Directivity measurements of environmental noise immission

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Summary

State of the art environmental noise monitoring systems are based on digital signal processing. In general, they perform computation and storage of noise levels, spectral filtering, narrowband spectral analysis, evaluation of statistical indices, wave recordings, detection of noise events based on thresholds, and other similar tasks. Increase in processing power can be further exploited to develop more sophisticated apparatus capable of complex processing of multichannel sound signals and other data. Consequently, a research has been undertaken to develop a new measurement method for environmental noise monitoring systems; the automatic identification of the dominant noise source direction. Implementation of this feature into noise monitoring equipment reduces a need for human resources, resulting in reduced measurement costs, and in more accurate results. The main advantage of the new measurement method is its ability to provide additional information which is necessary for design of proper noise control measures in complex noise environment.

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1. Introduction[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. Several measurements techniques can be implemented to determine the contribution of the selected noise source to overall noise pollution, among them:

1. Turning off the measured noise source and measure a noise level difference between the residual or background noise and the overall noise level.
2. Positioning the measurement locations to the vicinity of the selected noise source to gain signal to noise ratio, and extrapolate results from a close measurement location to the immission location of interest.
3. Noise propagation modeling, based on the noise source sound power data, or the sound power measurement, to the immission location of interest.

However, some 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, 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 trained personal. Personnel usually waits for longer time to be able to identify, classify, and record the proper sample of noise event, which is then included into the integration of equivalent levels for selected noise sources. Trained personnel identifies the proper sample of noise event by using two ears for detection of noise event direction, by individual noise event recognition and classification, and by subjective evaluation of the signal to noise ratio. Such procedure can be 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. Automatic classifiers of environmental noise events already exists, however they haven't found their way into the commercially available noise monitoring systems yet, due to their complexity and poor reliability. Algorithms for automatic recognition of environmental noise events also have quite 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. The main reason why environmental noise classifiers do not perform adequately is, that they are usually based on a single microphone signal, which cannot mimic the proper hearing of trained personnel. Therefore a new patented approach was introduced in the System for Automatic Noise Source Identification and Classification (SASNIC), incorporating the detection of the dominant noise source direction.

1.1. Theoretical Background

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

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

Sound pressure is a scalar physical value and sound pressure at the Measuring Location (ML) is a summation of all sound waves propagating from all directions towards the ML, as depicted in Fig.1. Sound pressure level at the ML therefore depends on surrounding noise sources. This can be written by Eq.2, with an identical structure compared to Eq.1, describing the L_{Aeq}.

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

$L_p(\varphi,t)$ in Eq.2 represent the contribution of the noise source from direction φ at the time t to the overall noise level $L_p(t)$. $L_p(\varphi,t)$ can be also presented as arrangement or allocation of noise sources and their contribution to the sound pressure at the measuring point in given time t, depicted as curve $L_p(\varphi)$ in Figure 1. It can also be understood as immission directivity. Three examples of correlation between immission directivity and overall noise level are also depicted in Figure 1. If noise propagates to the ML only from one direction, the maximum value of $L(\varphi)$ is equal to the measured noise level. If noise propagates to the ML from two directions with equal intensity, then the measured noise level is 3 dB higher then noise level for individual direction, Figure 1.

The immission directivity is three dimensional property; however for simplicity reasons we will consider it to be two dimensional. In majority of practically cases two dimensional immission directivity provides sufficient information about the dominant noise source location, [1, 2].

