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DISTRIBUTED SYSTEM FOR NOISE THREAT EVALUATION BASED ON PSYCHOACOUSTIC MEASUREMENTS

Józef Kotus, Maciej Szczodrak, Andrzej Czyżewski, Bożena Kostek

Gdansk University of Technology, Faculty of Electronics, Telecommunications and Informatics, Department of Multimedia Systems, Narutowicza 11/12, 80-233 Gdansk, Poland, (✉ ksm@sound.eti.pg.gda.pl, +48583471114)

Abstract

An innovative system designed for the continuous monitoring of acoustic climate of urban areas was presented in the paper. The assessment of environmental threats is performed using online data, acquired through a grid of engineered monitoring stations collecting comprehensive information about the acoustic climate of urban areas. The grid of proposed devices provides valuable data for the purpose of long and short time acoustic climate analysis. Dynamic estimation of noise source parameters and real measurement results of emission data are utilized to create dynamic noise maps accessible to the general public. This operation is performed through the noise source prediction employing a propagation model being optimized for computer cluster implementation requirements. It enables the system to generate noise maps in a reasonable time and to publish regularly map updates in the Internet. Moreover, the functionality of the system was extended with new techniques for assessing noise-induced harmful effects on the human hearing system. The principle of operation of the dosimeter is based on a modified psychoacoustic model of hearing and on the results of research performed with participation of volunteers concerning the impact of noise on hearing. The primary function of the dosimeter is to estimate, in real time, auditory effects which are caused by exposure to noise. The results of measurements and simulations performed by the system prototype are depicted and analyzed. Several cases of long-term and short-term measurements of noise originating from various sources were considered in detail. The presented outcomes of predicted degree of the hearing threshold shift induced during the noise exposure can increase the awareness of harmfulness of excessive sound levels.

Keywords: noise, environmental noise, dosimetry, measurements.

1. Introduction

Nowadays, noise is regarded as one of the most serious civilization threats [1]. High noise level effects can have very serious consequences to the hearing system. It may cause an irreparable destruction of the sensitive structures in the inner ear [2]. Various issues regarding the occupational noise threats are discussed in contemporary literature [3-5]. Among them, common use of audio equipment (such as portable mp3 players) and various types of entertainments are recognized as those that could pose a real threat to their users' hearing safety [6-10]. Current methods of noise-induction hearing loss estimation are based mainly on the equal energy hypothesis [5]. Such an approach focuses on assessment of energy quantity affecting the hearing system. The main emphasis is placed to the analysis of the A-weighted equivalent sound level, maximum A-weighted instantaneous sound level and the C-weighted instantaneous peak level for the assessment of impulsive noise. However, in many cases this approach could be insufficient. Numerous literature sources, including analysis of exposure to different types of noise, indicate that time and noise spectrum characteristics can have a direct implication in generating hearing loss [2]. Taking these data into consideration, a novel method of risk estimation of hearing impairment has been proposed by the authors. The proposed method constitutes quite a different approach to the problem of hearing risk

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estimation. It is based on the prediction of the temporary hearing loss that a person incurs due to a specific noise presence. In this paper the concept, implementation and practical use of the new type of noise dosimeter were presented. Their operation depends on the determination of the hearing effect induced by noise. The proposed method implemented in the form of the Psychoacoustic Noise Dosimeter (PND) can be applied to assessment of the noise impact on the hearing system for all kinds of noise exposure. The practical use of PND is possible as a part of the Multimedia Noise Monitoring System (MNMS). Results of noise measurements and simulations obtained in the different conditions are presented in Section 3.

2. Multimedia Noise Monitoring System

The experimental system designed for the continuous monitoring of acoustic climate of urban areas was developed and implemented. The assessment of environmental threats is performed based on online data, acquired through a grid of engineered monitoring stations. The system working architecture and designed monitoring station are shown in Fig. 1.

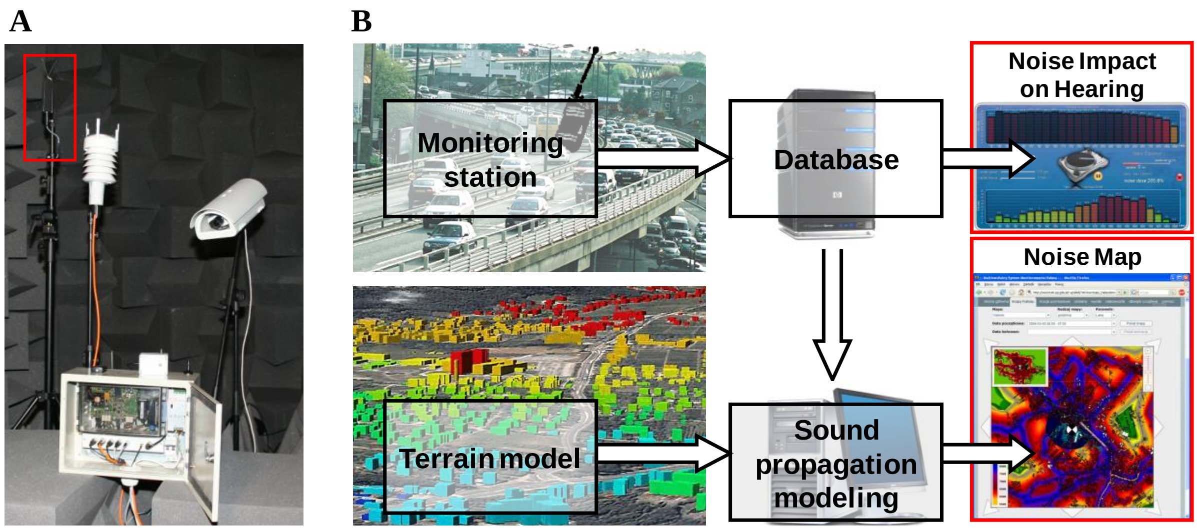

Fig. 1. Designed monitoring station with measuring environmental microphone indicated by red rectangle (A) and MNMS system architecture (B).

