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Microphone array method for determining noise angular energy distribution on building envelopes

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ABSTRACT

A method is proposed for determining traffic noise angular energy distribution on building envelopes using the microphone array as a source localization tool. Measurement procedure is presented with the results obtained by a nonuniform planar array developed for this purpose with microphone positions optimized for traffic noise measurements. The results are obtained in one characteristic urban configuration – a non-canyon street. Results are commented and their implications on the in-situ sound reduction index of the façade element are explained. The algorithms used for sound source localization are CB in the frequency domain, along with deconvolution algorithms DAMAS2 and CLEAN-SC, and their performance is compared. The paper addresses the problem of the computational complexity of the algorithms which results in long execution times and inhibits measurements on a larger scale. A method for algorithm optimization is presented that includes the analysis of key characteristic events instead of an overall noise recording. The sensitivity of output results on varying event recordings is analyzed. The goal is to create a time efficient measurement procedure which would enable the acquisition of a larger data set covering various urban terrain configurations.

Keywords: microphone array, noise angular distribution, traffic noise

1. INTRODUCTION

The proposed method for noise analysis in urban areas is motivated by the fact that the partitions used as façade elements are located in sound field conditions substantially different from laboratory conditions, in which their sound insulation properties are measured and specified. As oppose to the diffuse sound field with uniform angle of incidence probability used in laboratory measurements, in real scenarios these elements are located in a sound field where the probability of incidence is non-uniform and contains prominent directions from which the majority of noise energy arrives.

ISO standard defines two measurement methods for measuring in-situ sound insulation of a façade: global loudspeaker method, and global traffic noise method (1). The loudspeaker measurement involves a speaker positioned at an angle of 45±5° to the façade plane, in order to approximate traffic noise incidence angles. It was reported (2) that the $D_{2m,nT,w}$ values obtained by these two types of measurements differ by up to 8 dB. Among other factors, these differences are certainly influenced by the varying angular distribution of noise energy in real situations.

Microphone arrays are a modern tool that enable the localization of the sound sources. The idea of the proposed method is to utilize a microphone array in order to gain an insight into angular distribution of noise energy impeding building envelopes in urban environments. Initial research was focused on measurements and array signal processing algorithms in order to obtain a valid spatial distribution of sound sources. A microphone array was designed specifically for this application (3), and measurements were performed in urban environment (4,5). Certain array processing algorithms have been used, and DAMAS2 algorithm (6) has been chosen as the main processing algorithm. The goal of the research is to determine shapes of noise energy angular distributions specific to certain characteristic urban configurations such as canyon and non-canyon streets. Based on these distributions, conclusions can be drawn on the expected performances of certain façade elements when they are located in different urban configurations.

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The practical realization of measurements and subsequent signal processing proved to be extremely time consuming. This fact represents a problem which needs to be addressed in order to enable measurements on a larger scale. A large number of parameters which can be varied open a question of optimization of the measurement procedure. These parameters include spatial resolution of beamforming algorithm, time block length, the content of recorded signals, various algorithm specific variables, etc.

This paper examines a method for optimizing the measurement procedure by reducing the recorded signal time by recording and analyzing only specific events instead of a longer ambient recording. The goal of the analysis presented in this paper is the recognition of key events happening in a certain urban configuration and determining their characteristic shapes. Then, their individual influence on in-situ sound reduction index is assessed, and their contribution to the overall angular distribution, which was obtained for a longer overall signal recording.

Next section describes the measurement procedure and microphone array signal processing. Results for angular distribution are given for a characteristic non-canyon street configuration in section three. The fourth chapter presents the results obtained by reducing the signal length to specific events. The influence of this reduction on final results is discussed.

