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RESEARCH ON THE SOUND METRIC OF DOOR-SLAMMING SOUND BASED ON LEAKY INTEGRATION AND WAVELET DECOMPOSITION

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ABSTRACT−The evaluation of the sound quality of door-slamming has become one of the important issues in vehicle noise, vibration and harshness (NVH) analysis. For the sound quality evaluation of door-slamming, a new sound metric, named as sound metric based on critical band wavelet decomposition (SMCBWD), is developed. In the new sound metric, the sound signals of door-slamming are sampled and the signal component of the door-slamming sound which has the great influence on the quality of door-slamming is extracted by using the leaky integration method. The extracted signal component is then decomposed by wavelets based on the critical bands and the coefficients of wavelet decomposition are calculated. Based on the energy of the frequency weighted wavelet decomposition coefficients, the new sound metric, SMCBWD, is calculated. In order to verify the effectiveness of SMCBWD, the correlation coefficients between the new sound metric and the subjective sound quality performance value of door-slamming, as well as between the traditional sound metrics (loudness, sharpness) and the subjective sound quality performance value of door-slamming have been calculated, respectively. The results show that the new sound metric developed in this paper has the higher correlations with the subjective sound quality performance value when compared with the traditional sound metric of loudness and sharpness. Thus, SMCBWD can be used to evaluate the sound quality of door-slamming more accurately.

KEY WORDS : Leaky integration, Wavelet decomposition, Critical band, Vehicle NVH, Sound quality, Sound metric

1. INTRODUCTION

With the rapid development of the automotive industry, consumers have become more discriminating in regard to the quality of car. The consumers' first impression of the sound quality of a car is often from the door-slamming of the car, and it has great influence on the purchase intension of consumers. Therefore, the research on the sound quality of door-slamming of car has important significance.

At present, the researches of sound quality mainly focus on the sound quality prediction and the sound quality evaluation. In the former, a lot of the sound quality prediction models (such as the multiple linear regression, established and the accuracy of these prediction models neural network and support vector machine) have been has been investigated based on the correlation analysis of the prediction results and the subjective evaluation results (Lee and Lee, 2009; Lee, 2008; Shen *et al*., 2009; Wang *et al*., 2007; Shen *et al*., 2010). The latter is mainly divided into two parts: the sound quality subjective evaluation and the sound quality objective evaluation. The sound quality subjective evaluation is based on the subjective test methods. The main types of the sound quality subjective evaluation are the level evaluation method, the semantic segmentation method, the paired comparison method and so on (Mao *et al*., 2005). The sound quality objective evaluation is based on the numerical sound signal processing. The parameters (such as loudness and sharpness) obtained by the sound quality objective evaluation can reflect the subjective feeling of the sound. Recently, Lee and Kwon (2007) has developed a door slam index which can be used to reduce the time-frequency information into a single-value metric based on the time-frequency graphs. The door slam index is unsuitable to analyze the non-stationary signals quantitatively, as the impact information of the non-stationary signals is not extracted. Lee *et al*. (2010) has established a sound quality evaluation parameter based on the wavelet decomposition. In Lee's method, the sound quality evaluation parameter was established by optimizing a threshold parameter, but the optimization of the threshold parameter may lead to considerable subjective evaluation tests and time. Furthermore, the relationship between the sound and the human feeling was not considered.

Aiming at the problem of sound quality evaluation of door-slamming, a new sound metric named as SMCBWD is established for the sound quality evaluation of door-slamming. In SMCBWD, the leaky integration and the wavelet decomposition based on critical bands are combined in a unified framework. The critical bands are

