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Estimation of Noise Immission Directivity using small Microphone Array

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ABSTRACT

Ever increasing processing power enables the development of advanced equipment for environmental noise measurements, capable of complex processing of multichannel signals. Consequently a research has been undertaken to develop a handheld size beamforming system for two new measurement options: 1) immission directivity, 2) noise source classification, based on the immission directivity. In this paper a new physical property, called immission directivity, is defined in a way which enables traceability to SI units. Furthermore, the immission directivity and temporal direction of noise immission can be used as features for classification of noise sources arranged around the immission point. As such it can be used in real time for triggering of equivalent noise level integration. Statistical analysis shows, that it enables measuring of more random environmental noise sources and calculating their contribution to the overall noise level. Three case studies have been performed using proposed measuring options. Two new options revealed significant advantages over classical noise monitoring systems by improving the validity and the presentation capability of results. Implementation of these two options into noise monitoring equipment reduces human resources, resulting in reduced measurement costs, and provides more accurate results. Additional advantage of the new measurement options is their ability to provide information which is necessary for design of noise control measures.

Keywords: environmental noise, urban noise, traffic noise, immission directivity, noise annoyance, noise Classification, Beamforming

1. INTRODUCTION

Typical, commercially available environmental noise monitoring systems continuously measure sound levels without assigning these measurements to different noise sources in the acoustical scenes, because they are incapable of identifying the main noise source, [1]. Environmental noise measurements are often conducted with the purpose to evaluate and to quantify the contribution of a single selected noise source to the overall noise level. However, also other noise sources exist and the captured noise level is usually a result of a combination of the target and interfering sound sources: wind, cars, dogs and birds being examples. Several measurements techniques can be implemented to determine the contribution of the selected noise source to overall noise pollution, among them:

1. Listening through all the samples offline in the lab, as being very common. This requires a huge amount of resources because of a large amount of data due to often necessary long-term measurements. Also, if only noise levels are recorded, validation by listening is not possible, [1, 2]
2. Turning off the measured noise source and measure noise level difference between the residual and background noise and the overall noise level, [2].
3. Positioning the measurement locations to the vicinity of the selected noise source to gain signal to noise ratio and then to extrapolate results from closer measurement locations to the immission location of interest, [2].
4. Noise modeling, based on the noise source sound power data or on sound power measurements, of the propagation of noise from the selected source to the immission location of interest, [2].

However, some of the noise sources cannot be switched off, or they contain many uncorrelated noise sources. Example of such noise sources are large industrial premises, ports, train stations, refineries,

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airports, building sites, etc. Additional problem which usually arises is the operational simultaneity of many noise sources within such a complex sites. Measurements are therefore often performed by specialy trained personal. Personnel usually waits for longer time to be able to identify and record the proper sample of noise event, which is then included into the integration of equivalent levels, [2]. Trained personnel identifies the proper sample of noise event by using two ears for detection of the noise event direction, by trained noise event recognition and classification, and by trained evaluation of the signal to noise ratio. Such procedure can be very time consuming, therefore its automation is necessary. In order to emulate measurement procedures performed by trained personal, the automatic classification of noise events should be used, [2].

Adaptive algorithms and onset of AI is focused towards automatic noise event recognition. Automatic environmental noise events classifiers already exists, however they haven't found its way into the commercially available noise monitoring systems yet, due to their complexity and poor reliability. P. Maijala et.al. presented a feasibility study on a new monitoring concept in which an acoustic pattern classification algorithm running in a wireless sensor is used to automatically assign the measured sound level to different noise sources, [1]. Work has been done in the field of feature extraction methods, by using convolution neural networks, [3,4], and deep neural networks, [5]. Wavelet, as atom of individual noise events, has also been proposed for classification [6]. Selection of features is important and algorithms have been developed for this purpose [7, 8]. Fuzzy logic has been tested on well know signal features, [9]. Classification based on image recognition of spectrograms has been extensively tested [10,11,12]. An Environmental Sound Source Classification System Based on Mel-Frequency Cepstral Coefficients and Gaussian Mixture Models has been reported, [13,14]. k-NN algorithm [15], Support vector machine, [16], as well as Hidden Markov Model, [17] were tested for classification based on different features has been proposed. Using a time domain technique (the Autocorrelation Function (ACF)), pitch can be estimated and used for a noise event feature, [18].