2. MEASUREMENT PROCEDURE

The measurements were performed using a microphone array specifically designed for this purpose. It is a nonuniform planar microphone array with 24 omnidirectional microphones. The microphone array characteristics were optimized for use in traffic noise analysis (7). Figure 1 shows the measurement setup. Microphone array is placed parallel to the façade surface at the minimum possible distance from the façade. Since planar microphone arrays possess spatial ambiguity, i.e. they have symmetrical response in front and back plane, it is necessary to position the array as close to the façade as possible, in order to mitigate source “smearing” which would appear in resulting images as a consequence of façade reflections. Figure 1 on the right shows the street profile with relevant data for calculations, the elevation angles of 110° and 137° correspond to the edges of the traffic lanes and are important in the interpretation of the resulting maps. For the measurements presented in this paper the center of the array is positioned at 3.2 m, and the distance to the middle of the street is 6 m. In the presented scenario, there are no buildings opposite from the façade, hence this configuration belongs to the category of non-canyon streets. The street is in a busy urban area with frequent car, bus and trolleybus traffic.

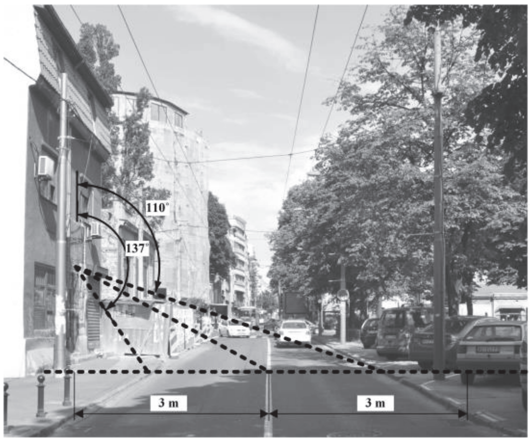

Figure 1 – Measurement setup: microphone array on the façade (left), street profile (right).

The incidence angle and its correlation to azimuth and elevation angles are shown in Figure 2. The figure on the left shows the incidence angle *Θ* defined in relation to the line perpendicular to the façade surface. In order to obtain the angular distribution of the incident noise energy, the energy contributions for circular rings of width *dΘ* have to be calculated. The figure on the right shows an example of the source distribution map obtained by beamforming algorithms. Since the spatial grid is defined by two angles: azimuth and elevation, the resulting map is presented as a two-dimensional graph with color coded values for sound source energy levels from different directions. The map shown in Figure 2 is hypothetical and shows a uniform distribution of energy. The circles shown on this map correspond to the *dΘ* rings on the left picture.

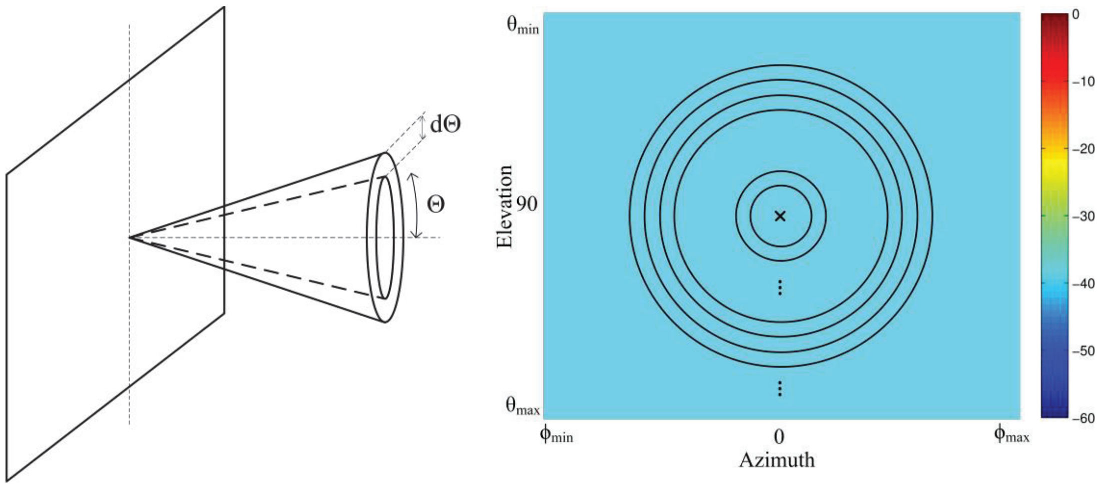

Figure 2 – Incidence angle (left), the procedure for determining probability density function (right).

