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Modelling for sound annoyance evaluation of vehicle noise based on neural network

***Abstract**. Based on the neural network (NN) technique, a new sound quality evaluation (SQE) model for synthetical annoyance of vehicle noises is proposed in this paper. Based on the measured noise signals of a sample vehicle, the psychoacoustical models for loudness, sharpness and roughness are investigated. Annoyance values of the measured vehicle noises are estimated by a jury test following an anchor-scaled scoring method. A NN-based model for annoyance evaluation of vehicle noise, so-called VNA-NNM, is carried out. Finally, the VNA-NNM model is verified by the leave-one-out algorithm. The results suggest that the VNA-NNM model is accurate and effective for estimating sound quality of vehicle interior noises, which is instructive and useful for vehicle acoustical designs.*

***Streszczenie.** Zaproponowano model oceny jakości dźwięku i rozdrażnienia dźwiękiem szumu samochodowego. Model bazuje na sieciach neuronowych i wykorzystuje zmierzony sygnał szumu samochodowego oraz model psychoakustyczny. (**Modelowanie dźwięków drażniących pochodzących od pojazdów mechanicznych z wykorzystaniem sieci neuronowych**)*

Keywords: Vehicle Noise, Sound Quality Evaluation, Synthetical Annoyance, Neural Network.
Słowa kluczowe: szum samochodowy, sieci neuronowe.

Introduction

Reduction of the ever-increasing environmental noise levels may improve sound quality and thereby our quality of life. Vehicle noises, which constitute about 40 percent of city environmental noise, have been considered in the past few decades, and vehicle noise control has become an active research area [1-3]. As found that vehicle interior noise increases the probability of traffic accidents, due to their physiological and psychological effects on vehicle drivers.

The majority of problems in vehicle acoustics concern acoustic comfort, not hearing damage. To evaluate sound quality, the psychoacoustic indices, such as the loudness, sharpness, roughness, fluctuation strength, etc., have been introduced in SQE engineering [4,5]. For sound loudness rating, the equal-loudness contours were first measured presented and later adopted by the standard ISO 532B. From 1970s, many calculation algorithms and procedures for the sharpness, roughness and fluctuation strength were studied and published in literatures [6,7]. The sharpness model has passed round robin tests. However, there still is no any mathematical algorithm for roughness can be completely recognized by the public. As references, the roughness models proposed by Fastl and Aures for sound roughness have been widely cited and adopted by literatures and commercial software [7,8]. It has been found that the sound pleasantness or annoyance is closely related to the psychoacoustical indices4. Thus, it is very useful to develop a new method for mapping the psychoacoustical indices to the human sensations in the SQE engineering. A large number of researches related to vehicle SQE have been performed [9,10]. Recently, the time-frequency analysis and the NN technologies were introduced for estimations of the sound pressure level, loudness and sharpness of nonstationary vehicle noises [11,12]. One may found that the methods proposed in these works cannot give overall evaluation index of a sound, such as the pleasantness or annoyance. As supplementary, it is also necessary to find new methods for sound synthetical evaluation. Therefore, in this paper we present a new SQE method, so-called VNA-NNM, for annoyance evaluation of vehicle noises, based on the NN technique. In view of the applications, The VNA-NNM method may be used to evaluate and compare sound quality of vehicles.

Vehicle noise measurement

In this present work, sample vehicle interior noises were prepared using the binaural recording technique with a signal length of 12 seconds and a sampling rate of 44100 Hz. The experimental conditions were set following the standard GB/T18697 [13]. An asphalt four-lane highway is selected as the test road. Around the test site, there have no sound reflecting buildings and other objects within 50 meters. A Volkswagen 1.6L Lavida was used as the sample vehicle in the measurements, and its working conditions were set at the idle and constant speeds from 30 to 90 km/h with an interval of 5 km/h. Under each working condition, the noise signals from the seats of driver, assistant driver and rear passenger are measured by using the B&K Pulse data acquisition system and saved in the computer in formats of ".mat" and ".wav", respectively. During measuring, the microphones were arranged at 0 or 0.2 meters from the centerline of the seats with a height of 0.7 meters, depending on the seated conditions, as those shown in Fig. 1. The total SNRs of the measured signals are above 25 dB. We totally saved 42 signals, which are prepared for both the objective and subjective evaluations of vehicle noises as follows.

