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Correlation Study on the Subjective and Objective Evaluation Indices of Sound Quality Based on Vehicle Noises

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Abstract: In this study, the automotive interior noises under various running conditions were acquired according to the standard GB/T 18697. Both the objective and subjective evaluations for sound quality of vehicle interior noises were conducted and the results were saved and analyzed. The results indicate that the psychoacoustic parameters, including loudness, sharpness and roughness obtained from the objective evaluations have a significant correlation with the annoyance acquired through subjective evaluation, but have little correlation with each other. The conclusions can be drawn that the loudness, sharpness, roughness may be regarded as independent indices for Sound Quality Evaluation (SQE) and the psychoacoustic parameters is more accurate to express human sense than the traditional SPL.

Keywords: Correlation coefficient, objective evaluation, sound quality, subjective evaluation, vehicle noise

INTRODUCTION

With the rapid development in noise reduction area, the consumers demand not only the vehicle with low noise level, but also with a pleasant and comfortable interior sound environment. Thus, the concept of sound quality has been introduced into the vehicle engineering field for reflecting the characteristics of the noise from the point of view of the human sense (Murata *et al*., 1993; Brandl and Biermayer, 1999; Lee *et al*., 2009). Generally say, the SQE approaches can be classified into two categories, i.e., objective and subjective evaluations. both of them have advantages and drawbacks. The researchers have been dedicating to develop new SQE models, which may combine the advantages of the two evaluation methods and can evaluate any types of vehicle noise rapidly and accurately (Trapenskas, 2002; Wang, 2009). However, due to the complex relationship between the psychoacoustical parameters and the human hearing, there still has no any approach can be completely recognized by public and directly used to map the objective evaluation parameters to subjective sensations. Therefore, based on some vehicle interior noises, an investigation on correlations between the subjective and objective evaluation parameters of sound quality is presented this study, which may be regarded as a reference in vehicle SQE engineering.

METHODOLOGY

Database establishment of vehicle interior noises: According to the standard GB/T 18697, the interior noises of a sample vehicle were measured firstly. The 5-channel PULSE data acquisition system with 1/2-inch microphones and Time Data Recorder software, which is developed by the B&K Corporation, is used for noise measurements in this present work. The positions of microphone are set as those in Fig. 1, following the experimental arrangements in the GB/T 18697 standard.

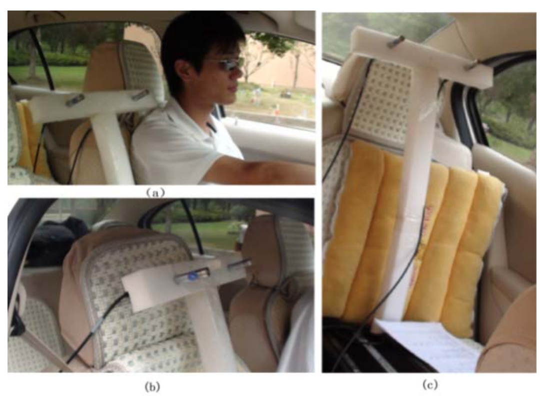

Fig. 1: The microphone positions in test (a) driver, (b) front passenger and, (c) rear driver

The LAVIDA 1.6L manufactured by the Shanghai Volkswagen Company is selected as the sample test vehicle. The running conditions are set in three states: idle, constant speed and acceleration. The constant speeds are from 30 to 90 km/h with an interval of 10 km/h. The accelerating conditions are from 30 to 50, 50 to 60 and 70 to 90 km/h, respectively. The test sites are

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elaborately selected at a suburban road near the Sheshan National Forest Park in Songjiang District in Shanghai (when the vehicle speeds are below 60 km/h) and at Songjiang section of G50 expressway for the other testing cases.

