ARCHIVES OF ACOUSTICS
**33**, 4, 435–440 (2008)

# THE NOISE-INDUCED HARMFUL EFFECT ASSESSMENT BASED ON THE PROPERTIES OF THE HUMAN HEARING SYSTEM

Józef KOTUS[1], Bożena KOSTEK[1],[2]

[1] Gdańsk University of Technology
Multimedia Systems Department
Narutowicza 11/12, 80-952 Gdańsk, Poland
e-mail: {joseph, bozenka}@sound.eti.pg.gda.pl

[2] Institute of Physiology and Pathology of Hearing
Excellence Center PROKSIM
Warszawa, Poland

(*received June 15, 2008; accepted November 5, 2008*)

In this paper a new method of assessing noise-induced harmful effects on the human hearing system is described. The method proposed determines the cumulative impact on hearing system produced by the excessive noise taking into consideration properties of the human hearing system. Based on the predicted effects of the noise exposure, the new types of noise indicators are engineered. The evaluation of these indicators employed various types of noise. The indicators proposed can improve assessment of the harmful effect caused by the noise exposure. An influence of the type of the critical band representation of the hearing system (Bark or ERB scales) on the noise indicator effectivness is also discussed.

**Keywords:** noise, temporary threshold shift, noise indicators, psychoacoustic noise dosimeter.

## 1. Introduction

This paper presents a new method of assessing noise-induced risk of a hearing loss. It seems important to recall first current definitions of the noise exposure limits. U.S. National Institute for Occupational Safety and Health (NIOSH), the current U.S. Occupational Safety and Health Administration (OSHA) Hearing Conservation Amendment as well as European regulations assess risk of hearing loss by determining the amount of noise received by a person during the workday expressed as a percentage of a certain reference level for a given duration. Occupational safety organizations recommend that the maximum exposure to noise is 40 hours per week at 85 to 90 dB(A). For every additional 3 dB(A), the maximum exposure time is reduced by a factor of 2, e.g. 20 hours per week at 88 dB(A). Sometimes, a factor of 2 per additional 5 dB(A) is used. However, these occupational regulations are recognized by the health literature as inadequate to protect against hearing loss and other health effects, especially for sensitive individuals. The usual allowable noise dose is typically set at 100% dose equivalent to an equivalent continuous noise level of 90 A weighted dB over a standard 8-hour working day. Other noise levels exist that are considered to represent the 100% noise dose but the time interval is almost always the 8 hour day. Daily 8-hour (or longer) time-weighted average (TWA) personal noise exposures or Daily Personal Noise Exposure level, which express the maximum duration of exposure permitted for various noise levels are frequent definitions for noise-induced adverse effects on health.

As mentioned already currently a noise dose is determined based on the aggregated acoustic energy that a person experiences in a certain acoustic environment. Such approach focuses mainly on the assessment of the amount of energy having a direct impact on the human hearing system [4]. The time characteristics of noise are ignored while the main emphasis is put on the equivalent noise level. Based on the available literature sources [1, 3, 14], it is important to emphasize that, both time and the spectrum characteristics may significantly contribute to hearing loss [7, 14]. Having this in mind the authors proposed a new method of the hearing impairment risk estimation [5, 6]. Taking features of the hearing system into account [8, 10], it concentrates on the prediction of the noise dose that a person is subjected due to the specific noise exposure.

## 2. Psychoacoustical noise dosimeter

Figure 1 depicts a general block diagram of the psychoacoustical noise dosimeter. In the first step, a spectrum of the signal power is determined using the Fast Fourier Transform (FFT) (block 2). Then (in block 3), the spectrum is conditioned by the outer