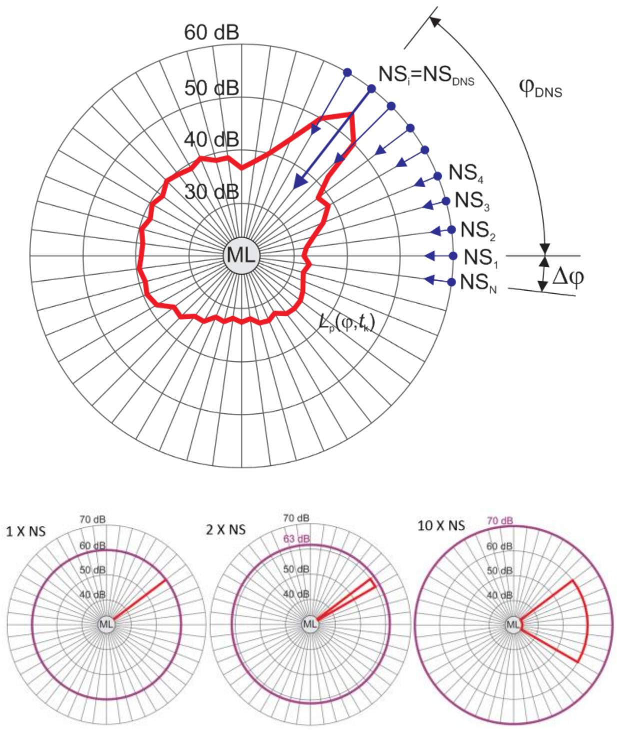

Figure 1. Noise immission directivity at the Measurement Location (ML) and partial contribution $L(\varphi)$ of surrounding Noise Sources (NSi) at direction φ_i and in time t.

By using a perfect immission directivity sensor for sound pressure in real noise measurement environment, we can calculate the contribution of noise sources from different direction to the overall noise level. Dominant noise source, from direction φ_{DNS}, contributes the majority to the overall sound pressure at the ML.

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, from the angle φ_{DNS}, is for more than 10 dB higher than the contribution from all other noise sources, then we can assume that measured noise level at the ML can be attributed only to the noise source at the direction φ_{DNS}. Such an example is given in figure 1. Consequently we can calculate equivalent level of immission directivity, as given in Eq.3.

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

However, a perfect immission directivity sensor does not exists at the moment. Large microphone array with large number of microphones can be used together with beamforming algorithm in order to obtain the immission directivity pattern. Large microphone arrays are unpractical for environmental noise measurements and monitoring, they are expensive and a lot of processing power is needed for beamforming algorithms.

A study on how to perform a simple transformation from the theory to the practical application, revealed a possibility to simplify the procedure, by assuming that during environmental noise monitoring we have enough time to extract sufficient data from long term noise measurements. Equivalent noise level can be calculated from extracted data in the same way as trained personal performs noise measurements. Trained personnel identifies only small part of the noise at the measurement location to be useful. This identification is based on subtle capability of detection the difference between measured noise level and background noise level. Additionally, personnel detects the direction of noise events and applies a spatial filtering of noise signal before the integration of the equivalent level L_{Aeq}. Therefore we developed three sub algorithms; a sub algorithm for detection of dominant noise source direction, a sub algorithm to estimate signal to noise ratio and a sub algorithm to mimic the trained personal for decision on noise event integration into L_{Aeq}. In this paper we will focus only on the decision algorithm for integration of L_{Aeq}.

1.2. Decision Algorithm

Let us assume a sensor for detection of the dominant noise source direction, with angle resolution $\Delta\varphi$, which also provides an estimate of the signal to background noise ratio (SN). By using such a sensor we can discretized the circle to M values, where $M=2\pi/\Delta\varphi$, as indicated in figure 1.

After the discretization of angels and the introduction of the integration criterion, based on the 10 dB SN ratio, we can simplify the Eq. (3) into a manageable form, as given in Eq. (4). According to Eq.4 L_{Aeq} is now calculated only at one discretized direction during one selected time (125 msec). Algorithm, based on Eq.4, is depicted with flowchart on figure 2. In order to be able to focus to a single noise source additional two conditions are implemented into the algorithm, [6,7,8]. The first one is angle of interest ($\varphi_{min}>\varphi_{DNS}>\varphi_{max}$), and the second one is classic triggering condition defined with noise level ($L_{min}>L_{DNS}>L_{max}$). With all conditions in the algorithm we can now focus towards the single noise source of interest and we can calculate the contribution of selected noise source to the total noise level at the ML.

$$L_{Aeq}(N,\varphi_{DNS}) = 10\log\left[\frac{1}{N}\sum_{i=1}^{N}10^{\frac{h_i L_{i,\varphi\max}}{10}}\right] \qquad (4)$$