Despite all research on algorithms for automatic recognition of environmental noise events, they still have limited capabilities to classify noise events with sufficient reproducibility. Additionally, a lot of time is needed to build appropriate data base and to teach the algorithm to perform satisfactory classification. Our hypothesis is that environmental noise classifiers do not to perform adequately due to the fact that they are based on a single microphone signal, and can therefore not mimic the proper hearing of trained personnel, [2]. Therefore a new patented approach was introduced in the System for Automatic Noise Source Identification and Classification (SANSIC), incorporating the noise immission directivity as a feature for noise source classification, [2,19].

1.1 Theoretical background of noise immission directivity - spatial analysis

Equivalent noise level L_{Aeq} is well known and defined in Eq.1. It can be described as running logarithmic average of measured noise level values. It is averaged value of measured noise sample of length τ_0. If sample size τ_0 is long enough, we can assume that L_{Aeq} describes an averaged level of all noise events within the same population of noise events.

$$L_{Aeq}(\tau_0) = 10\log\left[\frac{1}{T}\int_0^T 10^{\frac{Lp(t)}{10}} dt\right] \tag{1}$$

Sound pressure is a scalar quantity. Overall sound pressure at selected Immission Point (IP) is therefore a summation of all sound waves propagating from all surrounding directions towards the IP, as depicted in Fig.1. All surrounding noise sources $NS_i(\varphi, \vartheta)$, contribute to the sound pressure level at the IP. This can be written using Eq.2, with a similar structure to the Eq.1, for the L_{Aeq}.

$$L_p(t) = 10\log\left[\frac{1}{2\pi}\int_0^{2\pi}\int_0^{2\pi} 10^{\frac{Lp(\varphi,\vartheta,t)}{10}} d\vartheta d\varphi\right] \tag{2}$$

$L_{\mathrm{p}}(\varphi, \vartheta, t)$ in Eq.2 represent the contribution of the noise source $NS(\varphi, \vartheta)$, from the spatial direction φ, ϑ, at the given time t, to the overall noise level $L_{\mathrm{p}}(t)$. $L_{\mathrm{p}}(\varphi, \vartheta, t)$ can be imagined as allocation of sound sources and their contribution to the sound pressure at the measuring point in given time t. Therefore it can be understood as immission directivity at the given time t. Because noise sources are allocated around the immission point, the immission directivity is a three dimensional property with elevation angle ϑ and direction angle φ.

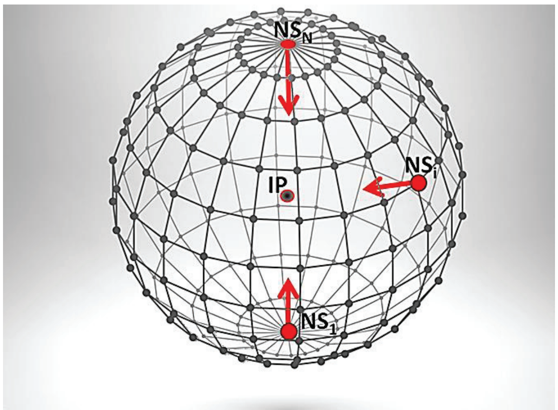

Figure 1 - All noise sources NS$_i$ arranged around the immission point contribute to the overall noise level at the selected immission point (IP)

For simplicity reasons we will consider it to be two dimensional and omit the elevation angle ϑ. Environmental noise sources are placed far from the measurement point, therefore the direction of propagating waves can be considered parallel to the ground, forming two-dimensional noise propagation in plan parallel plane. In majority of practically cases two dimensional directivity provides sufficient information about the dominant noise source location, [20,21]. A perfect immission directivity sensor would therefore provide sufficient information to calculate the contribution of noise sources from all different direction to the overall noise level.