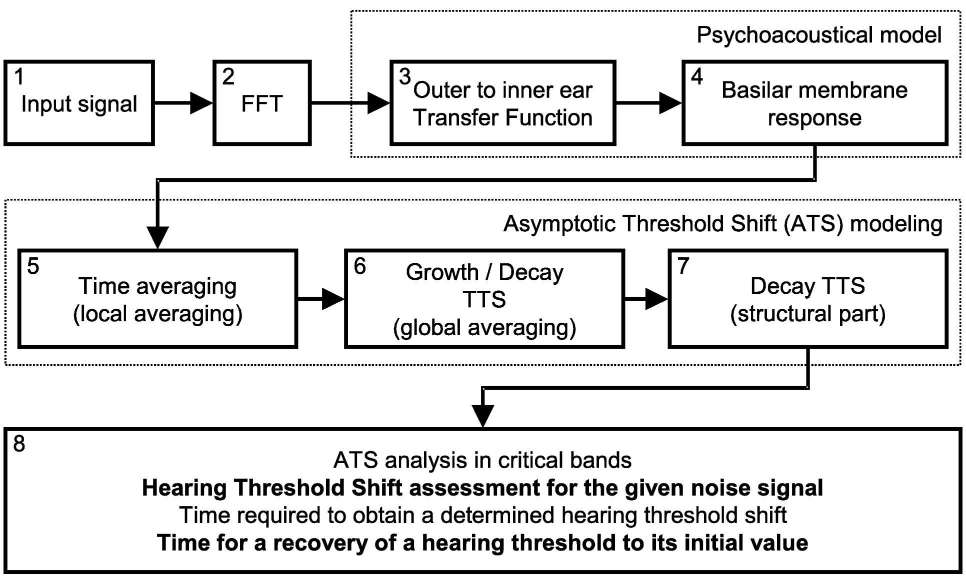


Fig. 1. Block diagram of the psychophysiological noise dosimeter (PND).

to the inner ear transfer function [10]. In step 4, spectral factors are grouped into critical bands using Bark scale [8]. Next, signal levels in different bands are determined, and the result reflects the excitation of the basilar membrane. The averaged values are used to estimate the Asymptotic Threshold Shift (ATS) level [11]. The ATS modeling block consists of three parts (blocks 5, 6, 7). In the following step, the instantaneous ATS values are fed to the block 5 which simulates the acoustic reflex mechanism. The algorithm used in this block averages the ATS level locally, operating accordingly to the acoustic reflex duration. Such situations happen when a sudden change of a signal level occurs in a sound. In this way, the processed ATS values are exponentially averaged (block 6), which reflects the process of Temporary Threshold Shift (TTS) of hearing (global averaging) during the noise exposure. Block 7 is activated right after the exposure is finished, when the level of noise does not cause TTS effect any more. The block task is to reflect changes in the TTS process fading out phase 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 stored in a file or presented on a display.

## 3. Noise indicators related to hearing loss

The new concept of noise dosimetry utilizes a simple psychoacoustic model to determine the effects of exposure to excessive noise levels [10]. Such result-based approach to dosimetry leads to the assumption that the occurrence of the TTS effect is an inexpedient reaction. This assumption was the basis for the definition of two new indicators of noise-induced hearing damages. Indicator $L_{JK}$ (Eq. (1)) is constructed through summing up the values of the TTS for particular frequencies at time intervals of one minute. The proposed indicator needs summing the TTS values over all critical bands. Subtracting 1 from the result of TTS level change assures that 0 TTS value on a linear scale is equal to 0 TTS on the decibel scale [2]. This is due to the very important physical interpretation. If the values were added without the subtraction, then 0 dB TTS would be 1 on a linear scale. Adding the value of 1, when TTS does not occur leads to false values of the indicator that mistakenly suggests great threat to hearing. Thus, subtracting 1 from TTS solves the problem. The $1/N$ factor was introduced to make the results independent from the number of considered bands. Using the indicator $L_{JK}$, it is possible to determine the absolute aggregate value of the hearing threshold shift caused by a defined exposure to noise, and it is done in conjunction with the time of the shift duration. The absolute value does not provide any direct information about the harmfulness of the particular exposure neither does it show the degree of exceeding the limit of the noise dose. For the clarity of interpretation, a parameter $D_{JK}$ was introduced that reflects the amount of hearing threshold shift (Eq. (2)).

$$L_{JK} = \frac{1}{N} \sum_{t=0}^{T+T_R} \sum_{i=0}^{N} \left( 10^{\frac{L_{\mathrm{TTS}}(i,t)}{10}} - 1 \right), \tag{1}$$

where $N$ – the number of analyzed critical bands (24 critical bands), $T$ – exposure time (expressed in minutes), $T_R$ – resting time (time required for hearing recovery), $L_{\text{TTS}}(i,t)$ – instantaneous value of the TTS level for $i$-th critical band and for time $t$.

$$D_{JK} = \frac{L_{JK\text{Exp}}}{L_{JK100}} \cdot 100\%, \tag{2}$$

where $L_{JK\text{Exp}}$ – absolute value of the $L_{JK}$ indicator for given noise exposure, $L_{JK100}$ – value of the $L_{JK}$ indicator for the reference exposure.