During data acquisition, the sampling rate f_s of the PULSE system is automatically set to 64321 Hz. For reducing the amount of calculation in further studies in this paper, we resampled the measured signals by f_s = 44100 Hz. The recording length of each sample noise is 10 sec. All the measured noise samples are saved in both the ".wav" and ".mat" formats, thereby a database of vehicle interior noises. The two formats of noise signals will be respectively used for subjective and objective evaluations of vehicle noise in the following text.

Sound objective evaluation: To study correlations of subjective and objective evaluations, firstly, the objective evaluations of tne measred interior noises need to be performed. The psychoacoustical parameters, shuch as the loudness, sharpness, roughness and A-weighted Sound Pressure Level (SPL), are considered in this study.

Loudness: Loudness of the vehicle noises is calculated, based on the standard Method for calculating loudness level (ISO 532B, 1975; Zwicker *et al*., 1985). The specific loudness N' can be calculated by:

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

where, E_{TQ} denotes the excitation threshold in a quiet environment, E_0 is the excitation level of a reference intensity $I_0 = 10^{-12}$ W/m^2. The total loudness N may be obtained by summing the N' in each critical band in psychoacoustics.

Sharpness: Sharpness may be directly computed by weighting and integrating the specific loudness (Zwicker and Fastl, 1999), as the empirical equation in Eq. (2):

$$S = 0.11\frac{\int_0^{24Bark} N' g(z) z d_z}{\int_0^{24Bark} N' d_z} acum \qquad (2)$$

where, S is the total sharpness, z is the critical band rate. g (z) is the weighting coefficients in frequency, which may be calculated by Eq. (3):

$$g(z) = \begin{cases} 1 & 0 \le z \le 16 \\ 0.066e^{0.171z} & 16 < z \le 24 \end{cases} \qquad (3)$$

Roughness: Roughness is carried out based on the improved Aures algorithm by Aures (1985) and Daniel and Weber (1997), the specific roughness R_i can be obtained by:

$$R_i = 0.25\sum_{i=1}^{47}(g_{zi} \times c_{i-1\&i+1} \times m_i)^2 \qquad (4)$$

where, $c_{i\&i\text{-}1}$ is the correlation coefficients between the i^{th} and $(i\text{-}1)^{th}$ channels, m_i is the modulation index, g_{zi} is the weighting coefficients of carrier frequencies. The above mentioned coefficients have been provided in the references (Daniel and Weber, 1997) and may be directly used in this study. Similar to that of loudness, the total roughness R may be obtained by summing the R_i in each critical band.

Sound subjective evaluation: In this study, 25 postgraduate students are orgnized as a jury for jury tests. The jury members with an average age of 24 have normal physiological and psychological conditions. All of them have the driver's licenses and are familiar with vehicle interior noise (Norm *et al*., 1999; Fastl, 1997; Haderlein *et al*., 2009).

The semantic differential method with a reference noise (Fastl, 1997; Odden *et al*., 1998; Guski, 1997) is adopted for subjective evaluation of vehicle noises in this paper. A reference noise as an anchor is introduced into the evaluations for improving accuracy of the jury tests. The words and scaling scores in the jury tesys are defined in Table 1.

The target of the jury tests is to evaluate the annoyance of the measured interior noises. This is an easy evaluation task. Preparations before evaluation is a brief explanation to the jury members, including the details of interior noise, evaluation words and the dynamic range of signals for giving scores quickly in the listening and estimating of all noise samples.

During the evaluation, the laboratory environment is kept quiet and peace to guarantee the jury member focusing on the noises. All the measured interior noises are listened and evaluated by the jury members, through the high-precise headphones.

