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A sound quality model for objective synthesis evaluation of vehicle interior noise based on artificial neural network

Y.S. Wang*, G.Q. Shen, Y.F. Xing

School of Automotive Engineering, Shanghai University of Engineering Science, Shanghai 201620, China

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ABSTRACT

Based on the artificial neural network (ANN) technique, an objective sound quality evaluation (SQE) model for synthesis annoyance of vehicle interior noises is presented in this paper. According to the standard named GB/T18697, firstly, the interior noises under different working conditions of a sample vehicle are measured and saved in a noise database. Some mathematical models for loudness, sharpness and roughness of the measured vehicle noises are established and performed by Matlab programming. Sound qualities of the vehicle interior noises are also estimated by jury tests following the anchored semantic differential (ASD) procedure. Using the objective and subjective evaluation results, furthermore, an ANN-based model for synthetical annoyance evaluation of vehicle noises, so-called ANN-SAE, is developed. Finally, the ANN-SAE model is proved by some verification tests with the leave-one-out algorithm. The results suggest that the proposed ANN-SAE model is accurate and effective and can be directly used to estimate sound quality of the vehicle interior noises, which is very helpful for vehicle acoustical designs and improvements. The ANN-SAE approach may be extended to deal with other sound-related fields for product quality evaluations in SQE engineering.

1. Introduction

With the improvement of people's living quality, the problem of noise pollution has been catching the public concerns. Vehicle noise, which constitutes about 85 percent of city transportation noise, is one of the foremost sources of environmental noise pollution. Vehicle interior noises have increased the incidence rate of traffic accidents, due to their physiological and psychological effects on vehicle drivers. Thus, a large number of researches about SQE of vehicle noises have been conducted in the past few decades [1–3].

To evaluate the quality of a sound, some psychoacoustic indices, such as loudness, sharpness, roughness, fluctuation strength, etc., have been introduced in SQE engineering [4,5]. The concept of sound quality was recently defined by Blauert as the anthropic appropriateness of sounds under a specific technical target or task [6]. For sound loudness rating, the equal-loudness contours were first measured by Fletcher and Munson in 1933, and later adopted by the standard ISO 532B. Furthermore, a new experimental determination was made by Robinson and Dadson, which was believed to be more accurate and became the basis for a standard ISO 226. Mathematically, from 1970s, many calculation algorithms and procedures for the other psychoacoustical indices, such as sharpness, roughness and fluctuation strength, were proverbially

* Correspondence to: School of Automotive Engineering, Shanghai University of Engineering Science, No. 333, Longteng Road, Songjiang District, Shanghai 201620, China. Tel.: +86 21 67791149; fax: +86 21 67791152.
E-mail address: jzwbt@163.com (Y.S. Wang).

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studied and published in some literatures [4,7,8]. Till now, only the equal-loudness-contours based Zwicker loudness model is widely accepted and the standard ISO 532B has been applied in some commercial programs. The sharpness model has passed round robin tests. For roughness calculation, however, there is no any mathematical model was completely recognized. As references, Fastl obtained the roughness values by calculating the modulation frequency and excitation differential of a sound [7]. The specific roughness of each auditory channel was carried out by Aures, using the calculated modulation index in each critical band [8]. Sottek computed the roughness considering nonlinear characteristics and autocorrelations within the excitation envelope of the sounds [9]. Based on Aures model, Daniel and Weber considered the phase differences and carrier frequencies between the critical bands, which made an obviously improvement of accuracy of the sound roughness model [10].