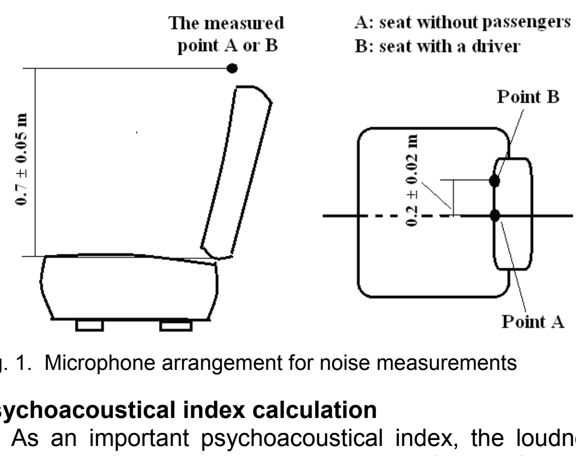

Fig. 1. Microphone arrangement for noise measurements

Psychoacoustical index calculation

As an important psychoacoustical index, the loudness depends on both sound intensity and the filtering functions of human auditory system. According to the standard ISO 532B [14], the specific loudness of a sound is defined as,

(1) $$N' = 0.08\left(\frac{E_{TQ}}{E_0}\right)^{0.23}\left[\left(0.5 + 0.5\frac{E}{E_{TQ}}\right)^{0.23} - 1\right]$$

where: N' – specific loudness, E – excitation of the sound, E_{TQ} – excitation in the quiet ambient, E_0 – excitation under a reference sound with intensity of I_0=10^{-12}*W*/*m*^{2}.

The total loudness can be calculated by,

(2) $$N = \int_0^{24Bark} N' dz$$

where: N – total loudness in sone, z – critical band rate in Bark.

From the calculated specific loudness of the interior noises in this work, a conclusion can be drawn that the loudness of vehicle noise is mainly distributed in the low frequency range below 5 Bark (500 Hz).

The sharpness reflects the degree of stridence of a sound. Based on the calculated specific loudness, specific sharpness S' in acum/Bark can be computed as,

(3) $$S' = 0.11 \frac{\int_0^{24Bark} N' g(z) z dz}{\int_0^{24Bark} N' dz}$$

where: *g*(*z*) – the weighting function.

The total sharpness S can be obtained by integrating the specific sharpness,

(4) $$S = \int_0^{24Bark} S' dz$$

As known that the roughness has a strong effect on annoyance sensation of sounds. A procedure combined by the Aures' and Daniel's models with a slight modification is performed in this study, as shown in Fig. 2. The sample noise signals are firstly cut in a set of successive frames with length of 200 ms. The FFT is performed for each frame, using Hanning window. Considering the transfer function of human auditory system, the frequency components of each frame are transformed into excitation patterns, by some overlapping critical band filters with 1 Bark bandwidth and center frequencies at $z_i = 0.5i$ Bark, i is band (channel) number (i=1, 2, …, 47). The calculated excitation levels are first weighted by the band-pass filters (BPFs) and then transformed into specific excitation time signal $e_i(t)$ by an inverse FFT (IFFT). The demodulated signal of $e_i(t)$ is represented as $e_{mi}(t)$. The weighting BPFs H_i (i=1, 5, 16, 21,42) is shown in Fig. 3. The weighting coefficients in other channels are defined in Table 1. For the ith channel, the modulation index can be computed as,

(5) $$m_i = \frac{rms_{ami}}{rms_{bmi}}$$

where: rms_{bmi} – root mean square before modulation, rms_{ami} – root mean square after modulation.

An impact factor representing phase effects of the (i-1)th and (i+1) channels on the ith channel can be defined as,

(6) $$c_i = c_{i-1} \times c_{i+1}$$

where: c_i – phase impact factor in the ith channel, c_{i-1} and c_{i+1} – correlation coefficients of the signal $e_{mi}(t)$ with those in the (i-1)th and (i+1) channels, respectively.

Thus, specific roughness in the ith channel R_i is,

(7) $$R_i = (g_i \times c_i \times m_i)^2$$

where: g_i – weighting of carrier frequency in the ith channel.

The weighting coefficients of all channels are shown in Fig. 4. the total roughness R may be computed,