Overall equivalent level of noise event with length of τ_0 can be expressed with Eq.3, which is obtained by inserting Eq.2 into Eq.1 and omitting the elevation angle ϑ, to reduce the three dimensional problem into the planar one. Eq.3 shows that equivalent noise level for selected time interval τ_0 depends on the spatial distribution and on the temporal distribution of noise sources arranged around the immission point.

$$L_{Aeq}(\tau_0) = 10\log\left[\frac{1}{\tau_0}\int_0^{\tau_0}\int_0^{2\pi} 10^{\frac{Lp(t,\varphi)}{10}}\, d\varphi dt\right] \tag{3}$$

A common practice in acoustics is that difference between measured noise level and background noise level should be higher than 10 dB in order to be able to neglect the influence of background noise on the measured value. Same practice can be adopted in the evaluation of immission directivity pattern. If the contribution of the dominant noise source at the dominant angle φ_{DNS} is for more than 10 dB higher than the contribution from all other noise sources, it can be assumed that the measured noise level at the immission point could be attributed only to the noise source at the direction φ_{DNS}. A statistical analysis of noise levels, generated by noise sources around the immission point, should be considered due to the temporal and spatial randomness of environmental noise source.

1.2 Theoretical background of noise immission directivity - temporal analysis

Technical standards do not provide any practical criteria for the choice of the temporal distribution of the samples, i.e. the number and duration of the measurement time. For example, ISO 1996-Part 2 states only: *"to select the measurement time interval to cover all significant variations in sound emission and propagation. If the noise shows periodicity, the measurement time interval should cover an integer number of at least three periods. If continuous measurements over such a period cannot be made, measurement time intervals shall be chosen so that each one constitutes a part of the cycle, so that, together, they represent the complete cycle"*. Unfortunately, this condition is generally not applicable for environmental noise where the acoustic signal is random, [22]. Acoustic signal at the immission point is random due to random intervals of noise sources operation and due to random character of noise levels generated by noise source itself.

Let us now consider a situation in a free field, with N noise sources, arranged around immission point, as shown in Fig.1. Noise levels $L_{Aeq,i}$ from different noise sources are not correlated and we can write an equation for combined equivalent level at the immission point for a selected time interval τ_0:

$$L_{Aeq,C} = 10 \log \sum_{i=1}^{N} 10^{0,1 LAeq,i} \tag{4}$$

Each noise source has its own probability distribution of noise levels, at the selected immission point. If individual noise source does not operate constantly we can attribute him the noise level of -∞ dB during its non-operation. Percentage of its non-operation time can be subtracted from its probability distribution of noise levels. Surface area under the distribution probability of noise sources is no longer 1, because of non-operation probability, and we can write Eq.5.

$$1 - P(-\infty) = \int_{0}^{Lp,\max} P(Lp)dP \tag{5}$$

Examples for two sources (A and B) are given in Figure 2. Exemplar noise source "A" operates only occasionally, with most probable contribution of -∞ dBA. During operation its expected levels range from 70 to 75 dBA. Exemplar noise source "B" operates constantly with its expected noise level between 30 and 35 dBA.

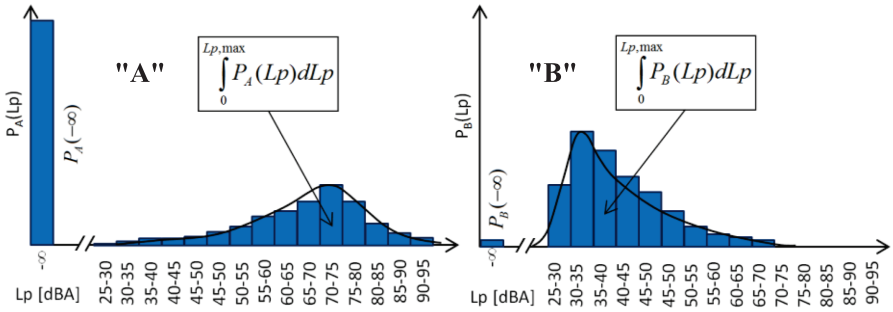

Figure 2 - Noise level distributions for noise sources around the immission point, with probability for non-operating $P_i(-\infty)$

Noise analysis and noise control are always focused towards the dominant noise source. But due to the random character of noise sources in the environment we can only calculate the probability of individual noise source to be dominant. This means that we can calculate the probability of classification. This probability describes to which noise source the measured noise level can be attributed during the selected time interval τ_0. If we want to classify the measured noise level toward the selected noise source j, then noise levels from all other sources should be lower for at least 10 dBA during the same time interval, as given in Eq.6.