Where $\varphi_{DNS} = \arg_{\varphi}\max L(\varphi)$

and $h_i = \begin{cases} 0, SN_i < 10 \\ 1, SN_i > 10 \end{cases}$

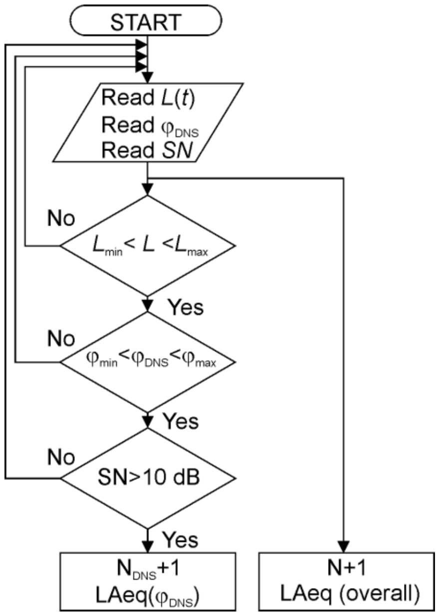

Figure 2. Algorithm for calculation of Equivalent noise level directivity

Equivalent level $L_{Aeq}(N,\varphi)$, as given in Eq.4, is a matrix with dimension N, M. During the calculations only one element is added in row N at the column corresponding to φ_{max} during one iteration of algorithm.

2. Experimental results

The first experiment with the SANSIC, [5] system was performed to evaluate its directivity resolution. The test was performed separately for vertical and for horizontal angle of incidence. Second experiment was designed in order to check if the beamforming algorithm is fast enough to calculate the direction of the dominant source and immission directivity pattern, and if this two features are sensitive enough for the decision algorithm. Third experiment was performed under realistic environmental noise measurement condition, to establish if the system conforms with expectations of development efforts.

2.1 Directivity

Simulation of the microphone array response to point source are depicted on the polar plot in Figure 3 left. Simulations were performed in Matlab. Measured microphone array response to white noise generated by the loudspeaker is presented on the right polar plot in Figure 3.

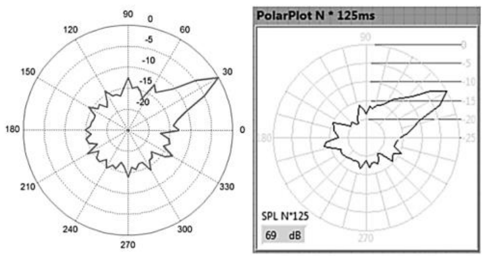

Figure 3. Simulated (Matlab) and measured (LabView) polar plot for random broadband noise

Measurements were acquired from the FPGA on the microphone array by using a protocol written in LabView. Measured results exceeded expectations based on results of simulations. Maximum in the polar plot is approximately 13 dB higher than the side lobe, while the attenuation at ±30 degrees is higher than 10 dB. This result confirms, that horizontal microphone array with 33 microphones provides directivity resolution and dynamics which can be used to evaluate dominant noise source direction and SN ratio, [3,4].

2.2 Influence of vertical incidence angle on directivity

Simulations and measurements were performed to establish the influence of the vertical angle of noise incidence on the performance of microphone circular array. Results are presented in Figure 4. Influence of noise immission for different vertical incidence angles on the directivity pattern is presented in Figure 4 (left). If noise source generates white noise and is placed in the same plane as circular microphone array then immission directivity pattern is very sharp and the polar diagram shows the direction of the noise source. If the same noise source is elevated above the microphone array plane, and vertical immission angle is increased to 15°, then the shape of directivity pattern changes. It still shows the direction of the source very clearly, only the pattern is slightly wider. Even if the vertical immission angle is increased to 30°, the directivity pattern still clearly shows towards the noise source, however it is significantly wider (dotted line in Figure 4-left). This results clearly confirms that circular microphone array in horizontal plane can be effectively used for determination of the dominant noise location.

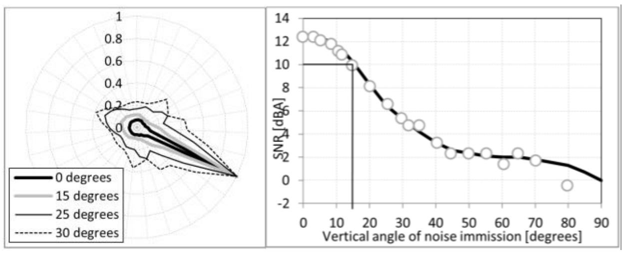

Figure 4. Directivity of noise immission for different vertical angles (left), and SN of microphone array as a function of vertical angle of noise immission (right)