The experimental verification of the proposed indicators was done based on simulations using three types of noise: white, pink and brown [9]. It is assumed that each signal carries the same amount of energy, which is referenced to the 8-hour work day and is expressed by the $L_{Aeq}$ indicator. The obtained simulation results for proposed $D_{JK}$ indicator, which specifies the degree of noise harmfulness with respect to reference level (brown noise, 85 dBA, 8 h), were presented in Table 1. A tendency that noise having spectra with high levels of high frequencies are greater threat to the inner ear than those of the low-frequency character is clearly visible. It is consistent with the literature sources related to noise exposure [12]. The tendency does not depend on the noise level.

**Table 1.** The relative values, expressed by means the $D_{JK}$ indicator (expressed in [%]).

| Type of noise | The noise level expressed in dBA, time in minutes | | | | | |
|---|---|---|---|---|---|---|
| | 85 / 480 | 88 / 240 | 91 / 120 | 94 / 60 | 97 / 30 | 100 / 15 |
| White noise | 498 | 632 | 770 | 707 | 362 | 119 |
| Pink noise | 309 | 376 | 448 | 429 | 250 | 98 |
| Brown noise | **100** | 110 | 122 | 121 | 91 | 51 |

## 4. Critical band scale representation

The application of the critical band scale determined in the Bark takes the opportunity of the detailed calculations of the Temporary Threshold Shift levels in all audible frequency range. That is why the Zwicker's Bark scale was suitable to use in the PND algorithm engineered especially because the ranges of the critical bands are precisely determined and covered whole audible range [8]. However, it is important to emphasize that the application of the different scale of the critical bands range in the PND model, for example expressed in ERB (Equivalent Rectangle Bandwidth) [13], proposed by Glasberg and Moore, is also possible. In Fig. 2 the critical band bandwidth comparison for ERB and Bark scale was presented. As presented in Fig. 2, Bark and ERB scales are quite compatible, especially for middle and high frequencies [13]. The essential differences between these scales are observed mainly for the lowest frequencies. If the ERB scale had been used in the PND algorithm, the new distribution of the critical band for the whole audible range would be required. Larger number of critical bands should also be required. It is important to notice that in the construction of the $L_{JK}$ indicator the normalized factor was introduced. It means that the value obtained using the $L_{JK}$ indicator is independent of the number of bands applied. It takes also into account a different number of bands in computation of these indicators (and the characteristics of the TTS effect). Moreover, bands could be also determined for different frequency ranges (eg. for 1/3 octave bands or determined by the ERB scale). It means that the applied scale of the critical bands bandwidth does not constitute a significant factor in the main idea of the indicators considered and for computations of the harmfulness effect caused by the noise exposure. Moreover, the Bark scale used in the PND algorithm has a big advantage due to its easy practical implementation and a good correspondence with the psychoacoustical model of the hearing system.

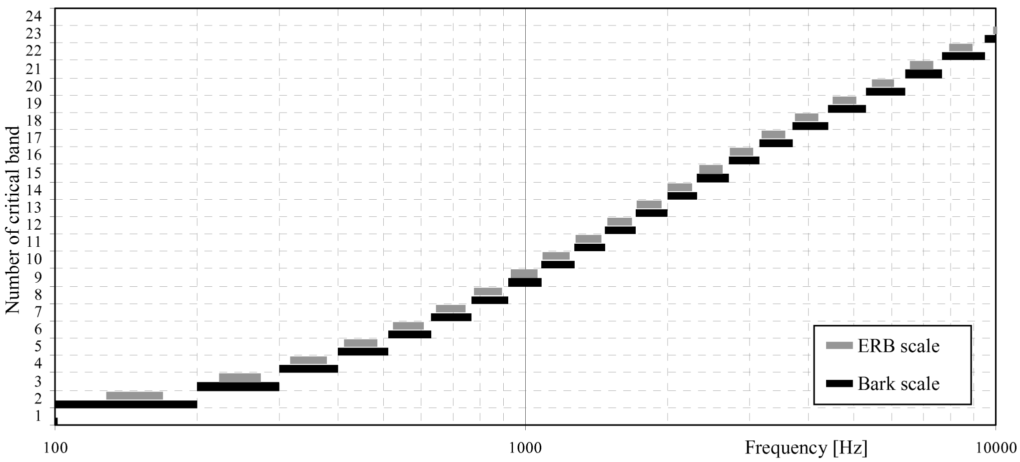


Fig. 2. The critical band bandwidth comparison of the Bark and ERB scales.