In the view of general evaluation of a sound, a lot of theoretical and experimental results suggest that the pleasantness or annoyance (human sensation) is closely related to the psychoacoustical parameters. Zwicker combined the loudness, sharpness and fluctuation strength and presented a model of unbiased annoyance [4]. Accordingly, a concept of psychoacoustical annoyance was defined by adding the roughness into the annoyance model [11]. In applications, a psychoacoustic model for overall evaluation of a voice was proposed, considering the effect factors, such as vocal tract formant frequencies, bandwidths and source spectral slope parameters, etc. [12]. The psychoacoustical parameters (loudness and sharpness) of refrigerator noises were evaluated and discussed by introducing the autocorrelation functions in real living environments [13]. The sound preference of the car closing door noises were investigated [14]. The results suggested that sound preference is mainly related to the timbre parameters (frequency balance and cleanness), not the loudness. It has been found that most of the in-situ models for pleasantness or annoyance are based on the algorithm of multiple linear regressions. The linear approximation may inevitably result in some errors, due to the complex nonlinear relationship between the psychoacoustical parameters and the human perception of auditory. It is thus necessary to develop substitution methods for mapping the objective evaluation parameters to the subjective sensations in the SQE engineering.

In the field of vehicle engineering, a large research effort related to SQE of vehicle noises has been performed, which have been proven useful in vehicle acoustical designs, especially in the areas of engine noise, interior noise, door-slam quality, air-conditioning sound, and axle gear noise [15–18]. The timbre description principles were successfully used for classifying the sounds of car interior, air-conditioning unit, horn, and closing door by performing a multinomial logistic regression procedure [19]. The artificial neural network (ANN) has been applied in developing annoyance index for quality evaluation of the stationary sounds [20–22]. The booming and rumbling sounds in passenger cars were objectively evaluated by using the ANN techniques [21,22], in which the booming and rumbling indices of the interior were introduced into vehicle SQE; and the correlation between sound metrics and subjective evaluated results were studied. The ANN approach for subjective evaluation of soundscape quality in urban open spaces has also been investigated [23]. More recently, some SQE methods based on wavelet analysis and/or neural network techniques, for estimating the weighted sound pressure levels (SPLs), loudness and sharpness of nonstationary vehicle noises were developed and performed [24–27]. In these works, it has been found that, due to the algorithm complexity and time-consumption in network trainings, the proposed techniques can only be used to evaluate the psychoacoustical indices separately, and cannot give the overall evaluation of a nonstationary sound. As supplementary, it is both necessary and useful to find a new approach for synthesis indices of sounds, such as pleasantness and/or annoyance.

From the above discussion, we concluded that sound perception as a neural response of humans is an ambiguous and statistical concept, depending on individual differences in perception among people; the objective SQE methods in common use cannot specify all sound sensations of human being; and it is very difficult to establish an exact mathematical model for mapping all of the psychoacoustical indices to a synthesis feeling of sounds, especially for the nonstationary sound signals. Based on a sample passenger car, a new SQE technique named ANN-SAE model for overall annoyance evaluation of vehicle interior noises is developed in this paper. Both the stationary and the nonstationary noise signals are considered in the modeling procedure. Thus, the model may be directly used for evaluating sound quality of the sample vehicle working under the conditions of constant speed and/or acceleration. In view of the application, the ANN-SAE technique may be possibly extended to more general cases for sound quality evaluations in other sound-related fields in engineering.

2. Theory of artificial neural networks

The ANN, a mathematical model inspired by biological neural networks, is composed of many simple, densely interconnected nonlinear computational elements (artificial neurons) operating in parallel. The feedback network with multilayered perceptrons, which allows signals to travel in both directions by introducing loops into the network, is very powerful and commonly used in engineering. In this work, a supervised feed-forward ANN with three-layer perceptrons is presented and shown in Fig. 1. The inputs are multiplied by related weights and are summed and then passed through a sigmoid function. The sample $\{x_k\}$ is fed to the network and produces an output $\{y\}$. The input pattern $\{x_k\}$ is propagated through the network in the following way:

$$y_i^{(2)} = f\left(\sum_{j=1}^{M} w_{ij}^{(2)} y_j^{(1)}\right) = f\left(\sum_{j=1}^{M} w_{ij}^{(2)} f\left(\sum_{k=1}^{N} w_{jk}^{(1)} x_k\right)\right) \tag{1}$$