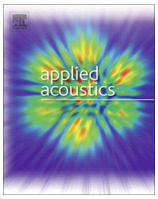
Applied Acoustics 103 (2016) 30–36

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust



Development and validation of a new adaptive weighting for auditory risk assessment of complex noise

Pengfei Sun [a], Jun Qin [a,*], Wei Qiu [b]

[a] Department of Electrical and Computer Engineering, Southern Illinois University, Carbondale, IL 62901, USA
[b] Auditory Research Laboratories, State University of New York at Plattsburgh, NY 12901, USA

ARTICLE INFO

Article history:
Received 8 May 2015
Received in revised form 8 October 2015
Accepted 8 October 2015
Available online 24 October 2015

Keywords:
Noise-induced hearing loss
Complex noise
A-weighting
C-weighting
Noise metrics
Kurtosis

ABSTRACT

Noise-induced hearing loss (NIHL) still remains as a serious occupational related health problem worldwide. A-weighted equivalent sound pressure level (SPL) L_{Aeq} has been widely used to assess the auditory risk of occupational noises in noise measurements standards. In addition, C-weighting is also used in the standards for detection of peak SPL of noise. However, both A-weighting and C-weighting have limitations on evaluation of high-level complex noise, which is often experienced in many military and industrial fields. In this study, we proposed a new adaptive weighting (F-weighting) for more accurate evaluation of complex noises. F-weighting is based on the blending of A-weighting and C-weighting through the weighting coefficients $\alpha_{A,T}$ and $\alpha_{C,T}$. To determine $\alpha_{A,T}$ and $\alpha_{C,T}$, two parameters, kurtosis (K_T) and oscillation coefficient (O_T) were introduced. Complex noise exposures in animal studies and noise signals measured in a mining facility were applied to validate the performance of F-weighting. The results show that F-weighting performs better than both A-weighting and C-weighting on the assessment of high-level complex noise. In addition, F-weighting based L_{Feq} shows higher correlation with the hearing loss of the animal experimental data compared with A-weighted L_{Aeq}, C-weighted L_{Ceq}, and Non-weighted L_{eq}. The proposed F-weighting could be a potential alternative weighting for the assessment of high-level complex noise in military and industrial applications.

1. Introduction

According to the World Health Organization (WHO), noise-induced hearing loss (NIHL) is one of the most common occupational related health problems worldwide. Exposure to excessive noise is the major avoidable cause of permanent hearing loss [1]. In the United States, an estimated 22 million workers are exposed to noise loud enough to be potentially hazardous [2]. Over time exposure to hazardous noise levels can result in damage to the hair cells in the cochlea. The eventual result is a permanent shift of hearing threshold, known as NIHL.

Noise can be classified into steady-state noise (*i.e.*, continuous Gaussian noise), impulsive noise, which includes impulse noise and impact noise, and complex noise, in which impulsive noise are embedded within steady-state noise [3–6]. All types of noises at high exposure levels could cause hearing loss. Animal studies showed that high-level complex noise could produce more hearing loss than steady-state noise with same equivalent energy [7–10]. Occupational noise exposures in various military and industrial fields are often subjected to high-level complex noise, which contains both stead-state and impulsive components.

The current noise measurement guidelines in the standards [11,12] were developed based on the Equal Energy Hypothesis (EEH), which states that NIHL mainly depends on the total acoustic energy of the noise exposure [13]. A-weighted equivalent sound pressure level (SPL), L_{Aeq}, has been used as the primary metric to assess the noise exposure levels. However, numerous researches on NIHL have indicated that L_{Aeq} is appropriate for steady-state noise but not for impulsive and complex noises [14–18].

In addition, the current standards used A-weighting for the calculation of equivalent SPL, and C-weighting for detection of the peak SPL. In 1961, the ISO/TC 43 proposed the noise rating curve, NR-85, as the limit for habitual workday exposure to broadband noise. Various frequency-dependent filters (*e.g.*, A-weighted and C-weighted filters) were introduced to mimic the frequency responses of the human auditory organ [19]. A-weighting, $AW(f)$, and C-weighting, $CW(f)$, can be expressed as following two equations, respectively [17].