The algorithms used for array signal processing are: CB (*Conventional Beamformer*) (8) and DAMAS2 (*Deconvolution Approach for the Mapping of Acoustic Sources*) (6). The CB algorithm is used as a first step in space-time signal processing, and DAMAS2 is then applied to eliminate the influence of the microphone array from the resulting spatial map. Other deconvolution beamforming algorithms were also examined, but DAMAS2 was chosen as the one giving the most accurate results (5). The results presented in the continuation also show the resulting map obtained by the CLEAN-SC algorithm (9) for the purposes of comparison.

3. NOISE ENERGY ANGULAR DISTRIBUTION

Figure 3 shows the resulting maps obtained by the three mentioned algorithms. The results shown in the Figure correspond to the 1/3 octave band at 1250 Hz. The conclusions drawn here are valid for other frequency ranges as well. The range of azimuth angles is from -90° to +90°. And elevation angle range is from 80° to 160°. The elevation angle range is reduced, since it was determined that there are no major sound sources present outside this region. All three figures contain black lines which signify the edges and the middle of the traffic lane. The lines appear curved because it is a two-dimensional representation of a half-sphere in front of the façade. The result obtained by CB algorithm is shown in the top-left position. Observing this result would indicate a nearly uniform distribution of sound energy, with only several directions containing sources of 10 dB higher power. The reason for this is the nature of CB algorithm, namely the fact that the results are highly influenced by the microphone array beampattern, which unavoidably contains certain sidelobes. This is why the application of the deconvolution algorithms is necessary. However, CB algorithm is a necessary first step in every deconvolution procedure. The top-right graph in Figure 3 shows the result obtained with CLEAN-SC algorithm. This result indicates concentrations of the sound energy in the zones that correspond to the traffic lanes, as expected. However, an approximately uniform distribution of the energy is observed in other directions, i.e. there is no increase in zones where the reflected sound is expected, such as parked cars and pavement. Since the CLEAN-SC algorithm is based on the coherence between the main lobe and the sidelobes, and by removing the coherent content, the algorithm will also remove the contributions of reflections arriving with a relatively short time delay compared to the direct sound, incorrectly identifying them as sidelobe content. The bottom graph in Figure 3 shows the results of DAMAS2 algorithm. This result also indicates the majority of the sound energy arriving from the direction of the traffic lanes. However, in this result other regions can be observed as well, in which there is an increase in sound energy level. These zones correspond to the location where reflective surfaces exist, and their levels are approximately 10 dB lower than the main energy regions, which is an expected result.