$$P_{\text{j=dominant}} = \prod_{i=1}^{N-1} \left(P_i(-\infty) + \int_{0}^{Lp,m-10} P_i(Lp)dLp \right) = \prod_{i=1}^{N-1} \left(1 - \int_{L_{p,m}-10}^{L_{p,\max}} P_i(Lp)dLp \right) \tag{6}$$

From Eq.6 we can see that the probability of non-operation of the individual noise source Pi(-∞) plays a significant role in the probability of classifying the measured noise level to the selected noise source. Higher the probability of the observed noise sources to be non-operational (higher Pi(-∞)), higher the probability that measured noise level can be attributed towards the residual noise source. Additionally, if noise level at the selected time interval τ_0 can be attributed towards individual noise source using directivity measurements, the probability of the selected noise source to be the dominant noise source significantly increases, especially if measured noise levels are within the probability interval of noise source with low noise level. If we break down the observation interval from τ_0=125 msec to 1 msec or less and implement the statistics of noise directivity in the time scale of the sampling rate, probability of dominant source is automatically converted into the probability of noise immission directivity.

Equivalent noise level can be calculated from extracted data in the same way as trained personal performs noise measurements. Trained personnel at the measurement location usually identify only shorter intervals of the noise signal, to be useful for further analysis and treat them like a sample. This identification is based on subtle capability of detection the difference between measured noise level and background noise level. Additionally, personnel detect the direction of noise events and apply a spatial filtering of noise signal before the integration of the equivalent level L_{Aeq}. Therefore we implemented an algorithm for detection of noise source direction, with the algorithm for evaluation of signal to noise ratio into a procedure which mimics the work of trained personal for classification of noise events. Basically, we implemented the noise immission directivity as a signal feature to trigger the integration of the Equivalent level.

2. EXPERIMENTAL SETUP

Microphone antenna composed from four microphones Behringer ECM8000 was designed for measurements of immission directivity, Figure - 3. Design enables measurements in a normal "A" weighted frequency range using folded configuration (on the left). By unfolding the microphones, the frequency range is extended down to 50 Hz, for special low frequency noise directivity analysis. Four channel soundcard Behringer U-Phoria UMC404HD was used for real time signal streaming to LabView programing platform via USB connectionn. An algorithm for detection of sound incidence direction was developed. During its development the special focus was on its speed and ability to run in real time on an average notebook using Intel Core i3 processor. Beamforming algorithm has been optimized to work in real time achieving time resolution of 2.03 msec. Its performance is presented in figure 4. Presented time signal is a recording of interruption in the operation of an audio source reproducing pink noise in the room with a reverberation time of 0.8 seconds. Red dots present direction of noise immission on the microphone antenna. A noticeable directivity can be clearly seen (towards noise source around 260^{O}) at the start of the signal. When the source is switched off, the directivity disappears and reflections from all directions occur. Such results clearly demonstrate that the detection of noise immission directivity is fast enough.

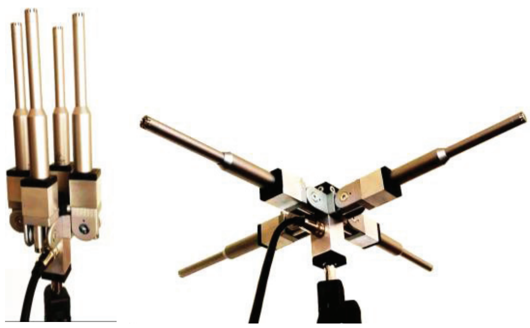

Figure 3 - Foldable microphone antenna, used during measurements of the environmental noise immission directivity.

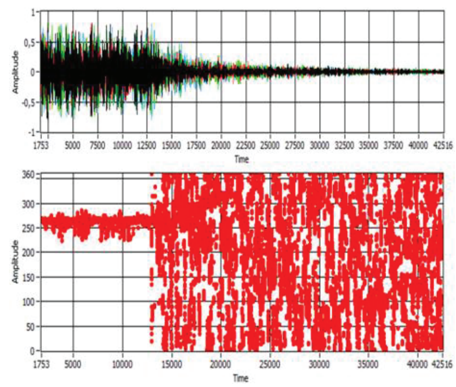

Figure 4 - Immission directivity during reverberation, in a room with T60=0,8 sec.