2.1. Measurement station

Each monitoring station is modularly designed to support various acquisition devices, i.e.: a noise meter, weather station, camera and air quality sensor. A high-resolution IP camera acquires image being further processed for obtaining desired information, e.g. traffic volume and characteristics. Weather conditions are known to contribute to the acoustic climate of a given area. Therefore the monitoring stations are equipped with meteorological stations. These devices measure typical parameters affecting noise propagation, such as: temperature, humidity, atmospheric pressure, wind velocity and direction, etc. Optionally, an installed air quality sensor acquires information about the concentration of benzene, fumes and all other harmful airborne factors. Due to the mobility, modular build and compact casing, that device may be used to monitor the acoustic climate in closed and opened spaces. Based on open source software components and utilizing a low-power consumption central unit, the discussed station is characterized by a low introduction and running costs. Moreover, acquiring comprehensive information about the acoustic climate, the grid of proposed devices may provide indispensable data for the purposes of long and short time acoustic analysis. The sensors in measurement stations deployed in the terrain acquire data continuously and transmit to the remote storage centre.

2.2. Data-gathering module

The discussed system is designed to create noise maps updated more frequently than strategic noise maps. This approach introduces a new feature which is called dynamic noise map. Strategic noise maps base on source data which originates from not frequently updated measurements and is averaged. In the presented system, parameters characterizing the source model are acquired through continuous measurements. The proposed concept is aimed at gathering non-acoustical parameters of a noise source from image analysis. This significant improvement of data acquisition allows keeping up-to-date short-term noise maps.

The data required for creating the noise map can be divided into static and dynamic ones. The former consists of mainly geodetic data and is provided as a numeric map. The latter consists of information gathered by the grid of monitoring stations. It is determined by the acquisition capabilities of a given station and mostly include traffic parameters and weather information.

The discussed static data define all architectural barriers propagating sound wave may encounter when passing through or is reflected from those barriers. Moreover, it contains a ground elevation model and may define the ground type in the specified location. The most important layers describe buildings and locations of acoustic sources.

Dynamic data is utilized in noise source and noise prediction modelling. Each monitoring station is modularly designed to support various acquisition devices, i.e.: a noise meter, weather station, traffic camera. A specialized algorithm, developed by the Multimedia Systems Department, is capable of extracting information from images recorded by a camera [11]. Any noise source parameters originating from moving objects like trains or cars can be evaluated by the system. An advantage of this approach is the possibility of setting the camera in a wide range of angles and distances to the source making it easy to place it along a road or a railway, compared with traditional traffic measuring systems, e.g. [12]. The algorithm is capable of recognizing aumber of vehicles passing-by with classification of them into desired category groups, as well as determining the average speed of these vehicles. For the road noise source the above categories can be divided into light, medium and heavy vehicles according to their dimensions.

2.3. Noise map calculation module

Computation of sound level distribution in apecified urban area is realized by noise map calculation software optimized towards working on a supercomputer cluster. The latter is imposed by the fact that the complexity of computational procedures concerning modelling of an acoustic field is rather high [13]. Moreover, the concept of a dynamic noise map assumes that the acoustic disturbance in an urban area is determined and presented in some short time periods.

The procedure of preparing the noise map requires knowledge of source data and the propagation environment. The model for calculating the acoustic field distribution in an urban area is based on the acoustic ray tracing method. Considering source models, we need to note that road and railway noise is the most frequent type of disturbance that people are exposed to [1]. The road noise source and the propagation model were based on the Harmonoise model [14, 15]. That model was expected to provide a basis for the development of a common method for environmental noise mapping in Europe.

Achieving a tolerable time of computation of dynamic noise maps required implementation of a method for parallel data processing. The applied method of noise modeling has such advantage that the sound level can be estimated at each point of the input grid, independently. In the discussed system the computer cluster named "Galera" installed at the Academic Computer Centre of Gdansk University of Technology is employed to perform parallel computations.

The authors developed their own code of the noise prediction model based on open source programming libraries. The main engine of the propagation model includes the implementation of the acoustic ray tracing method [16, 17]. The Point-to-Point programming library, developed by the Harmonoise project is aiding computation of the acoustic pressure attenuation occurring between a single source point and the receiver point. The data related to noise distribution in a specified region appear in the form of text or of a raster image.

For exploiting the computer cluster capabilities, a master-slave parallel programming paradigm was applied in connection with the MPI programming standard to achieve a proper load balance of cluster's cores. Implementation details of the software called Noise Prediction Model (NPM) employing the Harmonoise model were described in our earlier papers [18, 19]. The final step in the noise mapping process is the presentation of sound level distribution in an urban area. The output of the noise calculation module is presented in the form of vector graphics, constituting a novel approach while compared to the commonly used solutions presenting noise maps in the form of raster images. The discussed charts can be viewed by users in the prepared www service. The algorithms employed for visualization are thoroughly described in our paper [18].