## 5. Conclusion

It is worth emphasizing, that the indicators proposed by the authors illustrate a novel approach to the noise threat assessment. Although psychoacoustically motivated sound analysis systems have already been proposed in the literature (e.g. Fastl), their purpose being to simulate hearing sensations in sound measurement systems, the potential of such systems has not yet been transferred to the domain of assessing noise-induced harmful effects.

The construction of the indicators proposed in this paper is based on the analysis (namely the TTS effect occurrence) of noise influence on an average listener's hearing. Although, the TTS effect depends on the level of noise, the way it forms and fades out is related to the manner the acoustic energy is distributed over hearing range and it depends on a particular listener's vulnerability to acoustic harm. The application of the presented Psychoacoustic Noise Dosimeter and new indicators may significantly enrich the knowledge on noise-induced effects. This was the main reason to implement the algorithm engineered in a monitoring station of the Noise Monitoring System designed at the Multimedia Systems Department.

## Acknowledgments

This work was partially supported by the Polish Ministry of Science and Education within the project No. R0201001.

This article is a revised version of the paper presented at the Open Seminar on Acoustics 2008.

## References

[1] Ahroon W.A., Hamernik R.P., Davis R.I., *Complex noise exposures: An energy analysis*, J. Acoust. Soc. Am., **93**, 2, 997–1006 (1993).

[2] Bies D.A., Hansen C.H., *An alternative mathematical description of the relationship between noise exposure and hearing loss*, J. Acoust. Soc. Am., **88**, 6, 2743–2754 (1990).

[3] Borg E., Engstrom B., *Noise level, inner hair cell damage, audiometric features and equal-energy hypothesis*, J. Acoust. Soc. Am., **86**, 5, 1776–1782 (1989).

[4] *Criteria for a recommended standard, Occupational Noise Exposure*, U.S. Department of Health and Human Services, June, 1998.

[5] Czyżewski A., Kotus J., Kostek B., *Application of the psychoacoustic noise dosimeter for the determination of noise impact on hearing*, Proceedings INTER–NOISE 2007, 28–31 August, Istanbul, Turkey 2007.

[6] Czyżewski A., Kotus J., Kostek B., *Determining the noise impact on hearing employing psychoacoustical noise dosimeter*, Archives of Acoustics, **32**, 2, 203–217 (2007).

[7] Emmerich E., Richter F., Linss V., Linss W., *Frequency-specific cochlear damage in guinea pig after exposure to different types of realistic industrial noise*, Hearing Research, **201**, 90–98 (2005).

[8] Fastl H, Zwicker E., *Psychoacoustics – Facts and Models*, Springer, Third Edition, 2006.

[9] http://www.mediacollege.com/audio/noise/

[10] Johnston J.D., *Transform Coding of Audio Signals Using Perceptual Noise Criteria*, IEEE Journal on Selected Areas in Communications, **62**, 314–323 (1988).

[11] Melnick W., *Human temporary threshold shift (TTS) and damage risk*, J. Acoust. Soc. Am., **90**, 1, 147–154 (1991).

[12] Ordoñez R., Hammershøi D., *Effects of frequency content from exposures with the same A – weighted equivalent level*, Proceedings INTER–NOISE 2006, 3–6 December, Honolulu, Hawaii, USA 2006.

[13] Smith J.O. III, Abel J.S., *Bark and ERB bilinear transforms*, IEEE Transactions on Speech and Audio Processing, **7**, 6, 697–708 (1999).

[14] Strasser H., Chiu M.-C., Irle H., Grünig T., *Threshold Shifts and Restitution of the Hearing After Energy – Equivalent Narrow – Band And Wide-Band Noise Exposures*, Proceedings INTER–NOISE 2007, 28–31 August, Istanbul, Turkey 2007.