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Measurements of noise energy angular distribution at the building envelope using microphone arrays

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ABSTRACT

This paper presents an experimental procedure for determining the probability density function of incident noise energy angular distribution at the building envelope using a microphone array as a measuring device. The motivation for this analysis is the development of a methodology which would provide an insight into the actual structure of the sound field impeding the façades in urban environments. The procedure is based on spatial source localization using a microphone array mounted on the building façade. The results are presented for one characteristic situation in an urban area using different algorithms for space-time signal processing. It is assumed that measurements in different types of façade surroundings, such as canyon and non-canyon streets, would point to the specificities of energy distributions which can be expected in the given situations.

1. Introduction

The laboratory measurements of the sound reduction index of building partitions are based on the homogeneity and diffusivity of the sound field in the source room, i.e. uniform distribution of sound energy over the entire range of incidence angles. The values obtained from such measurements are used in the calculations for predicting the insulation values in buildings. However, when a partition is a façade element of a building in an urban environment, the conditions are substantially different from those in the laboratory. The impeding sound field is neither homogenous nor diffuse and potentially has prominent directions from which the majority of noise energy arrives at the façade. The angular distribution of incident noise energy at the façade depends, among other factors, on the terrain configuration. It is reasonable to expect different sound field structures in a narrow street surrounded by buildings (canyon street) compared to a street with buildings on only one side. The dependency of the partitions' sound reduction index on the angular distribution of incident energy has been analyzed in the literature [1,2]. This dependency is important since variations in the directions of outdoor noise arrival will influence the amount of energy transmitted into the receiving room. Vermeir et al. [3] have analyzed façade sound insulation on ten selected buildings. The measurements were performed using both the global loudspeaker method and the global traffic noise method. The two types of measurements showed differences in the $D_{2m,nT,w}$ parameter values of up to 5 dB. The authors also pointed out that the differences are even greater when observed in 1/3 octave bands. It is apparent that such variations are caused by the differences between the incidence of real traffic noise and of the loudspeaker placed at 45 ± 5° used in the global loudspeaker method [4]. When measuring using the existing traffic noise, sound energy is impeding the façade under the incidence angle which varies in time, which affects sound transmission through the façade elements. Therefore, the sound reduction index depends on the angular distribution of the incident energy impeding the façade, but potential shapes of this distribution are unknown.

A microphone array combined with a video camera enables a visualization and quantification of sound sources, i.e. the detection of sound arrival direction from a certain source. Such a system can be used to determine the spatial distribution of the incident noise energy impeding a façade. This paper presents the procedure for determining this distribution using a microphone array. The results presented in this paper were experimentally obtained for one characteristic urban terrain configuration. The results consist of the spatial distribution of outdoor noise sources and the resulting probability density function of noise energy angular distribution. The results were obtained using different space-time signal processing algorithms. Characteristics and significance of individual algorithms are analyzed. The goal of this paper is the development of a methodology which would enable the determination of distribution functions which correspond to certain characteristic terrain configurations in urban areas. These functions could then potentially be used for the calculation of corrective factors for the predicted values of the sound reduction index of partitions

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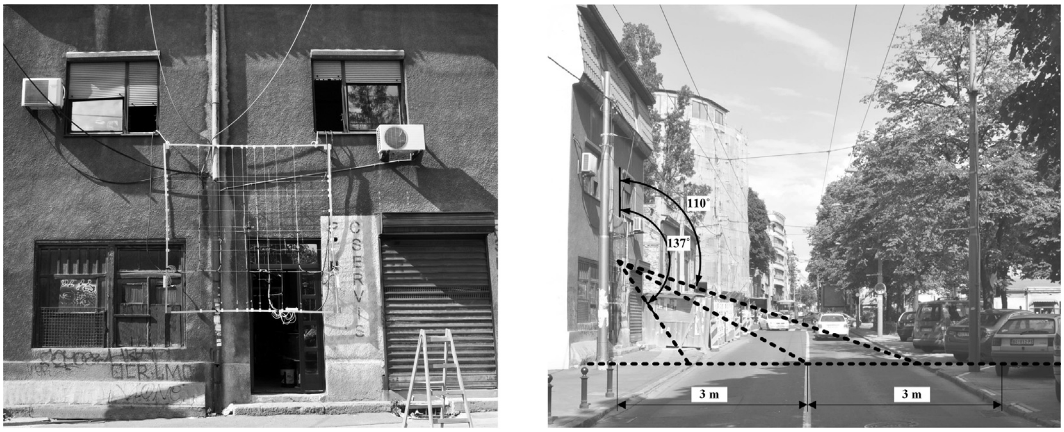

a) b)

Fig. 1. a) Microphone array on the façade, and b) the profile of the street.

located in different environments.