2.4. Estimation of noise influence on the hearing module

Another unique feature of the system, which has a great importance for utilization in practice, is the elaborated conception of a psychoacoustic noise dosimeter. The construction of the dosimeter is based on utilizing a modified psychoacoustic model of hearing and on the results of research on the impact of noise on hearing, performed with participation of

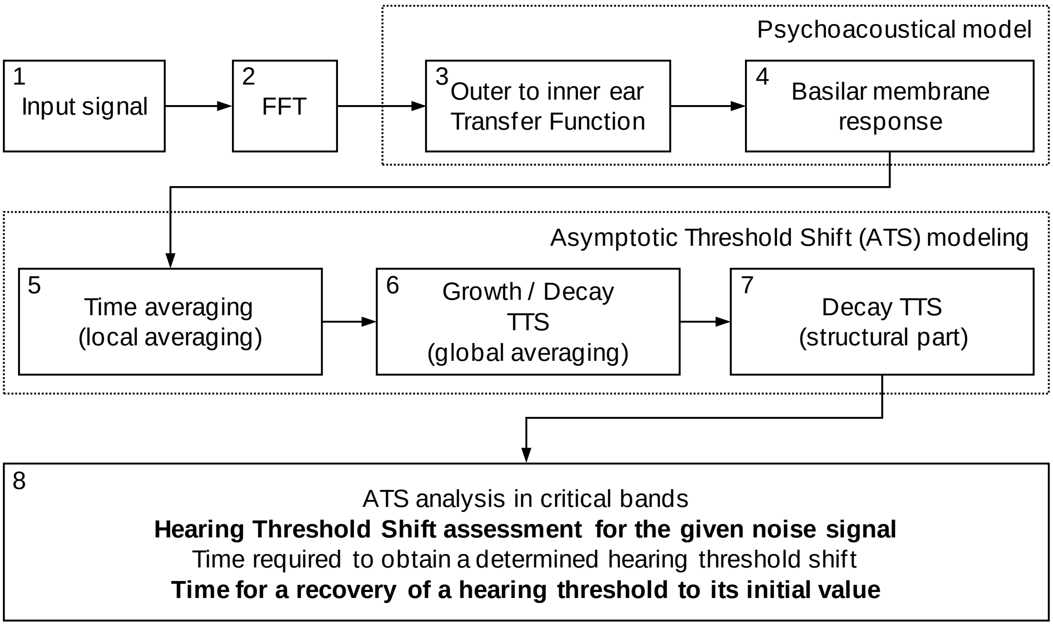

Fig. 2. Block diagram of a psychophysiological noise dosimeter.

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volunteers. The primary function of the dosimeter is to estimate, in real time, auditory effects which are caused by the exposure to noise. Fig. 2 depicts a general block diagram of the psychoacoustic model of the noise dosimeter.

Owing to that it is possible to recognize a character of the auditory threshold shift for a particular type of noise. Additionally, the dosimeter defines the time remaining to reach an acceptable auditory threshold shift. What is very important, the time which is necessary to restore the original auditory threshold is also being defined. Consequently, it is possible with this function to define hearing threats precisely in any acoustic conditions. Special procedures included in the system make it also possible to specify frequencies posing the main threat to hearing. The dosimeter was implemented specifically into the monitoring station as well as in the widespread SWF format. The above solution offers access to the application via every web browser.

Hitherto, a noise dose was determined based on the aggregate acoustic energy that a person experiences in a certain acoustic environment. The proposed method constitutes quite a different approach. It concentrates on the prediction of hearing fatigue that a person incurs due to the presence of specific noise. The method takes into account the processes occurring in the inner ear. Based on the measurement of the instantaneous acoustic pressure, the Temporary Threshold Shift (TTS) is determined. In the proposed solution, the modified Johnston's psychoacoustic model is used [20]. It enables to determine the global/maximal basilar membrane motion.

PND performance is based on the analysis of the basilar membrane response to noise in the critical bands of hearing [20]. In the first step, a spectrum of the signal power is computed using the Fast Fourier Transform (FFT) (block 2). Then (in block 3), the spectrum is corrected by the outer to the inner ear transfer function. In step 4, spectral factors are grouped into critical bands using the Bark scale. Next, signal levels in different bands are determined, and the result reflects the excitation of the basilar membrane. Its response is calculated through multiplexing levels of instantaneous excitation by the characteristics of the auditory filters relevant to particular critical bands. The obtained value of the basilar membrane deflection is then exponentially averaged. Such an operation reflects the inertia of the processes occurring in the inner ear. The averaged values are used to resolve the Asymptotic Threshold Shift (ATS) level [21].

