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Measuring Sound Absorption Coefficient Under a Synthesized Diffuse Acoustic Field.

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ABSTRACT

This paper proposes an experimental method to estimate the absorption coefficient of absorbing materials using a synthesized diffuse acoustic field in free-field conditions. Comparisons made with the standard reverberant room method and numerical simulations, using the transfer matrix method, show that the proposed approach do not exhibit non-physical trends of the reverberant room method and provide absorption coefficients in good agreement with those obtained by simulations for a laterally infinite material. Smaller samples than those required by standards can be used, together with a simplified implementation of absorption measurements under a precise and repeatable diffuse acoustic field.

1. INTRODUCTION

Two standardized methods are classicaly used for measuring the sound absorption coefficient of absorbing materials: the Reverberant Room method (ISO 354[1] and ASTM C423[2]) and the impedance tube method (ISO 10534-2[3] and ASTM E1050-12[4]). The impedance tube method allows measuring the normal incidence sound absorption on small samples, but mounting conditions of the samples can have non negligible influence on measured results[5,6].

The reverberant room method gives access to the absorption coefficient under a Diffuse Acoustic Field (DAF) excitation, which is more representative of practical utilization of sound absorbing materials. At the same time, size effects of tested materials in the reverberant room are known and documented since the 1930s[7,8], and the technical problem to be resolved was even in 1950 well summarized by London[9]: '*It would be of great technological importance if it were possible to determine from laboratory measurement on small samples the sound absorption coefficient one might expect to measure on large samples placed in a reverberant test chamber'*.

In fact, testing large samples as recommended by standards may prevent the obtention of a logarithmic sound decay rate in the reverberant room and lead to lower sound absorption coefficient than expected (in any case, by placing the sample into the room, diffuseness naturally diminishes). Measurements on small material samples lead to larger absorption results than predicted by theory as well. An important consequence is that the measured absorption coefficients using the reverberation room method often exceed unity. Significant deviations on measured absorption coefficient were also observed in round robin tests[10,11] depending on test room volume, sample mounting and diffusers effect.

This paper proposes a method for the estimation in free-field conditions of the absorption coefficient of an absorbing material under a synthesized DAF excitation at the material surface by using a synthetic array of acoustic monopoles facing the material. Instead of setting a material sample in a room in which the mathematical model of a DAF would be hypothetically reproduced (mainly depending on room volume and sample area) so that the basic assumptions inherent to the calculation of the Sabine absorption coefficients would be satisfied, the idea is here to accurately reproduce the statistical properties of a DAF on the surface of the material sample by using sound field reproduction approaches (and adequate sources array and acoustic environment) for estimating its absorption coefficient under such a synthesized pressure field. The reproduction of random pressure fields on plane surfaces was originally developed for the vibroacoustic testing of plane panels under DAF or Turbulent Boundary Layer (TBL) excitations[12,13]. In the present case, a database of measured reflection coefficients at normal and oblique incidence angles is first generated with the classical two-microphone approach and a source-image model[14], using a point source that is moved over a plane parallel to the material surface. An approach based on Planar Nearfield Acoustic Holography (P-NAH)[13] is then used to calculate a Cross-Spectral Density (CSD) matrix of source amplitudes to reproduce a target DAF on the material's surface. Coupling this calculated matrix to the measured reflection coefficients database, allows estimating in a post processing phase the absorption coefficient under a synthetic DAF.

2. DESCRIPTION OF THE PROPOSED METHOD

A. Absorption coefficient under a single point source

Figure 1(a) describes a simple and well-known situation[14]. A single point source is positioned at a given position i at a height $z=z_s$ above a layer of porous material. Two microphones denoted M_1 and M_2 are placed above the porous material and centered on its surface at heights $z=z_1$ and $z=z_2$, respectively. Under the assumption of an ideal point source (defined by its volume acceleration $q_i\,(\omega)$), the acoustic field at any of the microphone positions is a superposition of two spherical acoustic waves, generated by the source $q_i\,(\omega)$ and the corresponding image source $q'_i\,(\omega)$ positioned at a distance r_i and a distance r'_i from the receiver, respectively. For a small separation of the two microphones so that the angle θ_i is almost identical for both microphones, the measured acoustic pressure $p_{ij}(\theta_i,\omega)$ for a given position i of the point source at microphone M_j (j=1,2) can be written