---

* Corresponding author at: Department of Electrical and Computer Engineering, Southern Illinois University Carbondale, Mail Code 6603, 1230 Lincoln Drive, Carbondale, IL 62901, USA. Tel.: +1 (618) 453 3460; fax: +1 (618) 453 7972.

E-mail address: jqin@siu.edu (J. Qin).

http://dx.doi.org/10.1016/j.apacoust.2015.10.004
0003-682X/

$$AW(f) = K_A \frac{(f/f_1)^2}{1+(f/f_1)^2} \frac{\frac{f}{f_1}}{\sqrt{1+(f/f_2)^2}} \frac{\frac{f}{f_3}}{\sqrt{1+(f/f_3)^2}} \frac{1}{1+(f/f_4)^2} \tag{1}$$

$$CW(f) = K_C \frac{(f/f_1)^2}{1+(f/f_1)^2} \frac{1}{1+(f/f_4)^2} \tag{2}$$

where K_A, K_C, f_1, f_2, f_3 and f_4 are given by the following approximate values: $K_A = 1.258905$, $K_C = 1.007152$, $f_1 = 20.60$ Hz, $f_2 = 107.7$ Hz, $f_3 = 737.9$ Hz, $f_4 = 12194$ Hz. Both A-weighting and C-weighting are defined to have unity gain at 1 kHz. The corresponding gain in decibel may be obtained by $L_{weight}(f) = 20 \log(w(f))$, where $w(f)$ are the weightings.

The curve of C-weighting is quite flat at a very broad bandwidth, while the curve of A-weighting shows a great reduction at low frequency (<400 Hz) [17]. Therefore, the C-weighed filter retains most of the acoustic energy over frequency range 20–1 kHz, while the A-weighted filter only counts a little acoustic energy at low frequency. Previous studies showed that A-weighted filter is more appropriate at low SPLs, while C-weighted filter follows the frequency sensitivity of the human ear at high SPLs according to equal loudness contours [20].

For the steady-state noise, averaged energy might be well followed the A-weighted frequency-gain curve (FGC) due to the relative low SPL. However, in a complex noise, the peak SPLs of impulsive components could exceed the range (>90 dB) of the equal loudness contour which A-weighted filter is derived from. Therefore, the A-weighted FGC may not be appropriate for high-level impulsive components, and the C-weighted FGC may more accurately capture the peak SPL of such impulsive components [17,21]. Due to their abbreviated form, both A-weighting and C-weighting may not be appropriate for accurate assessment of a complex noise, which contains both steady-state and impulsive noise components. To evaluate the risk of hearing loss induced by complex noise exposures effectively, it is necessary and meaningful to develop an improved weighting that is suitable for both steady-state and impulsive noise components of complex noise [22,23].

In this study, we proposed a new adaptive F-weighting for the assessment of auditory risk caused by the complex noise. The proposed F-weighting is based on blending of A-weighting and C-weighting with assigning two different weighting coefficients $\alpha_{A,T}$ and $\alpha_{C,T}$, respectively. Two parameters, kurtosis (K_T) and the oscillation coefficient (O_T), were introduced to describe the steady-state and impulsive components in complex noises. A series of experimental animal noise exposure data, were utilized to validate the effectiveness of L_{Feq} on hearing loss prediction. Furthermore, noise signals measured in a mining facility were also used to evaluate performance of F-weighting on assessment of high-level complex noise in industrial fields.