Table 1: The words used in the semantic differential method

Extremely annoyance	Very annoyance	Annoyance	Little annoyance	No annoyance
5	4	3	2	1

Table 2: The results of subjective and objective SQE

Noise no.	Speed (km/h)	Loudness (sone)	Sharpness (acum)	Roughness (asper)	Averaged annoyance
1	70-90	22.4100	0.6494	0.37980	3.7143
2	F60	22.9200	0.5519	0.28900	2.8002
3	D50	18.0300	0.6269	0.25640	2.2001
4	R70	27.9500	0.5746	0.40360	4.7571
5	F70	21.9600	0.6380	0.37760	3.2023
6	F30	14.1250	0.5899	0.19260	2.2857
7	R90	35.3700	0.5058	0.40370	4.8015
8	Idle	8.2230	0.7934	0.04350	1.0000
9	40	16.1700	0.5906	0.18215	2.4286
10	50-60	22.9300	0.5379	0.28440	3.0121

Table 3: The correlation coefficients of SQE parameter

Coefficients	Linear SPL	Loudness	Sharpness	Roughness	Annoyance
Linear SPL	-	0.750	-0.349	0.070	0.626
Loudness	-	-	-0.146	0.366	0.923
Sharpness	-	-	-	0.164	-0.566
Roughness	-	-	-	-	0.755
Annoyance	-	-	-	-	-

CORRELATION ANALYSIS

Some of the objective and subjective evaluation results are listed in Table 2. And the calculated cross correlation coefficients of the objective evaluated linear SPL, loudness, sharpness,
roughness and the subjective evaluated annoyance are shown in Table 3. It can be seen that the correlation coefficients *P* are all greater than 0.5. A conclusion can be drawn that the psycho acoustical parameters, including loudness, sharpness and roughness, are significantly correlated with the annoyance.

The correlation coefficient between loudness and annoyance is the highest, reached 0.923. Referring to the correlation distribution shown in Fig. 2 and the signals in the noise database, it is indicated that the loudness increasing with the vehicle speed and the annoyances show a nearly linear changing with the loudnesses. According to the descriptions of the jury members after subjective evaluations, the loudness is the most important factor effects on their annoyance. For a noise with high loudness, the noise No. 7 (90 km/h) in Table 2, for example, has the highest loudness value of 35.37 sones, which made them very annoyed, even felt hurt though the noise sample is only 5 sec. Thus, the annoyance of this singal is the worst comparing with the other signals. Besides, it may be noted that the loudnesses at accelerating conditions are higher than those at stationary states with similar speeds, as well as the annoyance. For example, the noise No. 10 with running speed from 50 to 60 km/h at driver position has a larger loudness and annoyance levels than the noise No. 3 at constant 50 km/h at the same position. This implies that the engine is the main source of the interior noise and has a great influence on the annoyance of interior noise.

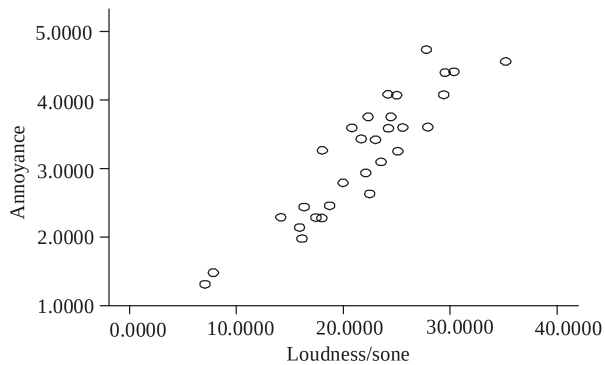

Fig. 2: The correlations of loudness and annoyance

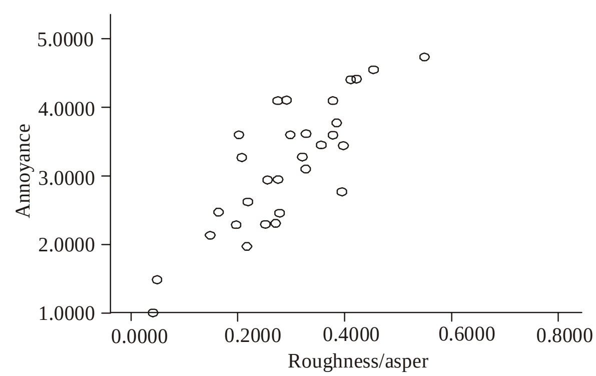

Fig. 3: The correlations of roughness and annoyance

The correlation between roughness and annoyance reaches to 0.755, which is lower than that of the loudness. Similarly, as shown in Fig. 3, it can be seen that the roughness increases with the annoyance linearly. According to the description of the jury members, the roughness is a significant factor that effects their annoyance when the loudness is not high.
Most of the jury members felt the rapid fluctuation of