$$p_{ij}(\theta_i,\omega) = \rho_0 q_i(\omega)\frac{e^{-jk_0 r_{ij}}}{r_{ij}} + R(\theta_i,\omega)\rho_0 q'_i(\omega)\frac{e^{-jk_0 r'_{ij}}}{r'_{ij}}, \qquad (1)$$

with ρ_0 the air mass density, ω the angular frequency, k_0 the acoustic wavenumber ($k_0=\omega/c_0$) with c_0 the speed of sound), r_{ij} the distance between the source at the i-th position and the microphone M_j, r'_{ij} the distance between the image source and the microphone M_j and $R(\theta_i,\omega)$ is the reflection coefficient of the material surface corresponding to the i-th position of the point source. The measurement of either $p_{ij}(\theta_i,\omega)/q_i(\omega)$ at each microphone or $H(\theta_i,\omega)$ (= $p_{i2}(\theta_i,\omega)/\ p_{i1}(\theta_i,\omega)$) allows calculating the reflection coefficient for a given incidence angle using the classical relation[14]

$$R(\theta_i,\omega)=\frac{\frac{e^{-jk_0 r_{i2}}}{r_{i2}}-H(\theta_i,\omega)\frac{e^{-jk_0 r_{i1}}}{r_{i1}}}{H(\theta_i,\omega)\frac{e^{-jk_0 r'_{i1}}}{r'_{i1}}-\frac{e^{-jk_0 r'_{i2}}}{r'_{i2}}}. \quad (2)$$

The corresponding absorption coefficient can be deduced using the relation $\alpha(\theta_i,\omega)=1-|R(\theta_i,\omega)|^2$.

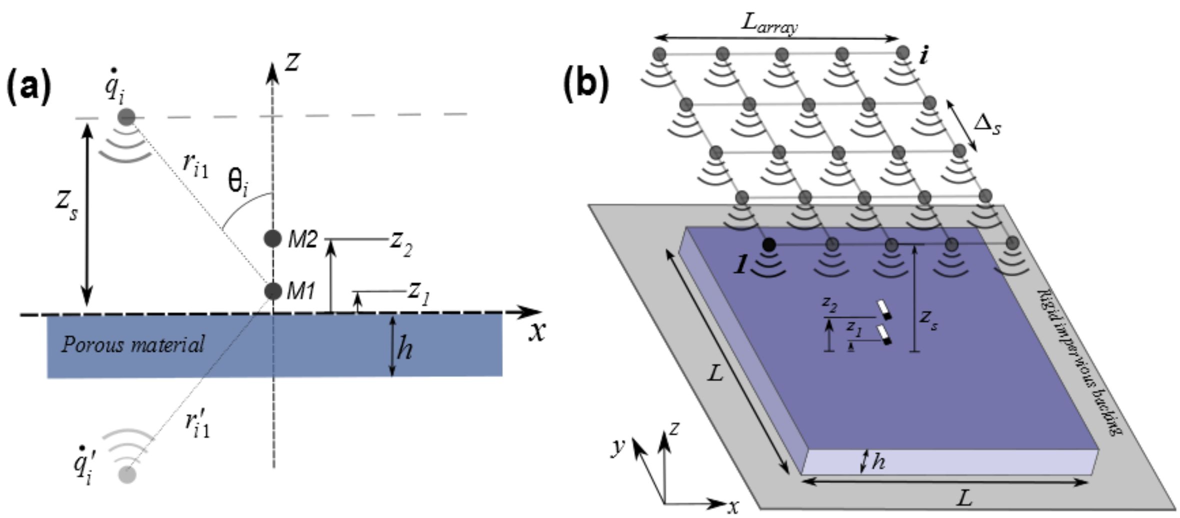

Figure 1 - Description of the problem and coordinate system for a spherical wave model using a single point source – (b) Description of the problem using a *i*-source array (the sidelength of the virtual array is L_{array}, with uniformly distributed sources positioned with the same source separation Δ_s) (from Robin[15]).

B. Reflection coefficient under a synthetized pressure field

Figure 1(b) illustrates the proposed approach. A square sample of porous material of sidelength L and thickness h is placed on a rigid impervious backing. The two microphones $M1$ and $M2$ and the array center point source are centered on the material's surface. Using the two-microphone method described in the previous section, the reflection coefficient can be measured under various incidence angles corresponding to successive positions i of a point source, thus creating a virtual array of monopoles in front of the material surface. The Green's functions corresponding to the propagation from the real (respectively image) point source to the microphone M_j will now be denoted $g_{ij}(\omega)=e^{-jk_0 r_{ij}}/r_{ij}$ (respectively $g'_{ij}(\omega)=e^{-jk_0 r'_{ij}}/r'_{ij}$).