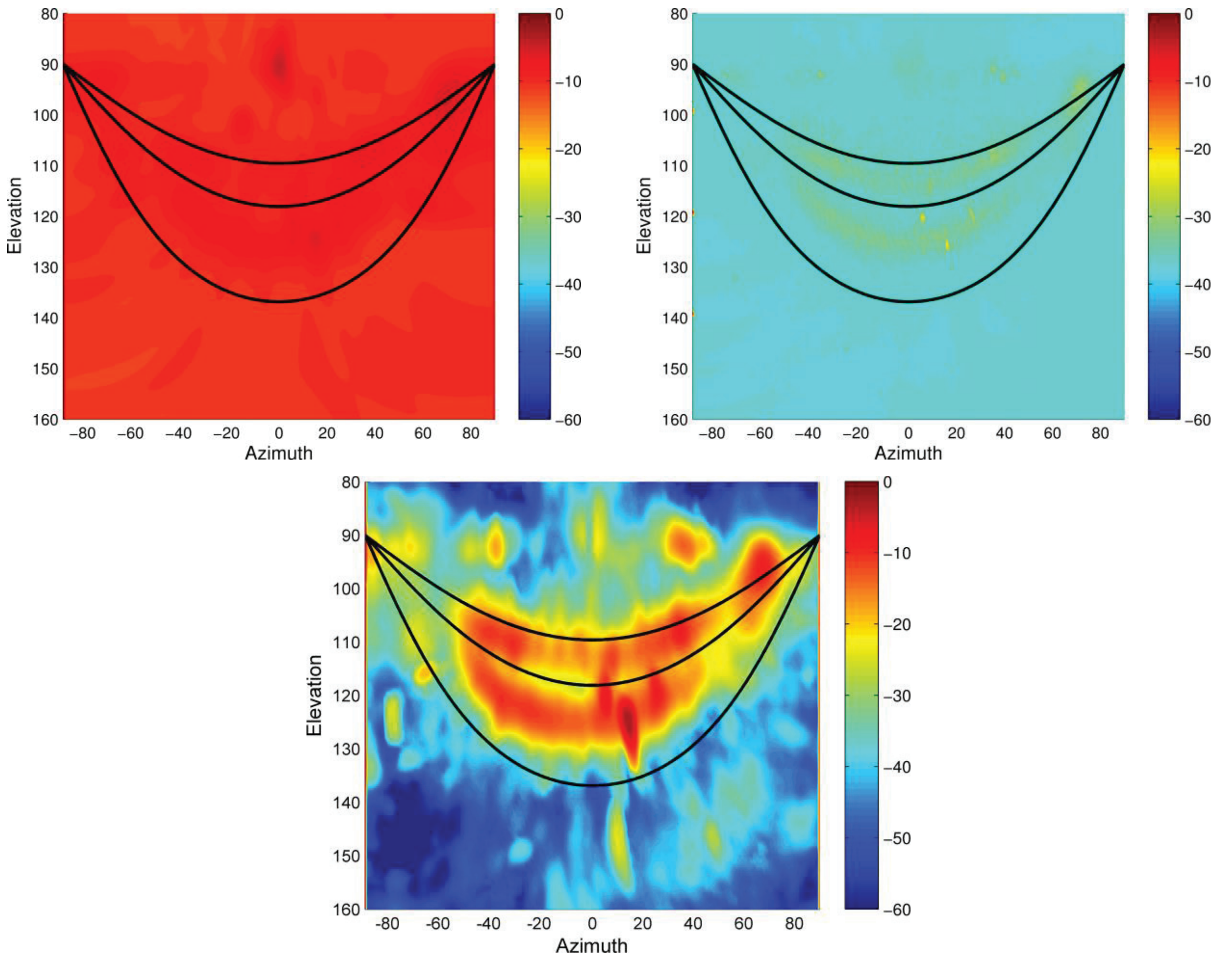

Figure 3 – Beamforming algorithm results. Conventional Beamformer (top-left), CLEAN-SC (top-right), DAMAS2 (bottom)

Based on the conducted analyses, the results of DAMAS2 algorithms will be used to calculate the probability density function of the noise energy angular distribution. However, CB and CLEAN-SC are also important algorithms: CB is the necessary first step in all deconvolution techniques and CLEAN-SC algorithm can be used to determine the locations of the primary sources in a source spatial distribution plot. For the purposes of comparison, the results obtained by energy summation of the results of all three algorithms are shown in Figure 4 for 1/3 octave band at 1250 Hz.

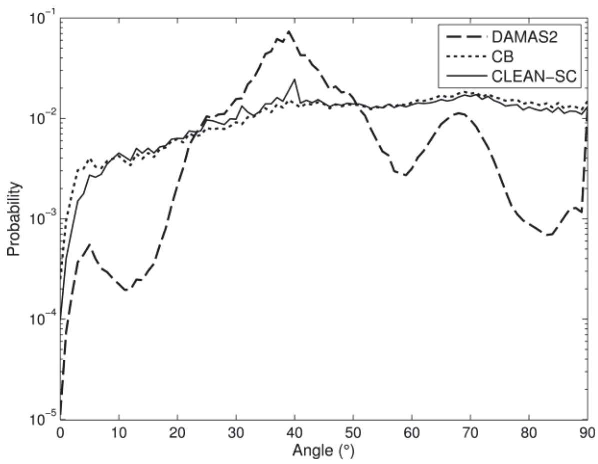

Figure 4 – Probabilty density functions for three different algorithms.