The ATS modeling block consists of three parts (blocks 5, 6, 7). In the following step, the instantaneous ATS values are fed to block 5 which simulates the acoustic reflex mechanism. The algorithm used in this block averages the ATS level locally, operating accordingly to the time of the acoustic reflex duration. In practice, it enables maintaining the ATS level temporarily (local averaging), especially when the ATS level changes are abrupt. Such situations happen when a sudden change of the signal level occurs in sound. In this way, the processed ATS values are exponentially averaged (block 6), reflecting the process of Temporary Threshold Shift of hearing (global averaging) during the noise exposure [21]. Block 7 is activated right after the exposure is finished, when the level of noise does not cause a TTS effect anymore. The block's task is to reflect the changes in the process of TTS fading in response to mechanic strain put on delicate cochlea structures. The block is activated by the level of TTS existing at the moment the exposure is stopped.

Block 8 produces final results, ready to be presented and stored in a file. Thus, the model enables determining TTS values in critical bands, the time elapsing till the specified hearing threshold occurs, and the time necessary to restore the initial value of the hearing threshold. The proposed dosimeter has also a very important feature, namely the ability to specify the shift of the hearing threshold at the time of exposure to a specified type of noise.

3. Experiments and results

The results of exploiting the Multimedia Noise Monitoring System are discussed in this section. The examples given here concern various types of noise and measurement procedures. In case of long-term measurements, the noise generated by the road traffic and the acoustic climate in a school were regarded. The short-term measurement results were illustrated by the noise present in the workplace and in the club. The Multimedia Noise Monitoring System has the extended functionality allowing not only for a versatile measurement of the acoustic climate and their effects on human hearing. In turn, the discussed system provides also simulations of assumed acoustic conditions. It is illustrated on an example of the outdoor concert. For this type of event, the map of distribution of the sound level generated by a loudspeaker system was calculated. Moreover, the temporary threshold shift that could happen to people attending the concert was estimated and presented in the form of a map.

3.1. Long term noise measurement of road noise

A series of long-term measurements was carried out in a village outside Gdansk near a straight section of a national road. The analysis of outcomes of the measurements which have been made during 10 consecutive months (from January to October) is presented below. The L_{Aeq} factor and the number of vehicles (averaging time equals one hour) were taken into consideration during the long-term continuous noise measurements. In Fig. 3 and in Fig. 4 the long-term noise levels and the traffic flow for each hour of the day and for selected days of a week was presented.

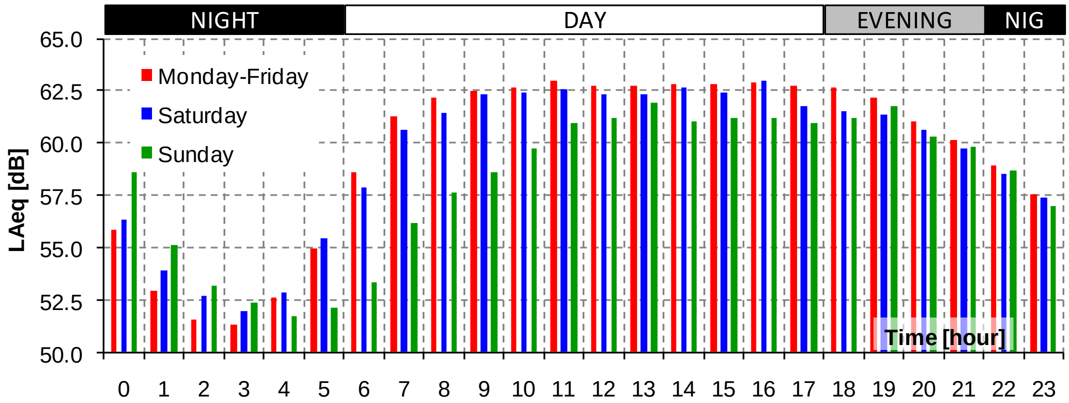

Fig. 3. Long-term noise measurement results for each hour of the day for selected days of a week.

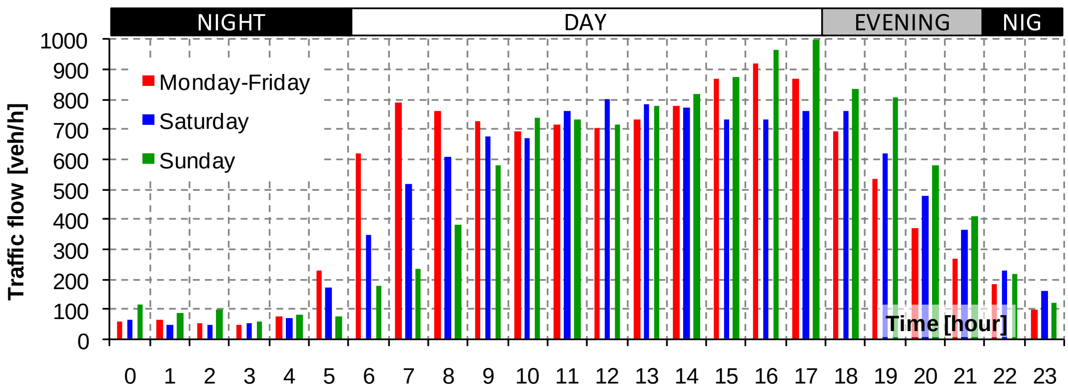

Fig. 4. Long-term traffic flow measurement results for each hour of the day for selected days of a week.

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For the considered road we can observe a high repeatability of noise levels from Monday to Friday. The greater differences can by noticed for Saturday and the greatest for Sunday. Such differences are the result of the character of the traffic flow. During the night from Saturday to Sunday we noticed an intensified traffic flow in comparison to other nights.