It can be shown (calculation details are omitted here for conciseness and can be found in Robin[15]) that with a database of measured reflection coefficients $R(\theta_i,\omega)$ at several i incidence angles and a calculated CSD matrix of source volume accelerations $\boldsymbol{S_{QQ}}$ (that when applied to all the virtual sources would lead to the reproduction of a desired pressure field at the material surface), Eq. (3) below provides the squared reflection coefficient $|R_{synth}(\omega)|^2$ under a synthesized pressure field at a post-processing phase

$$\left|R_{synth}(\omega)\right|^2=\frac{\boldsymbol{h_1^H S_{QQ} h_1}}{\boldsymbol{g_1'^H S_{QQ} g_1'}}, \quad (3)$$

where $\boldsymbol{h_1}=\{\cdots\ \rho_0 g_{i1}(\omega)\cdots\}^T, \boldsymbol{g'_1}=\{\cdots\ \rho_0 R(\theta_i,\omega) g'_{i1}(\omega)\cdots\}^T$ and ^{T} denotes the non-conjugate transpose (^{H} stands for the conjugate transpose). Note that the two microphones are needed for the calculation of the individual reflection coefficients $R(\theta_i,\omega)$ (following the procedure described in Sec.2.A), but the calculation of the squared reflection coefficient under a synthetic pressure field $|R_{synth}(\omega)|^2$ finally requires one of them.

The corresponding absorption coefficient can be deduced using the relation $\alpha_{synth}(\omega)=1 - |R_{synth}(\omega)|^2$. The CSD matrix of source volume acceleration $\boldsymbol{S_{QQ}}$ can be calculated using either the Wave Field Synthesis approach[12] or the P-NAH approach[13] (in this letter, only P-NAH is used), with a target pressure field defined by the CSD of a DAF[16].

3. LABORATORY MEASUREMENTS AND SIMULATIONS

Melamine foam samples of two different thicknesses and areas, and a glasswool sample of one thickness were tested. Their properties were measured in the Acoustic Materials Characterization Labs of Université de Sherbrooke, using the methods described by Doutres *et al.*[17], and given in Table 1. Reverberant room absorption tests of melamine foam of 0.0762 m (3 inches) and 0.0508 m (2 inches) thicknesses were made in the National Research Canada (NRC) reverberant room (volume ≈ 258 m^3) and in the Groupe d'Acoustique de l'Université de Sherbrooke (GAUS) reverberant room (volume ≈ 143 m^3), respectively. Tests for the glasswool sample of 2.75 inches thickness were also made in GAUS reverberant room.

The specimen area was 5.94 m^2 for the 3 inches melamine foam, 6.65 m^2 for the 2.75 inches glass wool and 3.35 m^2 for the 2 inches melamine foam, so that only the two first cases fulfill the ASTM C423 requirements in terms of sample area. For both experiments, samples were laid directly against the room floor and their perimeters were sealed by wood framing (see Fig. 2(a) for tests at NRC). Sabine absorption coefficients were calculated following standards procedures[1,2].

Table 1: Measured parameters for the tested sound absorbing materials.

Parameter	Tortuosity α_∞ [-]	Porosity Φ [-]	Resistivity σ [Nm^{-4}s]	Viscous length Λ [µm]	Viscous length Λ' [µm]	Foam mass density ρ_1 [kg.m^{-3}]
Melamine foam	1	0.99	10900	100	130	8.8
Glasswool	1	0.99	3240	160	300	8.4

Figures 2(b,c) illustrate the experiments conducted in an anechoic room using the proposed approach. The specimen area was 2.11 m^2 for the 3-inch melamine foam, and 1.49 m^2 for both the 2-inch melamine foam and the 2.75 inches glass wool. Each sample was laid on a rigid impervious backing, made up from a 1/2 inch thick medium density fiberboard panel covered with a 1/32 inch steel plate. An omnidirectional point source (LMS Qsource mid-frequency volume source) was manually translated using a rigid frame on a mesh of 7 by 7 positions above the material surface at a height z_s=0.2 m, with the center source position corresponding to the normal incidence case. The source separation Δ_s was set to 0.15 m with a corresponding virtual array sidelength L_{array} of 0.9 m. The maximum incidence angle θ_{max} that can be included in the database of measured reflection coefficients is defined by the source to reproduction plane separation z_s and the largest reproduction source to microphones distance. In the present case, $\theta_{max}=\tan^{-1}(L_{array} / \sqrt{2}.z_s) \approx 72°$.