3. ENVIRONMENTAL NOISE MONITORING USING IMMISSION DIRECTIVITY

A transformation from the theoretical background to the practical application revealed a possibility to simplify the automation of environmental noise measurements, by assuming that there is enough information in microphone array signals, to extract sufficient data for classification of noise sources based on their direction. The first practical measurements have been performed at port of Koper with the purpose to evaluated contribution of individual noise sources (ported ship, traffic noise and activities from the port) to the overall noise level measured at the immission point. Figure 5A depicts the result of the immission directivity, integrated over the 10 minute long interval. In figure 5B an acoustic picture is presented, obtained from 2 sec long interval, during which the noise from the ported ship was dominant. Acoustic camera is heavy, expensive, complicated to operate, and still not suitable for noise monitoring. Dynamic range of the acoustic camera is only few decibels, while the dynamic range of the proposed system is over 30 dB. Proposed system is estimated to cost 1/10 of the acoustic camera, and yet it can provide information on noise contribution from ported ship, noise from port and traffic noise as depicted in Figure 5A from a single 10 minutes long measurement.

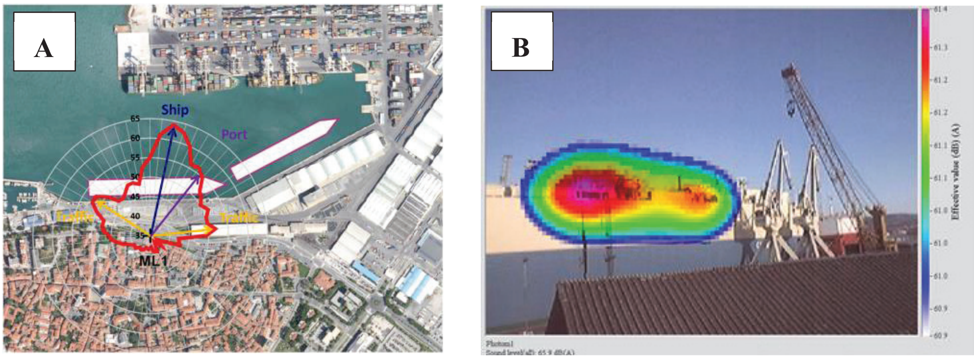

Figure 5 - Noise immission directivity integrated over 10 minutes (A) and acoustic picture integrated over 5 seconds long interval (B). Background is obtained from http://gis.arso.gov.si/atlasokolja/profile.aspx?id=Atlas_Okolja_AXL@Arso

