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

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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.

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.

An in-situ method using a single microphone was introduced in [11]. The method separates the direct component of an impulse

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response function from the reflected part for calculation of the impedance. It is simple in terms of instrumentation, but the method suffers from reflections from other surfaces as well as challenging cases in which the reflected part of impulse responses cannot be separated from the incident part, e.g., at near-grazing incidence angles. A more reliable estimation may be achieved by a p-u probe measuring sound pressure as well as surface velocity on a surface directly [12]. However, the method requires a time-consuming calibration procedure and seems to be sensitive to reflections from neighbouring surfaces [13].

Several array-based methods for measurement of material surface properties have been published. Tamura [14] introduced a method based on use of a double-layer regular rectangular array in combination with spatial-DFT-based Near-field Acoustical Holography. Using the pressure measured in two parallel planes, the method can resolve the incident and resulting reflected plane waves. For each available incidence direction, the reflection coefficient can be estimated as the ratio between the incident and the corresponding reflected plane wave. Due to the periodicity assumed by the spatial DFT, the method suffers from replicated aperture errors, which can be minimized using large planar panel sections and large arrays, using suitable spatial windowing, and/or by use of a source that focuses the incident field on a limited area. At the lowest frequencies, the method probably also suffers from the errors, which are a main motivation for the method of the present paper, related to the fact that the spacing between the two planar microphone layers must be less than half of the wavelength at the highest frequency of interest. This typically means that the layer spacing is much less than wavelength at the lowest frequency of 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 absorbed sound intensity components, I_{inc} and I_{abs}, on the material surface. Integration over a small surface area provides the incident and absorbed sound power, W_{inc} and W_{abs}, from which the average absorption coefficient across the selected area is calculated:

$$\alpha = \frac{W_{\text{abs}}}{W_{\text{inc}}} \tag{1}$$

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 Refs. [17,18] made use of a set of omni-directional 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.

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

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

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

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