The microphones *M*1 and *M*2 (BSWA MPA416 ¼ inch microphones) were positioned at the center of the sample at heights z_1=15 mm and z_2=59 mm, respectively. Amplitude calibration was performed for both microphones before measurements, and the volume acceleration of the point source was derived from an internal sensor. For each source position, a white noise was used to drive the point source and the transfer functions between the sound pressure at both microphones and the source volume acceleration were measured from 170 Hz to 2000 Hz, the low frequency limit being intrinsic to low frequency limitations of the volume source. With time averaging over 30 seconds for each successive test, a database corresponding to the 49 sources positions was obtained in approximately half an hour.

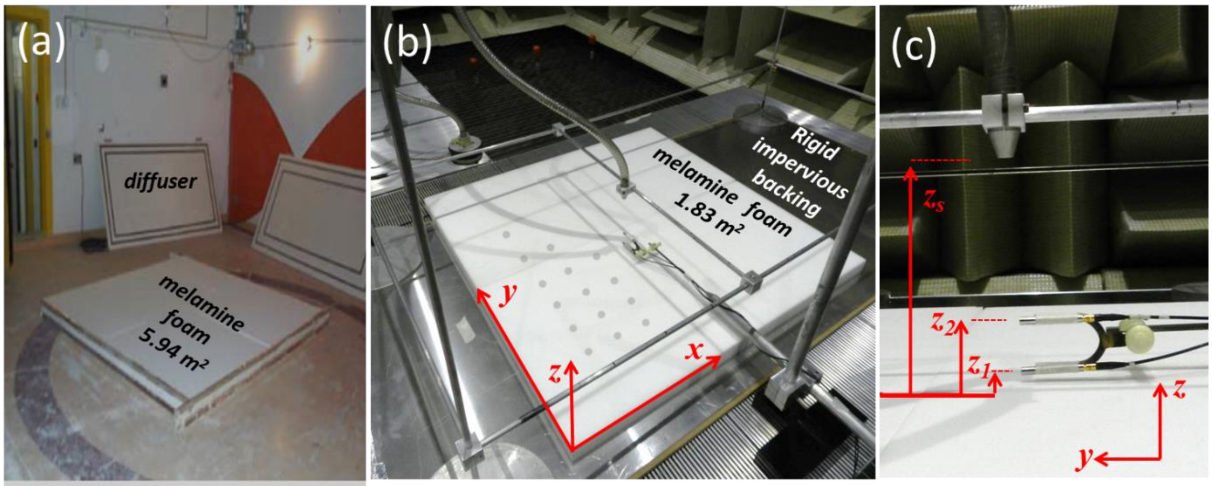

Figure 2 : Pictures of measurements performed on the melamine foam of 3 inches thickness: (a) Reverberant room measurement at NRC – (b) Measurement under a synthetic array in an anechoic room (the two microphones and the source are positioned at the center of the sample, and some successive source positions are indicated by gray circles) – (c) Close view of the two microphones and source positioned above the material's surface for the normal incidence measurement (from Robin[15]).

Finally, simulations based on the Transfer Matrix Method (TMM)[18] were performed. The layer of homogeneous material of infinite extent and backed by a hard wall was modeled under a limp frame assumption[18]. The parameters given in table 1 were used in simulations to compute the characteristic impedance Z_{ceq} and the wavenumber k_{eq} of the equivalent fluid element via the Johnson-Champoux-Allard model[18]. Since the DAF theoretically reproduced with the synthetic array implies a maximum incidence angle of 72°, the same maximum incidence value was used as an upper bound to define the DAF excitation in the numerical simulations.

4. RESULTS

Figures 3(a)-(b) show the results obtained for the two considered thicknesses of melamine foam. While the Sabine absorption coefficients obtained with the standard reverberant room method often exceed unity due to the finite size of the sample and to the room effects[7,8,11] (above 250 Hz for the 3-inch melamine foam in Fig. 3-(a) and above 500 Hz for the 2-inch melamine foam in Fig. 3-(b)), the absorption coefficients calculated with the present approach provide values in good agreement with those obtained from TMM simulations above the 400 Hz third octave band.