(8) $$R = 0.25 \sum_{i=1}^{47} R_i$$

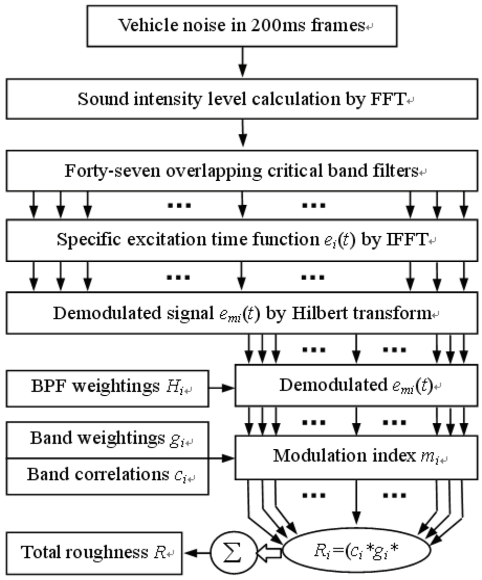

Fig. 2. A schematic diagram for roughness calculation

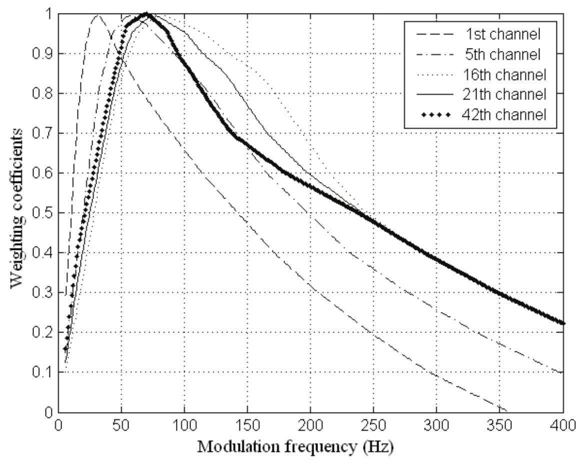

Fig. 3. The weighting coefficients with respect to modulation frequency H_i (i=1,5,16,21,42).

Table 1. Weighting Definitions for frequency modulation

Channel i	2-4	6-15	17-20	22-41	43-47
H_i	H_1	H_5	H_{16}	H_{21}	H_{42}

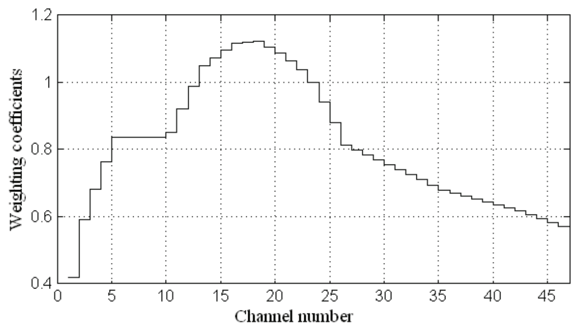

Fig. 4. The weighting coefficients of carrier frequencies

Table 2. Annoyance grade definitions in the jury test

Grade #	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Scores	1.0	2.0	3.0	4.0	5.0

Table 3. The subjective and objective SQE results

Signal #	Loudness (sone)	Sharpness (acum)	Roughness (asper)	Annoyance score
1	6.77	1.08	0.76	1.29
2	25.21	0.68	0.32	3.43
3	28.06	0.61	0.38	3.57
⋮	⋮	⋮	⋮	⋮
41	15.80	0.59	0.14	2.14
42	17.74	0.61	0.27	2.43

Jury test

A jury test of the measured vehicle noises for annoyance evaluation is conducted in this paper. A jury consists of 25 volunteers is organized by considering the physical and mental conditions, hearing experience of the estimators [15]. The high-precision headphones are used in the jury test. To eliminate effect of personal preference, a scale scoring method with anchor stimulus is performed in this work. Firstly, according to the calculated values of total loudness, sharpness and roughness of the measured vehicle noises, the signals with intermediate values of each psychoacoustical index are selected as anchor noises; and their subjective rating scores are defined as 3.0. Then, the noise signals for evaluating in the jury test with the same length of 11 seconds are dealt with by the Cooledit software. Each of these signals is sequentially combined by 5 seconds of an anchor signal, one second mute and 5 seconds of a signal for evaluation. During the jury testing of a vehicle noise, the estimators may first listen to an anchor sound and then the target noise. After hearing, a rating score can be given according to the estimators feeling of annoyance in Table 2. The total values of loudness, sharpness and roughness calculated in the above objective evaluations and the rating scores obtained in the jury test of the measured interior noises are listed in Table 3, where the annoyance score of each signal is the averaged value of the rating results of all estimators.

Modeling and verification

A three-layer NN is established as that seen in Fig. 5. The input layer has three neurons: the total loudness $LOUD$, sharpness $SHARP$ and roughness $ROUGH$. For training the neural network, an input matrix for each signal is defined as,

(9) $$I = [LOUD \quad SHARP \quad ROUGH]^T$$

For a network training with n signals, the dimension of the input matrix can be extended to $3 \times n$. In this paper, we take 35 signals from the measured interior noises to train the neural network, i.e., n=35. The output layer with one neuron is the annoyance rating score of the jury test.

The output matrix O for NN training has a dimension of 1×35 . Neuron number of the hidden layer is determined by the following empirical formula,

(10) $$H = \sqrt{I + O} + C$$

where: H – the neuron number in the hidden layer, C – a constant, C=1-10.

One may calculate H equals to 3-12. To find an optimal value of H, a set of training tests are carried out by assuming H values from 3 to 16. The results show that, when H equals to 11, the trained NN obtained a minimum averaged error.