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obtained by dividing the sensitive auditory frequency range of people into some specific frequency bands based on a large number of experiments and hearing tests. The advantage of the critical bands is that they have close relationships with the human hearing. The wavelet analysis can supply localized information in time and frequency domain, as it possesses the multi-scale character and "mathematical microscope effect" which make it capable to detect the sudden component of the signals. Therefore, wavelet analysis has been widely applied to non-stationary signals analysis in recent years. It is an effective tool for analyzing the impact sound signal and has been applied to the high impact signal analysis successfully (Chandrika and Kim, 2010). The leaky integration is very sensitive to the impact components of a signal and has been applied to the exploration of squeak and rattle (Zhu and Kim, 2010). By integrating the leaky integration, the wavelet decomposition and the critical bands in a unified framework, the new sound metric SMCBWD, which may possesses the advantages of the leaky integration, the wavelet decomposition and the critical bands, can be used for the sound quality evaluation of door-slamming. The procedure to establish SMCBWD is divided into three steps. At first, the signal component which had the greatest influence on the sound quality was extracted based on the leaky integration method. And then this signal component was decomposed by wavelet decomposition according to the critical bands. At last, SMCBWD was obtained based on the energy of the frequency weighted wavelet decomposition coefficients. SMCBWD is closely related with the human sensitive auditory frequency range and the signal component having the greatest influence on the sound quality. In order to verify the effectiveness of SMCBWD, the correlation coefficients between the new sound metric and the subjective sound quality performance value of door-slamming, as well as between the traditional sound metrics (loudness, sharpness) and the subjective sound quality performance value of door-slamming have been calculated, respectively. The results show that the new sound metric developed in this paper has the higher correlations with the subjective sound quality performance value when compared with the traditional sound metric of loudness and sharpness. Thus, SMCBWD can be used to evaluate the sound quality of door-slamming more accurately.

2. TRADITIONAL SOUND METRIC

In the traditional acoustic research, we usually evaluate the sound based on the A-weighted sound pressure. In the design of a car, we often pay attention to reducing the A-weighted sound pressure but ignore the subjective feeling of sound. Until the 1990s, people realized that two sounds which had the same A-weighted sound pressure can also give a person different feelings. Thus, the research of the sound quality which has a great significant on the evaluation, analysis and control of the noise of a car has becomes increasingly attractive. The traditional parameters used to evaluate the sound quality are loudness, sharpness and so on.

2.1. Loudness

Loudness level is equal to the sound pressure level in decibels, relative to 0.0002 microbar, of a pure 1000-hertz tone that is judged to be equally loud by listeners. The unit of loudness level is phon. Loudness level is related to the sound pressure level directly and it is convenient to be used. The unit of loudness is sone. 1 sone is equal to the loudness level for a normal person hearing a sound at 40 phon. According to the hearing test, 2 sone is as two times loudness as 1 sone. Based on a large number of experiments, the relationship between loudness level and loudness was obtained and can be expressed as (Ishibashi *et al*., 2006)

$$L = 2^{(L_N - 40)/10} \quad (1)$$

Where L is loudness; L_N is loudness level.

2.2. Critical Bands

Numerous experiments and hearing tests show that there are some specific frequency bands within the sensitive bands of hearing of human. These specific frequency bands were referred as the critical bands. Zwicker divided the frequency band of sound signals into 24 critical bands, which are expressed as 1 to 24 barks. The relationships between the critical bands and frequencies are shown in Table 1.

2.3. Sharpness

Sharpness is a psychoacoustic parameter that represents the proportion of the high frequency components in the frequency spectrum of sound. It indicates the subjective

Table 1. Relationships between critical bands and frequencies.

Critical band Z(bark)	Frequency f (Hz)	Band z(Hz)	Critical band Z(bark)	Frequency f (Hz)	Band z(Hz)
1	0~100	100	13	1720~2000	280
2	100~200	100	14	2000~2320	320
3	200~300	100	15	2320~2700	380
4	300~400	100	16	2700~3150	450
5	400~510	110	17	3150~3700	550
6	510~630	120	18	3700~4400	700
7	630~770	140	19	4400~5300	900
8	770~920	150	20	5300~6400	1100
9	920~1080	160	21	6400~7700	1300
10	1080~1270	190	22	7700~9500	1800
11	1270~1480	210	23	9500~12000	2500
12	1480~1720	240	24	12000~15500	3500

sensation of an auditor towards the high frequency sound and towards the degree of harshness of sound signal. The unit of sharpness is acum. 1 acum is equal to the sharpness of 60 dB narrow band with center frequency being 1 kHz and bandwidth being 160 Hz.