The energy summation is performed as was explained in section 2 and shown in Figure 2. The pdfs obtained by the CB and CLEAN-SC algorithms show a relatively uniform distribution for angles larger than 20°, with the difference around the incidence angle of 40° where CLEAN-SC algorithm has a slight increase. This is the angle which corresponds to the traffic lanes. Both these results would suggest a nearly uniform distribution of incidence energy for the angles between 20° and 90° degrees which does not correspond to the real situation. The results obtained by summing the DAMAS2 source distribution plot, show a highly non-uniform distribution with maximums around incidence angles of 40° and 68°. These angles correspond to the highest energy contributions from the traffic lanes. It is interesting to note that the highest energy arrives at the angle of 40° which approximately corresponds to the standard incidence angle used in the global loudspeaker method for measuring façade sound insulation.

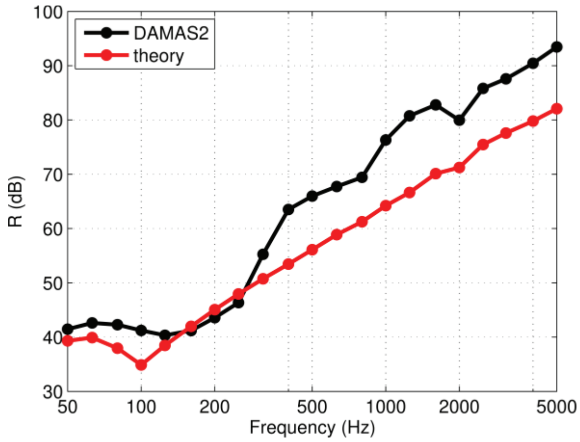

Figure 5 – Sound reduction index based on DAMAS2 results and theoretical distribution sin(2θ). Concrete 20 cm (left), glass 5 mm (right).

Figure 5 shows the sound reduction index calculated based on the angular distribution obtained by DAMAS2 algorithm and based on a theoretical uniform distribution sin(2θ). The calculations are performed for a concrete wall of 20 cm thickness and glass of 5 mm thickness. These two materials were chosen, as they are some of the more commonly used façade elements. The angular distributions were calculated based on DAMAS2 results for all frequency bands between 50 Hz and 5000 Hz. Based on these distributions sound reduction index is calculated as a function of frequency. Differences can be observed in the sound reduction index compared to the theoretical uniform distribution. These differences, for the concrete façade element are up to 12 dB for individual frequency bands. These differences lead to a large difference in weighted sound reduction index, and also mean that this type of façade will exhibit better sound insulation characteristics than theoretical calculation would suggest. In the case of a glass partition, the values obtained by measured pdfs are generally higher than theoretical values, except in the region of the frequency of coincidence for glass. This would suggest that at these frequencies, the angular distribution of sound energy is substantially different from a uniform sound field and favorizes larger incidence angles. It should be noted that these conclusions are valid only for this particular measurement situation – a non-canyon street, with microphone array height at 3.2 meters. In order to draw more general conclusions, a more extensive measurements in different configurations need to be performed.

4. MEASUREMENT OPTIMISATION

As was mentioned previously, signal processing stage is extremely time consuming. The deconvolution algorithms are time consuming since they are based on an iterative procedure. In order to calculate the probability density functions in all frequency bands for a 30-minute long recording, 100 hours are needed for computations on a standard PC. If there are any changes that need to be made in some of the parameters in order to perform comparative analysis, the computation time this long poses a serious problem. This is the reason, why steps are taken to optimize the measurement procedure by reducing the computation time. One of the first steps in this analysis is finding means of reducing the length of the signal that needs to be processed.