The dynamic noise maps for the road noise source, created by the Multimedia Noise Monitoring System are presented in Fig. 5 and in Fig. 6. The input data for calculation of the road noise source model emission level were provided by the monitoring station equipped with an image analysis module. Emission of noise for the typical workday in the case of various hours (4 AM, 12 PM, 8 PM) is presented in Fig. 5. Noise level distribution on 8 AM in case of workdays, Saturdays and Sundays is illustrated in Fig. 6.

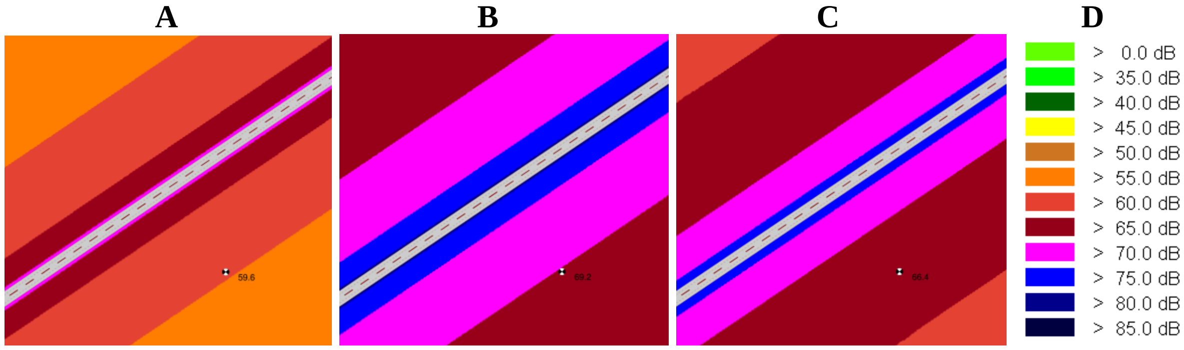

Fig. 5. Noise maps computed for road noise source for different time-periods based on measured traffic flow (averaged values observed from Monday to Friday)
A – acoustic conditions for 4 AM, B – 12 AM, C –8 PM. Part D – legend of noise levels

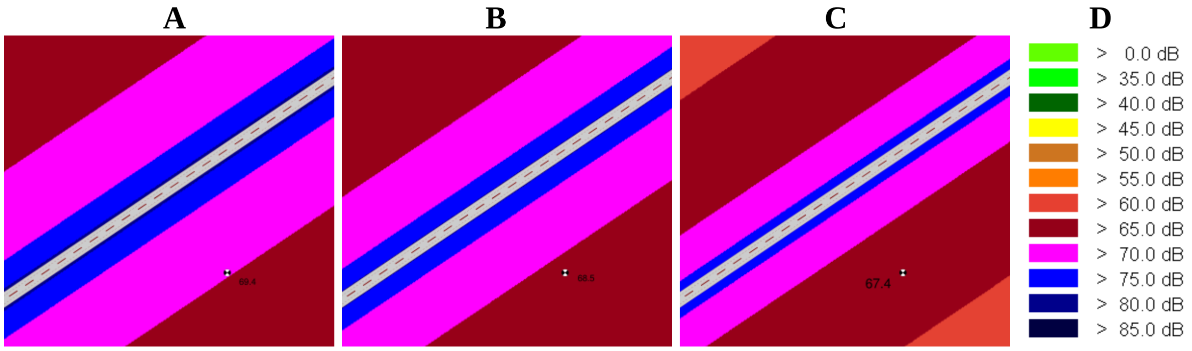

Fig. 6. Noise maps computed for road noise source for different time-periods based on measured traffic flow (averaged values observed on 8 AM, for different days of a week). A – acoustic conditions observed from Monday to Friday, B – Saturday, C – Sunday, D – legend of noise levels.

3.2. Long term noise measurement in selected school

The results of long-term continuous noise measurements made in two selected schools are presented in the paper. Noise characteristics were measured continuously there for approximately 16 months. Measurements started eight months prior to the acoustic adaptation of the school corridors of both schools. An evaluation of the acoustic climates in both schools, before and after the acoustic treatment, was performed based on the comparison of those two periods of continuous measurements. The autonomous noise monitoring stations, engineered at the Multimedia Systems Department of the Gdansk University of Technology were used for this purpose. Investigations of measured noise, especially its influence on the hearing sense, assessed on the basis of spectral analyses in critical bands, are discussed. Effects of occupational noise exposure, including the Temporary Threshold Shift simulation, were determined.

Before making an improvement of the sound levels in corridors, noise levels in the schools discussed were very high, especially during breaks between lessons. The A-weighted equivalent sound level, averaged over a one minute period often exceeded 90 dB, the A-weighted maximum noise level during every break between lessons exceeded 100 dB (see Fig. 7).