2. Methods and materials

2.1. Two parameters for noise evaluation: K_T and O_T

Kurtosis as a statistic value can be defined as the ratio of the fourth-order central moment to the squared second-order moment of the amplitude distribution. The time domain kurtosis (K_T) was expressed as:

$$K_T = \frac{\frac{1}{N}\sum_{n=1}^{N}(x_n - \bar{x})^4}{\left(\frac{1}{N}\sum_{n=1}^{N}(x_n - \bar{x})^2\right)^2} \tag{3}$$

where x_n refers to the data point, and index 'T' refers to each time segmentation ΔT, it includes N data points. Kurtosis was used as a measure of the "peakedness" of the noise exposures. A large kurtosis implied to more impulsive components in a complex noise. The kurtosis of a Gaussian noise (*i.e.*, steady-state noise) is 3. Both kurtosis and energy level are necessary to evaluate the hazard posed to hearing by a complex noise exposure [3,24,25].

Another parameter, oscillation coefficient (O_T), is introduced to calculate the energy density distribution of a complex noise in this study. O_T is derived from the concept of the Teager energy operator (TEO), which has been frequently used to obtain the energy density distribution of a signal [26]. O_T is relevant to the local transition level and frequency of a complex noise signal. In addition, O_T is a statistical parameter, and is independent from sampling rate of a signal. The oscillation coefficient O_T can be defined as:

$$O_T = \frac{\sum_{n=2}^{N-1}|(x_n - x_{n-1})(x_n - x_{n+1})|}{\sum_{n=2}^{N-1}x_n^2} \tag{4}$$

Eq. (4) focuses on the transitions between the differential values of adjacent data points in a noise signal. The product of differential values reflects the strength of local transitions. Two factors are relevant to O_T: frequency and transition strength (*i.e.*, the differential pressures for adjacent points). Both factors are correlated with hearing loss, and stronger transitions in a short time period could potentially lead to more serious hearing loss [27].

2.2. Development of adaptive F-weighting

As mentioned above that A-weighting is appropriate for steady-state noise while C-weighting is more suitable for impulsive noise. Thus neither A-weighting nor C-weighting could be appropriate for all types of complex noises. In this study, we propose a new adaptive weighting (F-weighting), which is based on blending of A-weighting and C-weighting. F-weighting takes the advantages of A-weighting and C-weighting, and it can achieve an universal criterion for evaluation of different types of complex noises.

The proposed F-weighting was defined as:

$$P_{Feq}(t) = \alpha_{A,T}(AW(t) * P(t)) + \alpha_{C,T}(CW(t) * P(t)) \tag{5}$$

where $AW(t)$ and $CW(t)$ refer to the A-weighed and C-weighted filters, respectively. '*' represents convolution calculating. The parameters, $\alpha_{A,T}$ and $\alpha_{C,T}$, are the weighting coefficients of A-weighting and C-weighting, respectively. Both $\alpha_{A,T}$ and $\alpha_{C,T}$ reflect the energy distribution of steady-state components and impulsive components in a complex noise signal. Since K_T and O_T are parameters correlated with hearing loss, the weighting coefficients $\alpha_{A,T}$ and $\alpha_{C,T}$ are defined as functions of K_T and O_T as below:

$$\alpha_{A,T} = \exp(\beta K_T O_T)\frac{1}{|\ln(O_T)| + 1} \tag{6}$$

$$\alpha_{C,T} = \exp(\beta K_T O_T)\frac{|\ln(O_T)|}{|\ln(O_T)| + 1} \tag{7}$$

Both $\alpha_{A,T}$ and $\alpha_{C,T}$ can be considered as the product of two components: the amplify component, referring as $\exp(\beta K_T O_T)$ and the oscillation components, $\frac{1}{|\ln(O_T)|+1}$ or $\frac{|\ln(O_T)|}{|\ln(O_T)|+1}$, respectively. The amplify component depends on both K_T and O_T. The β is a small positive constant to let the amplify component approximately equal to 1 for Gaussian noise ($K_T = 3$ and $O_T = 1$), and it was set as 0.01 in this study. Moreover, the oscillation components only depend on O_T, and they reflect the frequency information in a complex noise. When at low frequency ($0 < O_T < 1/e$), $\frac{1}{|\ln(O_T)|+1} < \frac{|\ln(O_T)|}{|\ln(O_T)|+1}$,