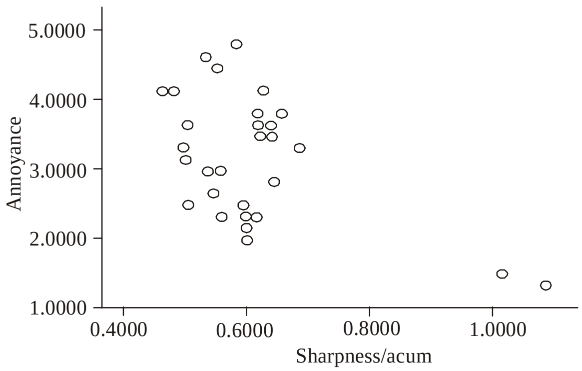

Fig. 4: The correlations of sharpness and annoyance

noise loudness. In that cases, the rough nesses are much easier to attract their attention than the loudness itself and made them feel very annoyed. The higher the roughness, the more annoyed the jury members feel. For example, comparing with the noise No. 2, the noise No. 1 in Table 2 has a similar value in loudness, but very different in calculated roughness and averaged annoyance from the objective and subjective evaluations, respectively.

The sharpness is also related with the annoyance, showing as a negative correlation. From Fig. 4, one may found that the annoyance decreases with the sharpness increasing. Although the changing trend is not so obvious as those of the loudness and roughness, it is no doubt that they have the negative correlation. As known that the interior noises mainly focused on the low frequency (f<500 Hz), because of the engine running at a low RPM in daily use. Besides, effective frequency ranges of the soundproof materials used on vehicle are at high frequency range, so there is no noise sample that felt sharp. According to description of the jury members after the subjective evaluation, when they listened to the noise with high SPL, the strong booming made them feel annoyed. With the running speed increasing, the sharpness releases the booming noise and reduces the annoyance sense. The sense in the low frequency range is the opposite parameter of the sharpness. This may explain why the sharpness and annoyance has a negative correlation. Since the sharpness can express the booming sense of annoyance of a vehicle interior noise, it is usually considered in vehicle SQE engineering.

In the view of SPLs, as seen in Table 3, the linear SPL is positively correlated with the annoyance. The coefficient is 0.626, which is much lower than that of the loudness. It can be found that the calculated loudness and SPL, which are usually used to reflect vehicle noise levels in engineering, have a correlation coefficient of 0.75. This indicates that the loudness and SPL cannot be treated as two independent indices for SQE modeling. The loudness, which considers the influence of human sense of hearing and introduces some weightings into the signal processing procedure, is therefore more suitable than the SPL as the index for vehicle SQEs. The cross correlations among the three psychoacoustic parameters in Table 3 are lower than 0.5. Thus, it can be concluded that the loudness, sharpness and roughness may be regarded as three independent indices in the SQE engineering.

CONCLUSION

This study investigated the correlation between the objective and subjective evaluations of sound quality, based on the vehicle interior noise acquired following the standard GB/T 18697. The objectively evaluation parameters, such as loudness, sharpness, roughness, SPLs and the subjective evaluated annoyance of the vehicle noises are compared and discussed. The correlation analysis's suggest that the objectively evaluated psycho acoustical parameters, which can reflect different aspects of human sense of vehicle noises, are more accurate than the traditional SPL and agree with the results from the subjective evaluations. The conclusions can be dawn that the psychoacoustic parameters, such as loudness, sharpness, roughness, which are significantly correlated with the annoyance of human sense, have a great influence on the SQE. These psycho acoustical parameters with very small correlation coefficient each other should be dealt with as independent indices for SQE of not only vehicle noises, but also any other sounds in engineering.

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