In order to validate the possibility to use horizontal microphone array as directivity sensor for decision algorithm for integration of L_{Aeq}, SN ratio was evaluated. Signal to noise ratio was defined as a logarithmic ratio between maximum value in polar diagram and averaged value of side lobes according to Eq.(5).

$$\mathrm{SN} = 10\log\left[\frac{\mathrm{d}_{\max}}{\frac{1}{\mathrm{D}-3}\sum_{i=1}^{D-3} RMS_i^2}\right] \qquad (5)$$

Signal to noise ratio of a given microphone array depends on the vertical angle of sound immission as depicted in Figure 4-right. If noise source is placed ±15° above or below the microphone array plane the time delay on the microphones changes for 3%. Such small change has practically negligible effect on the discretization of the delay. In general, we can estimate that circular array can provide valid results for directivity, if noise sources lie within vertical incidence angle ±15° based on the elevation of noise source above or below the microphone array plane.

2.3 Environmental noise monitoring

Encouraged by the promising results of simulation further measurements were performed with the prototype of the SANSIC system. The first practical measurement using proposed system was performed in a settlement with complex of houses, with two noise sources; motorway and residual or background noise. Residual noise was generated by residents, children, traffic within the settlement, lawn movers, and pets (barking dogs). Noise levels produced by two measured sources have approximately the same values. 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 5.

Results perfectly coincide with recorded activities in the settlement and traffic on the nearby highway. Noise generated by activities of the population living in the area is most intense during leisure period, and minimal during daily migration to work.

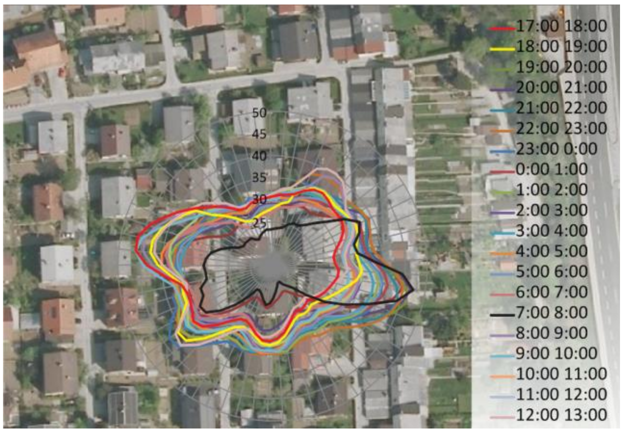

Figure 5. Immision directivity of noise at the ML in settlement near the highway, for different time intervals of the day.

Directivity pattern of noise immission is changing during measurement interval just like sound pressure level is changing during the same measurement interval. Simple averaging of directivity pattern, over the time intervals in which the direction of the dominant noise source is stable, increases signal to noise ratio of directivity pattern.

Example of data provided by the SANSIC system is given in Figure 6. Blue curve represents the overal noise level measured with calibrated sound level meter and the red dots represents the direction of the dominant noise source. Error bars on the red dots represent estimated signal to noise ratio. Signal to noise ratio is a difference between the noise level, generated by the measured noise source, and the noise level generated by all other noise sources, also known as residual or background noise. SANSIC system estimates the SN ratio diretly from the beamforming results.

Important feature of the SANSIC system is also its ability to distinguish between stationary noise sources and moving noise sources. This abbility enables easy classification of noise sources and faciliates the decision algorithm.

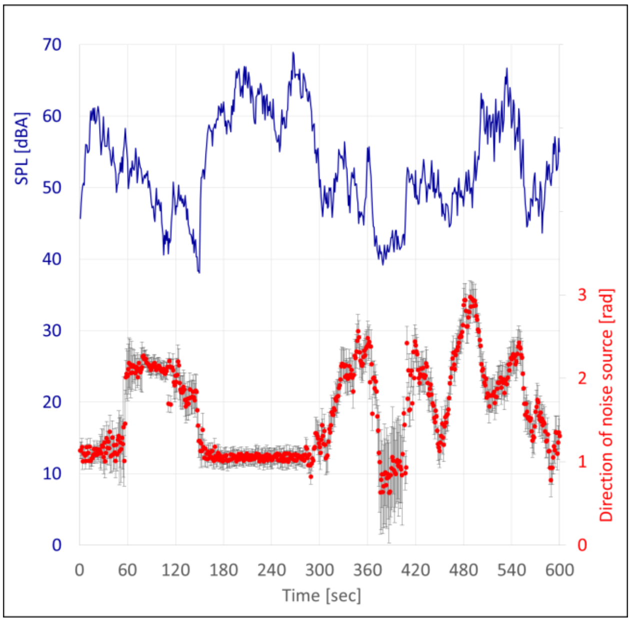

Figure 6. Sound pressure level and dominant noise source direction with estimated error based on signal to noise ratio.