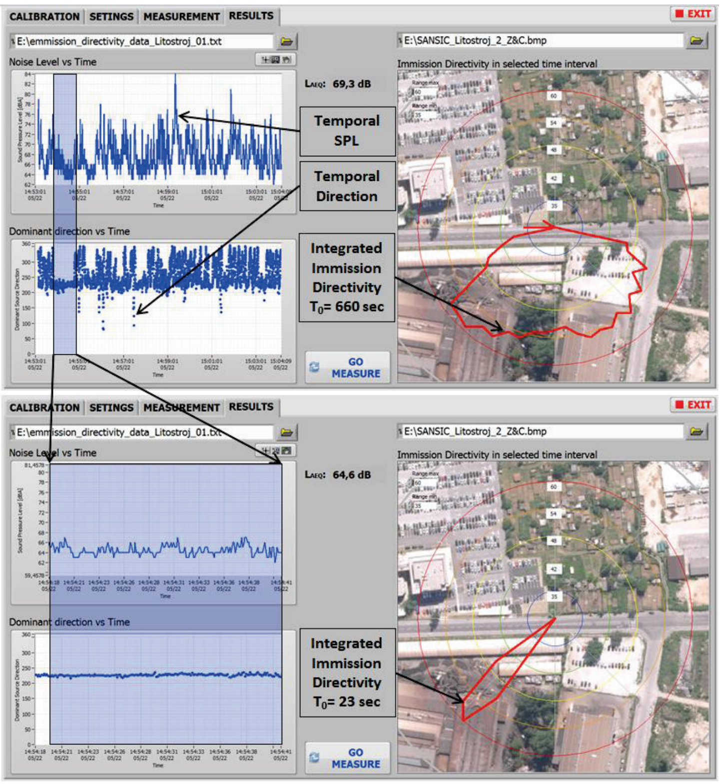

Figure 6 - Graphic user interface and temporal directivity as a noise feature for its classification. Upper part depicts 660 seconds long interval and picture below depicts a 23 seconds long selected interval with only one noise source. Background is obtained from http://gis.arso.gov.si/atlasokolja/profile.aspx?id=Atlas_Okolja_AXL@Arso

Second measurement was performed in order to validate the procedure on a well-defined acoustic situation. A 100 kW ventilation system, as dominant noise source, is positioned near a road with a traffic density of 3600 vehicles per day. Graphic User Interface for calculation of results is presented in Figure 6. On the upper part of the figure a 660 seconds long interval is presented with SPL levels and corresponding temporal directions of dominant noise sources. On the right part of the graphic user interface the integrated immission directivity is presented. Integrated immission directivity clearly shows, with dynamic range over 30 dBA, that all noise immission can be contributed to the traffic and to the ventilation system. Based on the temporal direction of detected noise source direction an automatic classification can be performed. Conditions for integration of equivalent level can be defined for several angels matching the directions of the observed noise sources. By integrating the equivalent level only during the operation of the individual noise source, we can obtain the contribution of such noise source to the overall noise level. Bottom part of the figure 6 depicts acoustic conditions during the 23 seconds long interval. During this interval no traffic was present and immission directivity clearly points towards the noise source and indicates for 4,7 dBA lower noise level as in the case when traffic and the source are working together. In such a way we can calculate noise level of traffic, even though the background ventilation noise was present all the time.

The third set of the noise immission directivity measurements was performed as a 24 hour monitoring. Proposed system was placed in a settlement with complex of houses, with distinct noise source; highway with approximately 20.000 vehicles per day. Residual noise was generated by residents, children, traffic within the settlement and pets (barking dogs). Noise levels, produced by traffic, are approximately the same in comparison to the residual noise level. Direction of the noise immission was recorded together with measured noise level, in order to evaluate the contribution of individual noise source to the total noise level. Results are presented in Figure 7. Results clearly indicate that during evening hours in summer, activity of inhabitants dominates in the total noise level. Strong directivity is consequence of canyoning effect of noise propagation. During morning rush hours, the traffic noise dominates in the total level. From measured immission directivity $L_{\mathrm{Aeq}}(\varphi)$ we can calculate the exact contribution of noise source $\mathrm{NS_i}$ around the immission point using a simple Eq.7:

$$L_{Aeq,NSi} = 10\log\left[\int_{\varphi_{NSi,1}}^{\varphi_{NSi,2}} 10^{\frac{Lp(\varphi)}{10}} d\varphi\right] \tag{7}$$

Figure 7 - Results of long term monitoring of immission directivity in a populated area.
Background is obtained from:
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4. CONCLUSIONS

When observing noise sources from long distances in comparison to their size and height, we can consider the noise propagation to be a two dimensional problem, by neglecting the influence of meteorological condition. Temperature, pressure and humidity gradients have very limited effect on the two dimensional plan parallel noise immission directivity. Wind on the other hand can influence the observed immission directivity. The main advantage of considering noise propagation to be two dimensional in plan parallel plane is the possibility of implementing one-dimensional beamforming. One dimensional beamforming has low computational demands, it can run in real time, and it can provide the immission directivity pattern.

In this paper a new physical property, called immission directivity, is defined in a way which enables its traceability to SI units. Furthermore, the immission directivity and temporal direction of the noise immission can be used as a feature for classification of noise sources arranged around the immission point. As such it can be used for triggering of equivalent noise level integration enabling simultaneous measuring of the contribution of more environmental noise sources to the overall noise level. Implementation of the approach was performed on three case studies. In all three cases the approach proved to add significant advantage and validity to measured noise levels in the environmental noise.

Even with the most basic equipment very good results have been obtained. Further design of more sophisticated equipment for frequency dependent noise immission directivity will provide new approaches in monitoring of environmental noise.

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