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Sources of measurement uncertainty in determination of the directional diffusion coefficient value

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ABSTRACT

Values of the directional sound diffusion coefficient, according to recommendations of ISO 17497-2 standard, are measured in the free field of an anechoic chamber. The procedure proposed in the standard for determination of directivity patterns characterizing reflection of sound wave from an examined structure is biased by a measurement uncertainty following from the effect of individual elements of the measurement chain and operations performed on the recorded signal. Further sources of uncertainty can be related to the sample itself due to possible imperfections of workmanship.

The paper presents an analysis of possible sources of the measurement uncertainty encountered when the directional sound diffusion coefficient is determined and an attempt to evaluate the effect of individual sources on the expanded uncertainty of the measured parameter. Using the Fraunhofer approach to the wave equation and the Monte Carlo method, the effect of the measurement angular resolution, microphone and sample position, repeatability of generated and recorded signals, the signal-to-noise ratio, and precision of sample workmanship on uncertainty of the directional sound diffusion coefficient was determined. For the value of 0.025 adopted as the admissible maximum of the expanded uncertainty of the parameter, maximum allowable values for uncertainties of individual input parameters were identified.

1. Introduction

In the room acoustic, the most important parameters characterizing boundary surfaces defining the examined interiors are, apart from the sound absorption coefficient being the subject of ISO 354 standard [1], the scattering coefficients and the diffusion coefficients. The standards ISO 17497-1 [2] and ISO 17497-2 [3] define two parameters related to the nature of sound wave reflected from a structure. The directional sound scattering coefficient (ISO 17497-1) is a measure of this portion of sound wave energy incident on a sample which is reflected in a non-specular way. The quantity was first introduced by Mommertz and Vorländer in 1995 [4] and is typically used in simulations of acoustic parameters of rooms in which much more precise results are required [5]. In 2001, Cox and D'Antonio have defined the directional sound diffusion coefficient [6] as a quantity describing uniformity of the directivity pattern produced by sound wave reflected from a sample. High values of the parameter are of particular importance for small rooms such as recording studios or listening rooms where each of individual reflections from boundary surfaces can affect quality of the perceived music [7]. Another important merit of the directional sound diffusion coefficient is the fact that it is directly related to the acoustic pressure distribution over the sample and can be therefore determined by solving the Helmholtz-Kirchhoff equation with the use of the finite elements method or other simulation techniques using finite-difference schemes in the time domain [8]. Departing from the wave equation and adopting a number of simplifying assumptions, it is possible to determine values of the acoustic pressure in sound wave reflected from a structure characterized by a known reflection coefficient value relatively easily and with high degree of accuracy. This allows predicting precisely values of the parameters of interest and ensures reliability of the performed analyses of many different sound-diffusing sequences. Dimensions of samples needed to measure values of the sound diffusion coefficients are smaller compared to those required to determine values of the sound scattering or sound absorption coefficients, therefore also the related verification tests carried out on the laboratory setup are relatively inexpensive.

Each result of any measurement concerning acoustic properties of materials and structures is subject to an uncertainty which can directly affect results of predictions concerning acoustic properties of rooms and, as a consequence, the proposed design solutions [9]. To be complete, each result of any measurement procedure should

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be therefore supplemented with an information about uncertainty to which it was actually determined. As far as the sound absorption coefficient is concerned, the currently applicable standard ISO 354 gives only a recommendation concerning calculation of the uncertainty of determining the reverberation time with the use of the interrupted noise method, leaving the issue of repeatability of the measuring process for future investigations. Numerous round robin tests [10,11] proved that the differences between the obtained values are significant and depend on numerous factors. According to [12], the most important factor behind these discrepancies were spatial fluctuations of decay curves. Using the concept of propagation of uncertainty, the authors of the above-quoted paper have proposed a relatively simple formula for the uncertainty of the sample absorption coefficient u_α depending on the sample absorption coefficient α_s, the reverberation time of the empty chamber T_1, band center frequency f_c, the number of measurements M, and a geometrical constant K:

$$u_\alpha = 1.075K(Mf_cT_1^3)^{-\frac{1}{2}}[(\alpha_sT_1/K)^3 + 3(\alpha_sT_1/K)^2 + 3(\alpha_sT_1/K) + 2]^{\frac{1}{2}} \quad (1)$$

The formula shows a good consistence of results with the standard deviation calculated for the measured sound absorption coefficients and allows to determine the number of measurements necessary to maintain an assumed precision of measurement for given values of the reverberation time of the empty chamber and the sound absorption coefficient of the sample. The formula can lead to a paradoxical conclusion that the uncertainty of measurement results decreases with decreasing reverberation time of empty reverberation room. It should be noted that the formula disregards actual unevenness of decay curves and is based only on purely theoretical quantities. Therefore, the possibility of different acoustic field diffusion patterns in different reverberation chambers is not admitted.