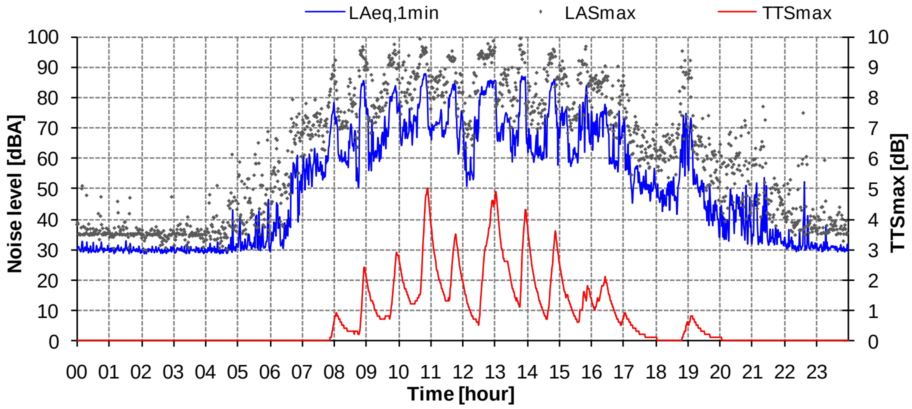

Fig. 7. Noise levels (equivalent and maximum values) and maximum instantaneous values of the TTS effect caused by noise for school 2 - the whole day. A sample 5-day average exposure (before adaptation).

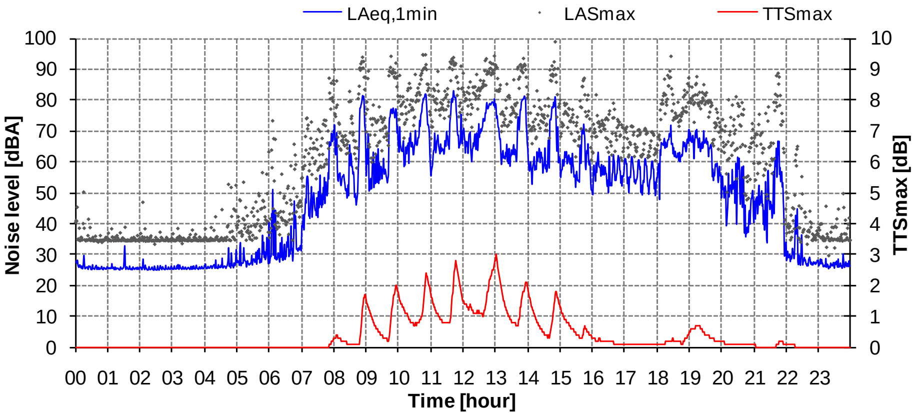

Fig. 8. Noise levels (equivalent and maximum values) and maximum instantaneous values of the TTS effect caused by noise for school 2 - the whole day. A sample 5-day average exposure (after acoustic adaptation).

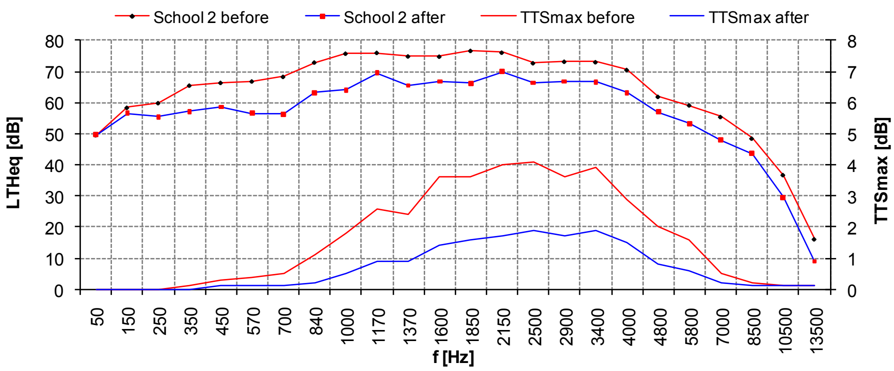

Fig. 9. Equivalent level of noise in critical bands corrected according to Therhard's transfer function from outer to inner ear and maximum values of the TTS effect evoked by noise during breaks among lessons, before and after the acoustic treatment.

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Fig. 8 presents results of the equivalent noise level and the TTS analysis after the acoustic adaptation of the ceiling. The equivalent level LAeq, 1min has been reduced, thus it does not exceed 82 dB anymore. The existence of the acoustic treatment of corridors has also a significant influence on decreasing the TTS effect by 3 dB during breaks. It should be emphasized strongly that before the change of the acoustic characteristics of the school corridors, large TTS values were observed in frequency ranges essential to speech perception (frequency band from 1600 to 3400 Hz). After the refitting of the corridors, the TTS in the mentioned band decreased nearly twice. The graphical illustration of this situation is provided in Fig. 9.

3.3. Short-term noise measurement at the workplace and in a musical club

The use case of the Multimedia Noise Monitoring System for the short-term measurements along with evaluation of harmfulness of noise was depicted by two examples of exposing people to a high sound level. The first example concerns the noise observed in a workplace and the second one focuses on a typical effect of visiting a music club [10, 22]. Such a comparison of noise emitted by industrial sources and music club acoustical sources is intentional. In both places the observed noise level, denoted by the equivalent sound level averaged for 1 minute, A-weighted, reaches 100 dB. Such a high noise level causes a real threat for the hearing system of the people being exposed to noise. In case of the workplace the employer is obliged by regulations to provide hearing protection solutions to the employees. In contrast to the latter, such a protection is usually not used by the people attending the music clubs.