For the 3-inch melamine foam (Fig. 3-(a)) and for the 400 Hz third octave band, the proposed approach gives an absorption coefficient value of 0.63, while the TMM results and reverberant room provide coefficients of 0.76 and 1.27, respectively. Above the 400 Hz third octave band, the difference between absorption coefficients obtained by the present method and TMM results is below 0.1. For the 2-inch melamine (Fig. 3-(b)), and between the 400 Hz and 2000 Hz third octave bands, the highest deviation between the proposed method and the TMM results occurs at the 1630 Hz third octave band, with a difference of 0.03 between experiments and simulations. A better adequation with TMM results is seen compared to the 3-inch case, but was not explained.

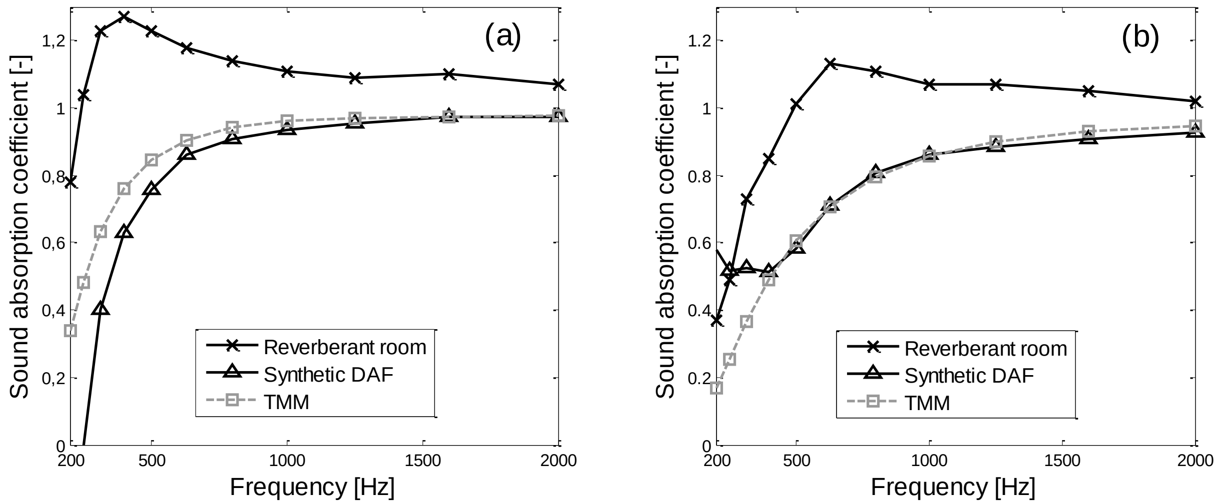

Figure 3: (a) Absorption coefficient of the 3-inch melamine foam – (b) Absorption coefficient of the 2-inch melamine foam.

Below the 400 Hz third octave band, the accuracy of the method seems insufficient for both thicknesses, with absorption coefficients that either decrease quickly to zero and even negative values for the 3-inch melamine case (Fig. 3(a)) or remain nearly constant for the 2-inch melamine case (Fig. 3(b)). This adverse effect is mainly thought to be related to the finite sidelength of the array. The finite size of the sample may also explain these low frequency limitations and discrepancies with TMM results, since this simulation assumes laterally infinite material. As commented in Allard and Champoux[14], the use of Eq.(2) could involve some discrepancies for low values of $k_0 r$. Source positions and their precise positioning could be optimized by testing other source distributions and using motorized translation axes.

