11 show a higher low-frequency absorption at oblique incidence (Fig. 11) than at normal incidence (Fig. 10). However, in general the agreement is good, and it shows the robustness of the method against different room conditions.

Fig. 8. Effect of the rooms on the estimations for 0° incidence angle. The upper curves in the impedance plot are real values, and the lower ones are imaginary values.

For realistic in-situ measurements, objects under test are not always large, and surfaces are not necessarily planar. Figure 9 compares the measured impedances and absorption coefficients between the different panel sizes for the case of sound incidence at 0° in the anechoic room. Clearly, the estimated material properties are very similar between the medium and the large panel. Differences are seen with the small panel below 400 Hz due to reflection from the surrounding rigid backing surface (“floor”) and diffraction around the wooden sample frame. At 400 Hz, the frame dimensions are approximately equal to $\frac{1}{4}$ wavelength.

Fig. 9. Effect of panel size on the estimations in the anechoic room for 0° incidence angle. The upper curves in the impedance plot are real values, and the lower ones are imaginary values.

5. Discussion

The results presented in section 4 have all been dealing with measurements with an $8 \times 8 \times 2$ element array on 100 mm thick Industry Modus material. For that material, the absorption coefficient is quite close to 1 over the major part of the considered frequency range, so the reflected wave is weak, and the particle velocity at the material surface is close to that of the incident field. The present section will describe

some simulated measurements to investigate the effects of array size, microphone phase mismatch and material thickness. An infinite sheet of Industry Modus material mounted on a rigid backing and with a specified flow resistivity equal to $10900 \text{ Nm}^{-4}\text{s}$ is used, and simulations are performed using the Miki model. Reconstruction of pressure and particle velocity on the material surface from simulated array measurements has been performed using a quite high 30 dB dynamic range with SONAH. This provides high reconstruction accuracy, but it also amplifies noise and errors as we shall see.

In Figs. 10 and 11, still 100 mm thick material is considered, but phase errors with rectangular random distribution within $\pm 0.25^\circ$ have been added to the simulated complex microphone pressure values. The phase errors were generated independently for each one of the 1000 simulated frequency lines. This of course does not represent a typical microphone response, but it will show the spreading of the results that can occur due to the phase errors. Three different double-layer arrays are considered with 3×3 , 5×5 and 8×8 microphones, respectively, in each one of the two parallel layers with 29 mm in between. The corresponding calculation meshes on the material surface have 1×1 , 3×3 and 6×6 points, respectively, i.e. with edges removed. Figure 10 shows the results for the case of normal incidence: The relative errors $100\% \cdot |\tilde{Z}_s - Z_s|/|Z_s|$ on the estimated surface impedance and the absorption coefficients (true and estimated values). Clearly, the smooth part of the impedance error decreases with increasing array size, because the SONAH calculation becomes more accurate and due to averaging over a larger area. For the 3×3 array there is only one calculation point, i.e. no area averaging. The fluctuations due to phase errors also decrease with increasing array size, because SONAH can better filter out the errors, and because of the larger averaging area. Considering the estimated absorption coefficient, the values from the different-size arrays agree quite well, except at frequencies just below 5 kHz. But again, the larger arrays can better suppress the effects of phase errors. Figure 11 contains results equivalent to those in Fig. 10, only for the

case of plane-wave incidence at 60° angle from the surface normal. Basically, the same trends are observed. In particular for the small 3×3 array, an increased impedance error level is observed above 2 kHz, probably because the small array has very poor angular resolution.

Fig. 10. Effect of array size with microphone phase errors within $\pm 0.25^\circ$ for 0° wave incidence angle. Material thickness is 100 mm.

Fig. 11. Effect of array size with microphone phase errors within $\pm 0.25^\circ$ for 60° wave incidence angle. Material thickness is 100 mm.

Figures 12 and 13 contain results equivalent to those in Figs. 10 and 11, only with the 100 mm thick material replaced by a 15 mm thick infinite sheet mounted also on a rigid backing. For the thinner material, the absorption coefficient is very low at the lowest frequencies, and the normal component of the particle velocity is very small on the material surface. Accurate reconstruction of that small component from the measured pressure data requires a large applied dynamic range in the SONAH holography calculations, and therefore the reconstruction will be very sensitive to measurement errors and noise. Even with the applied 30 dB dynamic range, quite large errors (neglecting fluctuations due to phase errors) are observed in the estimated impedance below approximately 1 kHz. The error level could be reduced by an increase of the dynamic range applied in SONAH, but at the cost of even larger fluctuations due to the phase errors. Increasing the applied dynamic range to 35 dB reduced the low-frequency impedance error by approximately 10% for the 5×5 array with 0° sound incidence, but increased the fluctuations. In real measurements, the effects of phase errors on the impedance and absorption spectra will not be fast fluctuations as seen here, but smooth variations because the microphone phase errors will be smooth functions of frequency. That makes the effects harder, if not impossible, to distinguish.

Despite the larger impedance errors, the general trend of the absorption coefficient is accurately estimated, but with fluctuations due to phase errors. At the lowest frequencies, the surface impedance has a large dominating imaginary part, which is not accurately identified as can be seen from the impedance error spectra. But as long as the imaginary part is dominating, $Z_s \approx jY_s$ with $Y_s \gg 1$, the reflection coefficient of Eq. (4) will always have an amplitude close to one, and the absorption coefficient will be small, even with large errors on Y_s . Figure 12 shows the results for the case of normal wave incidence, while Fig. 13 contains results for oblique incidence at 60° from the surface normal. When comparing with Figs. 10 and

11, phase errors clearly have a larger impact for the thinner material, in particular with oblique sound incidence, where the small 3×3 array shows very poor performance. This is due to the required reconstruction of a very small particle velocity component at the surface of the thin material sample.

Fig. 12. Effect of array size with microphone phase errors within $\pm 0.25^\circ$ for 0° wave incidence angle. Material thickness is 15 mm.

Fig. 13. Effect of array size with microphone phase errors within $\pm 0.25^\circ$ for 60° wave incidence angle. Material thickness is 15 mm.

Concerning the selection of array size, a dual layer 3×3 array seems to be too small, providing poor SONAH reconstructions and no area averaging in the impedance calculation. The large 8×8 array provides best accuracy, but requires also a large, nearly planar, homogeneous sample to make full use of the area-averaging possibility. A 5×5 array supports averaging over an area of the same size as the central 3×3 sub-array, and it provides quite good accuracy.

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6. Conclusion

The paper has described a new method for in-situ measurement of surface impedance and absorption coefficient using a double-layer array of microphones. Based on a sound pressure measurement with the array, the pressure and particle velocity (normal component) on the material surface are computed using SONAH. This allows the surface impedance to be calculated as the ratio between the two quantities using a least-squares approach that introduces an area averaging. Provided the incident field is mainly from a single direction, and provided the material sample is sufficiently large and planar, the absorption coefficient can be calculated from the surface impedance. Simulated measurements on infinite planar material samples using the Miki material model showed that the SONAH reconstruction of the sound field on the material surface introduces only very small errors. Real measurements were performed on material samples of different sizes under anechoic conditions and in a fitted room. Good agreement was found between the measurements in the two different environments for all sample sizes. Good agreement was also observed between the measurements on different sample sizes, except for the lowest frequencies as one should expect. Except for very large off-normal sound incidence angles, the measured absorption coefficients agreed well with the predictions directly from the Miki model.

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