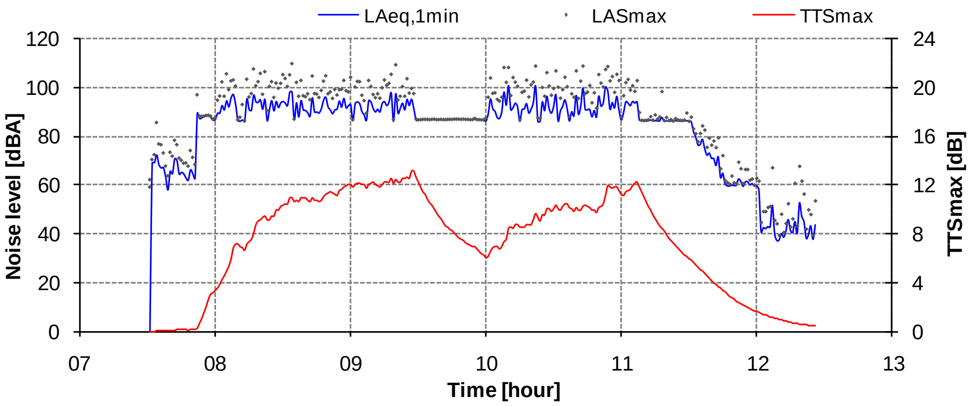

Fig. 10. Noise levels (equivalent and maximum values) and maximum instantaneous values of the TTS effect caused by noise produced by an industrial mill during its operation.

It should be noticed that exposition to a loud sound can cause shifting of the hearing threshold of more than 15 dB after about 90 minutes of exposition. This outcome was achieved for the considered music club. In the other clubs, acoustic conditions can be even more adverse.

A comparison of the noise level in critical bands in case of exposition to industrial noise and in the music club is presented in Fig. 12. It should be noticed that despite the smaller noise level in the club, a much higher shift of the hearing threshold occurred there. It is caused by the continuous impact of noise. In case of industrial noise, a 30-minute break occurred during the exposition (see Fig. 10), which has minimized the harmful effect of noise to hearing. Therefore, an advice for enthusiasts for loud music listeners can be formulated, namely taking breaks during the exposition are essential for reduction of the risk of hearing degradation.

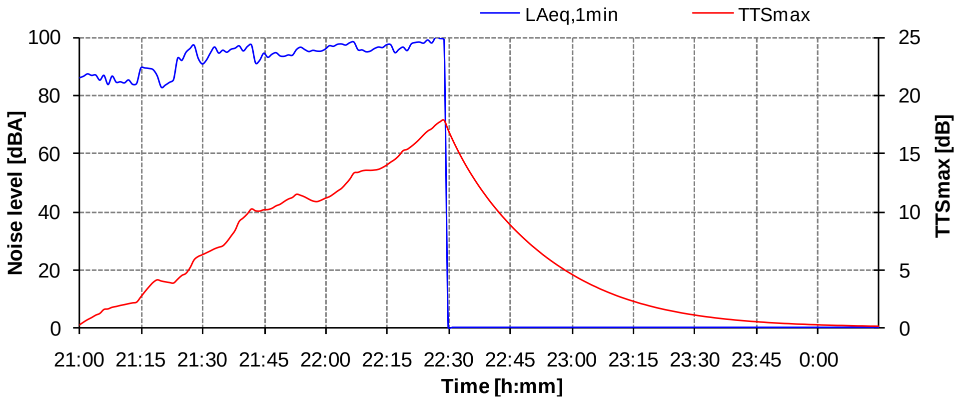

Fig. 11. Equivalent noise levels and maximum instantaneous values of the TTS effect caused by noise observed in typical student club during the 90 minutes exposure.

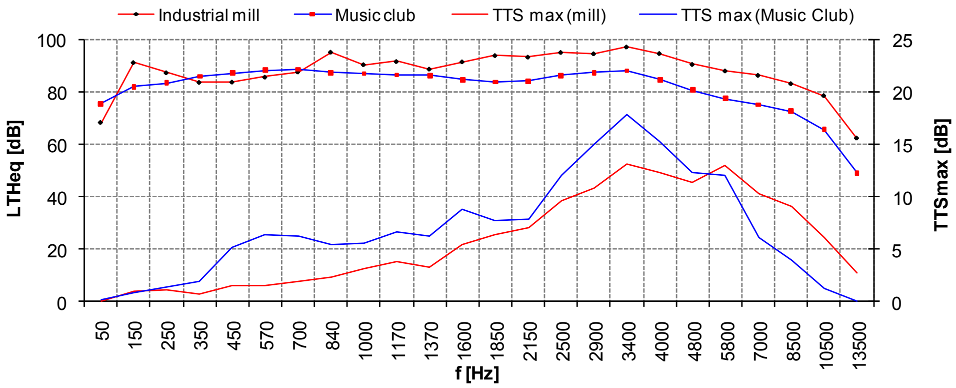

Fig. 12. Equivalent level of noise in the critical bands corrected according to Therhard's transfer function from outer to inner ear and maximum values of the TTS effect evoked by noise during exposure in two different conditions: at work (the red lines - industrial mill), at typical student musical club (the blue lines).