The NN training procedure is conducted by a Matlab program. Due to the nonlinear characteristics of human auditory system, the nonlinear tangent sigmoid function, gradient descent algorithm with momentum and the Levenberg-Marquardt back-propagation function are used. After training, the parameters in the neural network for annoyance evaluation of vehicle noises, so-called VNA-NNM, are finally determined. The training performance of the VNA-NNM is shown in Fig. 6. As seen that the model has a fast convergence speed and good stability.

The leave-one-out method is adopted to investigate the accuracy of the trained VNA-NNM. We, respectively, fed the total loudness, sharpness and roughness of the rest seven signals to the VNA-NNM model for annoyance simulation. The output results of the VNA-NNM model are compared with the annoyance rating scores obtained in jury test, as seen in Fig. 7 and Table 4. It may be found that, the VNA-NNM results are in accord with those from the subjective evaluations, and the maximum error is about 0.17 at the drive position under a vehicle running speed of 40 km/h. Error percentages of the seven signals are all below 7%, which implies a good accuracy of the VNA-NNM model in annoyance evaluation of the vehicle interior noises.

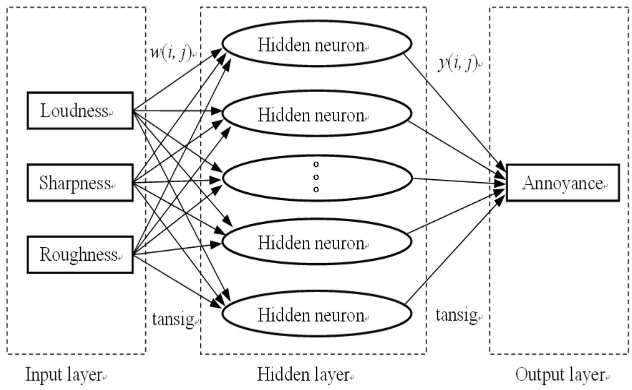

Fig. 5. The neural network structure with a hidden layer

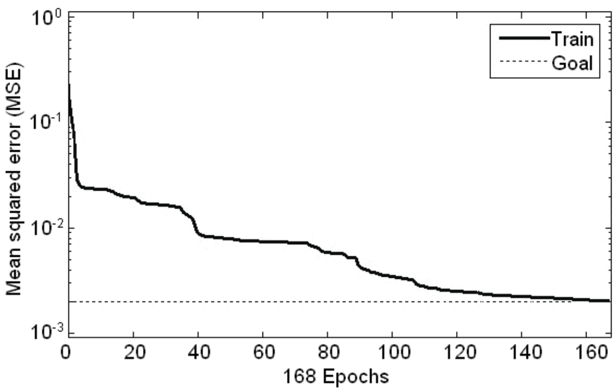

Fig. 6. Training performance of the VNA-NNM

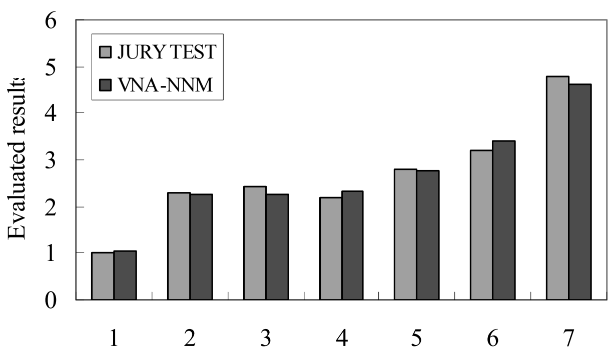

Fig. 7. Evaluated result comparisons of the annoyance from the VNA-NNM model and jury test

Table 4. Comparison of the results from the VNA-NNM model and jury test

Measured points	Speed (km/h)	Jury test	VNA-NNM	Error percent
Rear passenger	idle	1.00	1.05	5.3%
Front passenger	30	2.29	2.26	1.3%
Driver	40	2.43	2.26	7.0%
Driver	50	2.20	2.34	6.4%
Front passenger	60	2.80	2.76	1.3%
Front passenger	70	3.20	3.40	6.4%
Rear passenger	90	4.80	4.63	3.6%

Conclusions

This paper proposed an intelligent approach for evaluating annoyance of vehicle interior noises. The noise signals under different working conditions of a sample vehicle were measured and saved. The psychoacoustical indices, such as loudness, sharpness and roughness, were mathematically modeled and calculated. Using the anchor-scaled scoring method, the annoyances of the measured noises were estimated by jury test. Based on the evaluated results and neural network technique, the VNA-NNM, was developed for annoyance estimation of vehicle interior noises. Verifications suggest the newly developed VNA-NNM is accurate and effective for sound annoyance estimation of vehicle noises. Instead of the subjective SQE methods, the VNA-NNM model can be directly used to estimate and compare sound quality of vehicles, and its applications will be promising research topics in the future.

Acknowledgments. This work was supported by NSFC under Grant No. 51175320, and partly supported by the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning, China.

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