2. Methodology

2.1. Microphone arrays. Space-time signal processing

Traffic noise has the largest contribution to overall noise in an urban area. Traffic noise sources are various types of vehicles which generate noise signals of different levels and spectral content. The traffic noise reference spectrum is defined in [5]. The spectra obtained by measurements in urban environments can be found in the literature [6,7]. These measurements were performed in typical urban configurations such as crossroads, roundabouts etc. The traffic noise spectra obtained by measurements correspond approximately to the reference spectrum, with a steeper decrease towards lower and higher frequencies. Based on the shape of the reference spectrum, and the spectra obtained by measurements, the frequency range of interest was defined for the microphone array to be used in the sound field analyses in urban environments. The experiments presented in this paper were performed using an array of microphones, the positions of which were optimized for the traffic noise analyses [8]. The optimized planar array has minimized values of the sidelobe amplitudes and the main lobe width within the frequency range of 250 Hz to 2000 Hz.

Three algorithms for space-time signal processing were used: CB (*Conventional Beamformer*) [9], DAMAS2 (*Deconvolution Approach for the Mapping of Acoustic Sources*) [10] and CLEAN-SC (CLEAN *based on Spatial Coherence*) [11]. The CB algorithm is based on the cross-spectral matrix (CSM) of the signals measured by the array and steering vectors determined by the geometry of the array [9]. The resulting matrix element that corresponds to a point in the scanning grid (*p,q*) can be obtained by the following expression:

$$Y(p,\,q) = \frac{e_{p,q}^{T}\,G\,e_{p,q}}{m_0^2}. \tag{1}$$

Parameter m_0 is the number of microphones in the array, G is the cross-spectral matrix, and $e_{p,q}$ is the steering vector for the direction corresponding to the p,q point in the scanning grid. The result obtained by the CB algorithm is a convolution of the spatially distributed sound sources and the array response. Therefore, the resulting spatial distribution will not be an exact match to the actual sound source distribution. This result can be presented as:

$$AX = Y, \tag{2}$$

where matrix A models the array characteristics, matrix X is the actual sound source distribution, and matrix Y is the distribution obtained by Conventional Beamformer.

Deconvolution techniques have the goal of determining the actual spatial distribution of sound sources, regardless of the characteristics of the array used for signal measurement. The goal is to calculate X with measured Y and known A. The influence of the array is removed by an iterative procedure [9–13]. The original DAMAS algorithm [9] solves the problem in (2) using a system of linear equations. The initial step in DAMAS is the result obtained by the CB algorithm. Solving this type of system of equations is time consuming, which is why approximation techniques that reduce the computational complexity have been developed [10,12]. The DAMAS2 algorithm is an upgrade of DAMAS, in which the problem (2) is solved iteratively using 2D FFT transformation. The DAMAS2 technique is considerably less computationally demanding than DAMAS and converges in a smaller number of iterations. The CLEAN algorithm is based on the *point spread* function (the response of the array to unit excitation) and the assumption that the sound field is composed of a finite number of incoherent point sources. As with DAMAS algorithms, CLEAN also initializes using the spatial distribution obtained by the CB algorithm. The contributions of individual sound sources are detected and removed iteratively. The CLEAN-SC algorithm is a modification of CLEAN and is based on the spatial coherence of sources. CLEAN-SC improves the performance of CLEAN by removing the influence of the sidelobes. This is performed by removing the coherent content from the spatial distribution maps, assuming that the entire coherent content is a result of the sidelobes.

2.2. Façade measurements

An experiment which implements the procedure for determining the angular distribution of traffic noise energy in an urban environment was conducted. The microphone array was mounted on the building façade and recording of the noise signals was performed over the specified time interval. Due to the relief of the façade and other elements, such as the outdoor units of HVAC devices, the array needed to be mounted carefully so that it was positioned as closely to the façade surface as possible.

Fig. 1a) shows the planar microphone array mounted on the building façade. The center of the array is at the height of 3 m above the pavement, which corresponds to the position between the ground floor and the first floor. The building is located in a busy urban street, in which cars, motorcycles and public transportation vehicles (buses and trolleybuses) are present.

Fig. 1b) shows the profile of the street in which the measurements were performed. The picture shows two traffic lanes, and pavements and parking places on both sides of the street. The building is facing a park on the opposite side of the street, so this location is in the category of non-canyon streets. The distance of the microphone array plane from