3.4. Simulation of noise exposure during an outdoors concert

A simulation of outdoor concert acoustic conditions was performed. The considered auditory area was of 100 x 100 meters. The stage width was 20 m. Two loudspeakers were located at both sides, between the stage and auditory at 2 m distance. The assumed duration of the concert was 3 hours. The sound source spectral characteristics was similar to the one measured in the music club and the sound level was 120 dB. The simulation results are presented in the form of a map of sound level distribution as a function of distance from the stage and as a map of predicted maximum temporary shift of the hearing threshold (for all frequency ranges). The above-mentioned outcomes are depicted in Fig. 13. The spectrum distribution of the acoustic energy of the noise source and the TTS effect evoked by the exposure to that noise expressed in critical bands of hearing as a function of the distance from the noise source is presented in Fig. 14.

The observed temporary threshold shift exceeding 20 dB extends in a radius of about 20 meters from the center of the stage. The hearing recovery time required for the people being present in this area is 450 minutes. The safe area which can be regarded as distant from the stage lies about 70 meters away of this stage, where the TTS is kept at the level of 5 dB.

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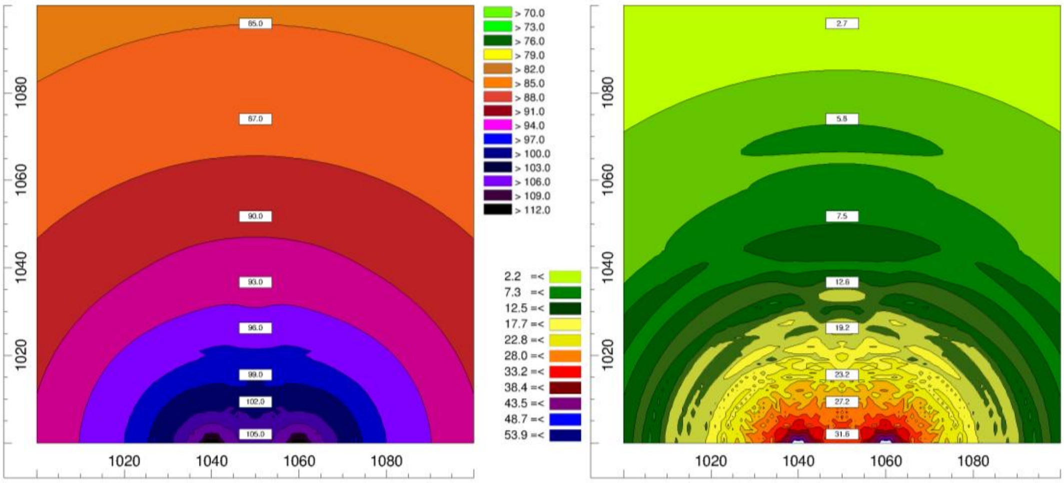

Fig. 13. Noise map for the outdoor loud acoustic event (open field musical concert) – left, and the map of maximum TTS values that could be evoked in the considered acoustic condition – right

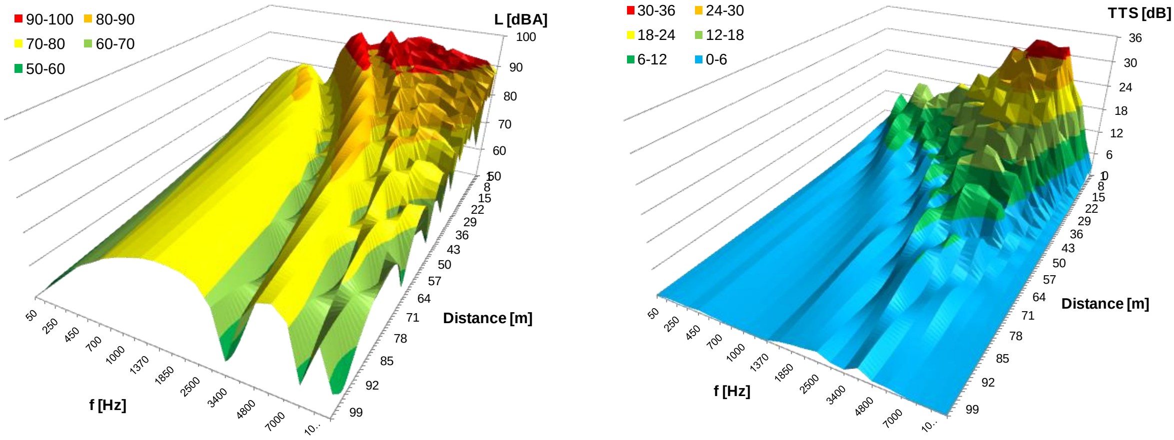

Fig. 14. Spectrum distribution of acoustic energy of noise source (left) and TTS effect evoked by the exposure to that noise expressed in critical bands as a function of distance from the noise source (right).

5. Conclusions

Considering the obtained results it was shown that the estimation of harmful effects produced by noise exposures is possible and can be done in real time. As it was shown on the basis of different kinds of real measurement data prepared for various noise sources, the application of the presented Psychoacoustic Noise Dosimeter and its functionality connected with displaying the influence of noise to the hearing system evoked by the noise exposure may significantly enrich the knowledge on noise-induced effects. The designed and implemented algorithm, owing to its functionality, can have many practical applications to hearing conservation programs related to preventing occupational noise diseases. Information about the degree of the hearing threshold shift induced during the noise exposure can positively influence the effectiveness of occupational noise control methods. That was the main reason for implementing the designed algorithm to the monitoring station proving a part of the Multimedia Noise Monitoring System engineered at the Multimedia Systems Department.

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