In case of the random incidence sound scattering coefficient, which still awaits a dedicated inter-laboratory measurement verification project, the standard specifies only the method for determination of the measurement uncertainty based on the uncertainty propagation principle under the assumption of absence of any correlation between the input quantities. As it has been proved in [13] on the grounds of Monte Carlo simulations, such assumption can result in some underestimation of the uncertainty value.

A theoretically derived formula for the uncertainty of determination of the random incidence sound scattering coefficient similar to (1) was proposed in [12], where the identified sources of the uncertainty were similar to those specific for the sound absorption coefficient measurements.

Shtrepi et al. [14] tested the effect of microphone positions, sample surface area, height of air gap under turntable, and sample shape on the obtained results of measurements of the random incidence scattering coefficient.

An attempt to assess repeatability of results or measurements of the directional diffusion coefficient and determine the dependence of measurement uncertainties on the sample positioning uncertainty was undertaken in [13]. On the tested setup, the measurement of the same structure was repeated 25 times and the obtained maximum standard deviation was 0.03. As far as position of the sample is concerned, linear relationship between displacement of the measured structure and the measurement uncertainty was found.

The present paper is an attempt to identify the main sources of the uncertainty of values of the directional diffusion coefficient measured according to the method specified in ISO 17497-2 standard. The uncertainty budget was compiled on the grounds of numerical simulations taking into account uncertainties relating both to the sample and the measurement chain. The uncertainty propagation was examined with the use of the Monte Carlo method [15] in view of high complexity of formulas describing diffusion phenomena occurring in the sound field.

2. Theoretical background

2.1. The directional diffusion coefficient measurement procedure

Strictly speaking, the uncertainty of determination of the directional sound diffusion coefficient value depends on all components of the measurement chain and all geometrical features of the examined sound diffusor. Results presented in [13] prove that the repeatability of measurements for given embodiment of a sound diffusing structure and an established geometry of the measuring setup is high. Multiple measurements recommended to be performed in order to determine type A measurement uncertainty would require also fabrication of a dozen or so copies of the examined structure as the uncertainty of workmanship also affects the uncertainty of the measurement result. The multitude of involved factors makes such measurement a very laborious task without possibility to extend validity of the obtained results over other structures or different geometries of the measuring setup.

Therefore, the present paper focuses on determination of type B measurement uncertainty. The assumed objective was to identify the most important factors capable to affect results of measurements and, based on numerical calculations, evaluate contributions of these factors to the combined measurement uncertainty depending on uncertainties characterizing individual components of the measurement chain.

The directional sound diffusion coefficient is measured in the free field of an anechoic chamber. ISO 17497-2 recommends to determine the impulse responses by recording the signal from a microphone situated on an arc with radius of at least 5 m, with the arc center located at the midpoint of the measured sample. According to the standard, the angular resolution of the measurement should be at least $\Delta\theta \le 5°$. The sound source should be situated at least 10 m from the sample. The requirement to keep some minimum distance from the measured structure is dictated by the need to go beyond its near field. According to [16], the minimum distance equaling three times the length corresponding to the lowest frequency of the diffused wave would be recommended. The distance of 5 m is therefore suitable for sound diffusion measurements carried out for structures with the design frequency of above 200 Hz.

Another recommendation concerning the measurement provides that at least 80% of the impulse responses are recorded outside the specular reflection zone. This condition imposes a limitation on the maximum width of the measured sample.

The determined impulse responses are subjected to digital processing consisting in filtering the signal through band-pass filters and cutting out the fragment corresponding to the wave reflected from the sample. By subtracting the impulse response corresponding to the measurement setup with no sample mounted on it from the analyzed signal, it is possible to clear the signal of interference representing deterministic reflections from other components of the anechoic chamber equipment.

Each of the components of the measurement chain and each step of the procedure of calculating the diffusion coefficient value can be a source of measurement uncertainties, and therefore should be taken into account when the combined uncertainty of a measurement is established.

2.2. Numerical simulations

The above-described measurement is carried out in the free field, and the directly measured quantity is the acoustic pressure