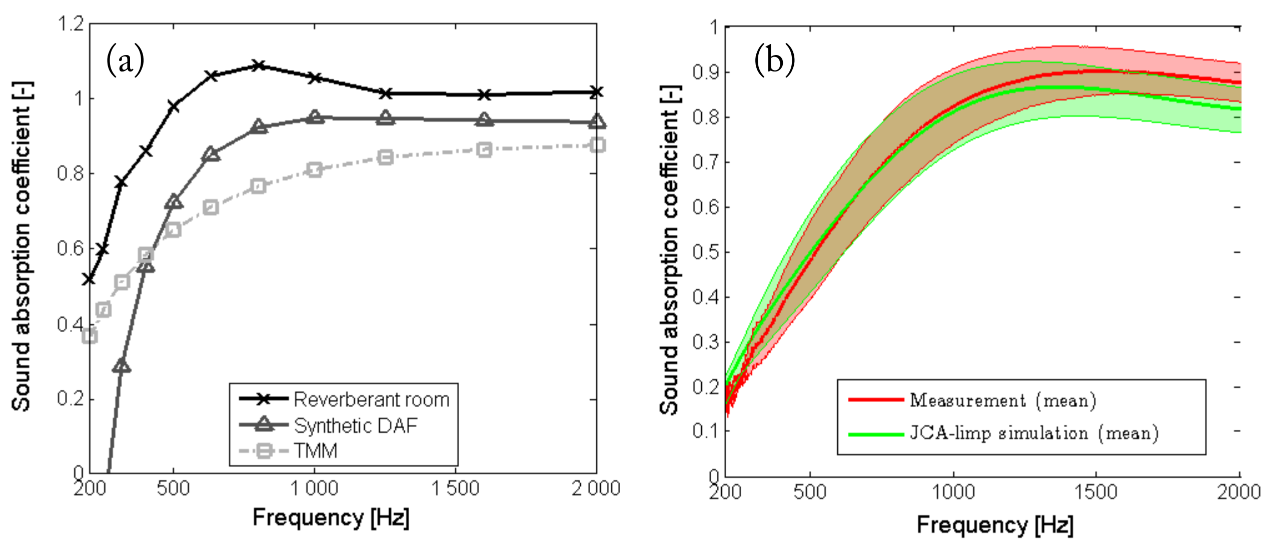

Figure 4: (a) Absorption coefficient of the 2.75-inch glass wool – (b) Mean value for measurements made in an impedance tube and simulations for a normal incidence plane wave held with the Johnson-Champoux-Allard model (the confidence interval is indicated for both case).

For the 2.75 inches glass wool (Fig. 4-(a)), the conclusions are somewhat similar to those given for the melamine foam. While the results obtained with the reverberant room method exceed unity above the 500 Hz third octave frequency band, those obtained with the presented method never exceed a value of 1 but quickly decrease to even negative values below the 315 Hz third octave frequency band.

The agreement with the TMM result is poorer compared to the melamine foam case. In fact, the assumptions of a homogeneous and isotropic material used in simulations are not satisfied for the glass wool, this material being highly heterogeneous (contrarily to the melamine foam). Figure 4-(b) shows the mean obtained value for measurements in impedance tube[17] and simulations using the Johnson-Champoux-Allard model, both presented with their confidence interval (for simulations, the variability due to physical properties uncertainties is estimated by the Monte-Carlo method). Such discrepancies between measurements and simulations when the material's anisotropy was not taken into account were also noticed in other works[19]. Note that measurements were made on a single measurement point on the material surface, because of the assumption of a homogeneous material. Complementary tests on several measurement points by translating the two-microphone probe are considered.

5. CONCLUSIONS

A method for the estimation in free-field conditions of the absorption coefficient of an absorbing material under a synthesized DAF excitation was presented. The theory concerning the estimation of absorption coefficient under synthesized pressure fields was briefly described. Comparisons were then made between simulations using the TMM and experimental results obtained using the present approach and the reverberant room method. The main conclusions are:

- The estimated absorption coefficients using a synthesized DAF excitation are in good agreement with those obtained from the TMM for homogeneous materials above a frequency of 400 Hz (for the used setup), within a physical range (i.e. between 0 and 1) and do not exhibit size effects as seen in reverberant room results even if smaller samples were used. Such measurement results could be directly used for room acoustics computations without any corrections.

- Instead of using sources positioned on arcs of circle and a linear averaging of source contributions (as in Refs. 19 and 20 for example), a synthetic plane source array combined with adequately weighted reproduction source complex amplitudes provides the basis for a simplified implementation of absorption measurements under a precise and repeatable DAF excitation, with a reduced setup and testing time, and no need for specific preparation of specimens.

- Based on the used setup and presented results, the accuracy of the method is currently insufficient below a frequency of 400 Hz. This could be explained by the finite size of the sample. Possible improvements and optimization of the virtual source antenna are currently underway using numerical simulations, and translation of the two-microphone probe is also considered.

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