This analysis is based on the assumption that the overall probability density function observed at a 30-minute time interval, is a combination of several key pdfs observed for characteristic events such as a car passing by, a trolleybus passing by, ambient hum observed with no characteristic events etc. If this assumption is proven correct, it would mean that the measurement time and signal processing time can be greatly reduced by recording only those key characteristic events and performing analyses only on those recordings, given that all the types of events are known as well and their frequency of occurrence in a given situation.

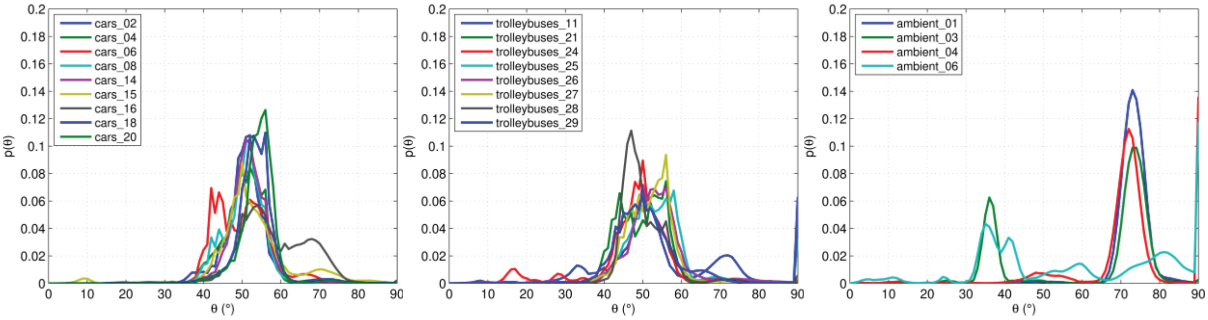

Figure 6 – Probability density functions for different types of events. Cars (left), trolleybuses (middle), and ambient sound (right).

Figure 6 shows the pdfs obtained for recordings of characteristic events excerpted from a 30-minute recording in the measurement scenario presented in Figure 1, in the 1/3 octave frequency range at 1600 Hz. It can be seen that certain types of events produce similar pdfs. Both traffic events, cars and trolley buses have pdfs with energy concentrated in the angular range from 40° to 60°. This corresponds to the energy contributions from the directions of the traffic lanes. The pdfs obtained from the recordings of ambient sound, with no events, have maximums for larger angles of incidence. This is an important observation, knowing the fact that the sound reduction index values are lower for larger angles of incidence.

In Figure 7 sound reduction index graphs are shown for two types of façade elements, and three types of events. The top row represents the results for concrete wall of 20 cm thickness, and the bottom row results for glass of 5 mm thickness. In all graphs black line represents the sound reduction values calculated for the overall probability density functions obtained for a 30-minute recording. The grayed area represents the sound reduction index value range for each of the calculated event pdfs.