Within the specific critical bands, sharpness is related with the critical bands and is calculated by using the following equation

$$S(z) = \frac{0.11L(z)g(z)z}{\sum_{1bark}^{24bark} L(z)\Delta z} \quad (2)$$

Where z, the critical bands (bark), is an integer and discrete variable shown in Table 1; $S(z)$ is the sharpness (acum); $L(z)$ is the loudness (sone); Δz denotes the width between the neighboring barks; $g(z)$ is the weighting function which is expressed as

$$g(z) = 0.066e^{0.171z} \quad (3)$$

The total sharpness S can be expressed as

$$S = \sum_{0bark}^{24bark} S(z)\Delta z \quad (4)$$

3. SOUND METRIC SMCBWD

3.1. Feature Extraction of a Sound Signal Based on Leaky Integration

The leaky integration is the infinite impulse response (IIR) filter with low pass. It has been successfully used in the detection of squeak and rattle. There are two advantages of leaky integration: one is that leaky integration is sensitive to the sound impact and therefore it is efficient in sound signal extraction. The other one is that the leaky integration can extract the squeak and rattle which are the main contributions to the sound quality. Thus, the leaky integration is adopted to analyze the door-slamming sound of a car and to extract the main signal component that affect the door-slamming sound quality of a car. The leaky integration is defined by

$$N_s'(i) = (1-\alpha)N_s'(i-1) + \alpha N_s(i) \quad (5)$$

Where N_s is the original door-slamming signal; N_s' is the sound signals after the impact signal component is removed; i represents the ith time step; α denotes the integration constant. The signal N which mainly contributes to the sound quality is expressed as

$$N = N_3 - N_s' \quad (6)$$

3.2. Wavelet Decomposition Based on Critical Bands

3.2.1. Analytical wavelet decomposition

Wavelet decomposition is useful for the impact sound signal analysis because of its good time-frequency concentration, time-invariance and shift-invariance feature. The key point of wavelet decomposition is the selection of a suitable mother wavelet. Researches proved that the analytical wavelet has achieved good results in the analysis of the high impact sound signals (Zhu and Kim, 2010). The mother wavelet is defined as

$$\psi(t) = g(t)e^{j\eta t} \quad (7)$$

Where $j = \sqrt{-1}$; η is the parameter related to frequency; $g(t)$ is the Gaussian function

$$g(t) = \frac{1}{(\sigma^2\pi)^{1/4}}e^{-t^2/2\sigma^2} \quad (8)$$

The wavelet transform of sound signal $f(t)$ is

$$W(u) = \int_{-\infty}^{+\infty} \frac{1}{s}f(t)g\left(\frac{t-u}{s}\right)e^{-j\eta(t-u/s)}dt \quad (9)$$

Where s is the scale factor and u is the shift factor.

Table 2. Frequency parameters of mother wavelet.

Wavelet	Lower limit frequency fl (Hz)	Center frequency fc (Hz)	Upper limit frequency fu (Hz)
1	0	50	100
2	100	150	200
3	200	250	300
4	300	350	400
5	400	455	510
6	510	570	630
7	630	700	770
8	770	845	920
9	920	1000	1080
10	1080	1175	1270
11	1270	1375	1480
12	1480	1600	1720
13	1720	1860	2000
14	2000	2160	2320
15	2320	2460	2700
16	2700	2925	3150
17	3150	3425	3700
18	3700	4050	4400
19	4400	4950	5500
20	5300	5850	6400
21	6400	7050	7700
22	7700	8600	9500
23	9500	10750	12000
24	12000	13750	15500

3.2.2 Selection of wavelet parameters

Wavelet decomposition based on the critical bands is used to create 24 wavelets according to the classification of critical bands and the suitable wavelet parameters (η, σ, s). The frequency parameters of the lower limit frequency, the upper limit frequency and the center frequency of the mother wavelet are shown in Table 2.

According to the studies on wavelet parameters in Ref. (Zhu and Kim, 2010), the center angular frequency ω_c can be expressed as

$$\omega_c = 2\pi f_c = \frac{\eta}{s} \tag{10}$$

The lower limit angular frequency and the upper limit angular frequency can be defined as $\omega_l = 2\pi f_l$ and, $\omega_u = 2\pi f_u$, respectively. The energy difference between the upper limit frequency and the center frequency of wavelet can be expressed as

$$\Delta dB_l = \left|20\ \log_{10}\frac{g(\eta - s\omega_l)}{g(\eta - s\omega_c)}\right| = \sigma^2\eta^2\left(1 - \frac{\omega_l}{\omega_c}\right)^2 / \log_e 10 \tag{11}$$

Similarly, the energy difference between the lower limit frequency and the centre frequency of the wavelet and can be expressed as

$$\Delta dB_u = \left|20\ \log_{10}\frac{g(\eta - s\omega_u)}{g(\eta - s\omega_c)}\right| = \sigma^2\eta^2\left(1 - \frac{\omega_u}{\omega_c}\right)^2 / \log_e 10 \tag{12}$$

The energy of the upper limit frequency and the lower limit frequency are half of the center frequency and can be expressed as $\Delta dB_l = \Delta dB_u = 3$ dB.