With the SANSIC system we were able to determine noise levels of the nearby highway and noise levels generated by the inhabitants and their activities like lawn mowing, pruning hedges, barking of dogs, etc. Results showed that traffic noise from the highway was more than 4 dB lower then noise generated by inhabitants in the settlement.

To confirm our hypothesis and our decision algorithm we compered measured L_{Aeq} values of noise at ML and integrated values of L_{Aeq} from immission directivity obtained with beamforming. Integration time for L_{Aeq} was 3600 sec. Within each integration time the decision algorithm classified 28800 measured noise levels $L(t)$ according to detected direction of the dominant noise source. Result of these classification is immission directivity plot. Backward calculation of L_{Aeq} from directivity plot $L(\varphi)$ should provide exactly the same values as obtained from calibrated sound level meter. Results are presented in figure 7. Results clearly indicate that decision algorithm for creating the immission directivity curve is working properly and only slight error occurs during backward integration.

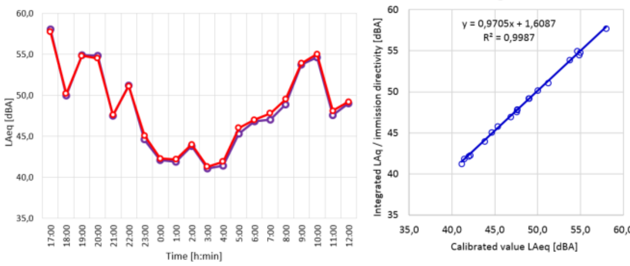

Figure 7. Integrated L_{Aeq} from immission directivity compared to directly measured L_{Aeq} using calibrated sound level meter.

After the validation of the SANSIC system and the decision algorithm for determination of immission directivity pattern, the system was tested in real environment for measurements of noise from port of Koper. Measurement locations were selected with a purpose to determine if the noise from vessels or noise from the traffic dominates in the overall noise level, perceived by the inhabitants. Noise from ships was steady and traffic density was approximately 1600 vehicles per hour. Integration time was 30 minutes. Wind speed was lower than 2 m/s. Measurement location was 40 m above the see level.

Selected results are presented in Figures 8 – 10. Results clearly show that measuring system provides unequivocally information about noise immission. From measured results presented in Figure 8 it is clear that noise from vessel does not dominates in the overall noise level, and that the traffic noise was dominant during measured time interval.

Results presented on figure 9 and on figure 10 are given for two different measurement locations 50 m from each other. By comparing the immission diagram from figure 9 and figure 10 it can be seen that both indicate towards the same part of the vessel. Such results clearly indicates that immission directivity can be used to pinpoint the dominant noise source, which might be tricky if low frequency noise is in question, just like in the case of vessel noise.

Figure 8. Noise immission directivity at ML1 indicates that traffic noise is dominant for given noise propagation conditions

Figure 9. Noise immission directivity at ML2 indicates that at the middle of the closest ship is dominant noise source for given noise propagation conditions

Figure 10. Noise immission directivity at ML1 indicates that at the middle of the closest ship is dominant noise source for given noise propagation conditions

3. Conclusions[2]

Experiments and simulations confirmed that microphone array can provide valid results for the immission directivity of dominant noise source within a vertical incidence angle ±15°.

Results under real environmental conditions confirmed theoretical hypothesis that longer interval of noise measurements can provide sufficient information for extrapolation of noise immission directivity.

Results also confirmed that classification of measured noise level with its dominant direction can provides traceable results.

Simple algorithm, based on features from the microphone array and beamforming algorithm, (spatial information and spatial stability of the noise source), together with some others features of noise signals, can provide basic binary classification used to trigger the L_{Aeq} measurement for more sources around immission position during one measurement.

Combination of 1D beamforming with combination of multiple classification algorithms yields towards new type of environmental noise measurements. Introduction of 1D beamforming can significantly improve usability of SLM.

Acknowledgement

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