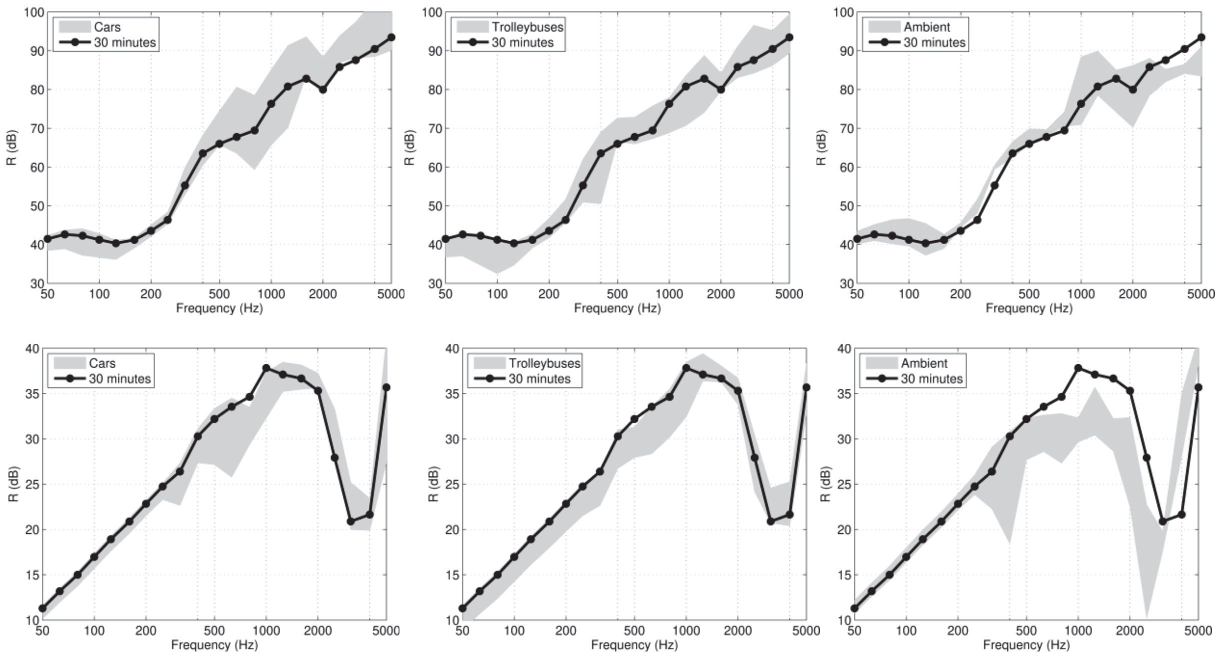

Figure 7 – Sound reduction index calculated based on different events pdf compared to a 30-minute recording. Concrete 20 cm (top), glass 5 mm (bottom).

In the case of a concrete wall, for both types of traffic events, the sound reduction index curve calculated for the overall recording is within the range of values spanned by different events, and the largest differences are in the frequency range from 500 Hz to 2000 Hz. However, in the case of ambient noise recording, the values of overall curve are outside the range of individual events. Similar conclusion can be drawn for glass wall, with the largest differences observed in the case of ambient noise recordings. The largest differences in the case of ambient noise recordings for glass elements, between the overall curve and curves based on event pdfs are in the range from 2000 Hz to 2500 Hz, which is around the coincidence frequency of 5 mm thick glass. As was demonstrated in Figure 6, the pdfs for ambient noise recordings have maximums at angles close to 90°, where sound reduction index is reduced. This effect results in a large discrepancy in this case. It should be noted though that the energy levels for these types of events are generally lower than for traffic types of events, which is the reason why these discrepancies have a lower influence on the overall sound reduction curve.

5. FINAL REMARKS

The paper proposes a measurement procedure for determining angular distribution of incident noise energy in urban environments. The goal of such analysis is to determine specific shapes of distributions in characteristic urban configurations such as canyon, non-canyon streets, etc. Microphone arrays are used as a tool for determining sound source spatial distribution. It was shown that the choice of algorithm for array signal processing significantly influences the final result, and DAMAS2 algorithm was chosen as the most reliable. The results for predicted sound reduction index based on measured energy distributions show certain differences compared to theoretical values. In order to draw more general conclusions, measurements need to be conducted on a larger scale: on different locations with different terrain configurations. The measurement procedure and signal processing need to be optimized in order to solve the problem of significant computation time needed to obtain the results. The idea is presented for reducing the processing time by recognizing key events and analyzing only their recordings. This procedure is based on the assumption that the overall angular distribution is a combination of individual distributions characteristic for these events. It was shown that the value of the sound reduction index depends on the type of sound source. In urban areas there are different types of sources (cars, buses, trolleybuses, trams, etc.) which leads to a change in the structure of the sound field. The consequence of this is the time dependence of the façade element sound reduction index. The influence of a certain type of source is dependent on the concrete terrain configuration in which the façade is located, the size of the source, the spectral content of its noise etc. This is the reason why the same type of source, such as a car, can result in different distributions, and hence different sound reduction index values. This means that the simple summation of results based on different types of events will not lead to the same result as the one based on overall recording. It is therefore necessary to determine certain correction factors which would take into account the nature of different sources and their influence on the general sound reduction index result. Introducing these correction factors will be the focus of future research.

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