As is listed in Table 2

$$\omega_c - \omega_l = \omega_u - \omega_c \tag{13}$$

Therefore

$$-\frac{\omega_l}{\omega_c}\Big)^2 = \left(\frac{\omega_c - \omega_l}{\omega_c}\right)^2 = \left(\frac{\omega_u - \omega_c}{\omega_c}\right)^2 = \left(1 - \frac{a}{a}\right. \tag{14}$$

According to Equations (11) to (14), we can obtain the following formula

$$\sigma^2\eta^2 = \frac{3}{\left(1 - \frac{\omega_u}{\omega_c}\right)^2 / \log_e 10} = \frac{3}{\left(1 - \frac{\omega_l}{\omega_c}\right)^2 / \log_e 10} \tag{15}$$

As ω_c, ω_l and ω_u are constants for a given critical bands, $\sigma^2\eta^2$ shown in Equation (15) is also a constant and is marked as A. According to Zhu and Kim (2010), the values of σ and η selected in this paper are $\sigma = 1$ and $\eta = \sqrt{A}$. Based on Equations (10) and (15), the values of parameters of 24 wavelets are obtained and are listed in table 3.

Table 3. Values of wavelets parameter based on critical-band.

Wavelet	Frequency f(Hz)	Scale factor	Frequency shifting factor η
1	0~100	0.008366	2.628212
2	100~200	0.008366	7.884637
3	200~300	0.008366	13.14106
4	300~400	0.008366	18.39749
5	400~510	0.007605	21.74248
6	510~630	0.006972	24.96802
7	630~770	0.005976	26.28212
8	770~920	0.005577	29.61119
9	920~1080	0.005229	32.85265
10	1080~1270	0.004403	32.50684
11	1270~1480	0.003984	34.41707
12	1480~1720	0.003486	35.04283
13	1720~2000	0.002988	34.91768
14	2000~2320	0.002614	35.48087
15	2320~2700	0.002988	46.18145
16	2700~3150	0.001859	34.16676
17	3150~3700	0.001521	32.73319
18	3700~4400	0.001195	30.41217
19	4400~5300	0.000761	23.65391
20	5300~6400	0.000761	27.95462
21	6400~7700	0.000644	28.506
22	7700~9500	0.000465	25.11403
23	9500~12000	0.000335	22.60263
24	12000~15500	0.000239	20.65024

3.3. SMCBWD

The sound signals of door-slamming of a car are the impact signals whose main components contributing to the sound quality can be efficiently extracted by the leaky integration. Besides, wavelet decomposition is a useful tool for the impact sound signal analysis due to its good time-frequency concentration, time-invariance feature and shift-invariance feature. Based on the leaky integration and the wavelet decomposition, SMCBWD is established for the analysis of the door-slamming sound quality of a car. The calculation procedure of SMCBWD is as follows

(1) Extraction the main component contributing to the sound quality. By employing the leaky integration, the main component contributing to the sound quality can be extracted from the actually recorded door-slamming sound signal of a car according to Equation (6).
(2) Wavelet decomposition based on the critical bands. Firstly, 24 critical-band-based mother wavelets are acquired from the wavelet parameters in Table 2; secondly, the signal $N(t)$, which is the main component contributing to the sound quality, is decomposed into 24 signal components $N_i(t)$ (i=1,2,3…24) by the analytical wavelets based on the critical bands.

(3) Calculating the energies of frequency weighted signal components. As is well known, the high frequency components have greater influence on the subjective feeling of people when compared with the low frequency components. In order to highlight the effect of high-frequency components in sound signals, the frequency-weighted components $N_i'(t)$ (i=1,2,…24) are obtained by multiplying the 24 components with their center frequency values. Therefore, the bigger the center frequency value of $N_i(t)$ is, the bigger the frequency-weighted value is. Based on the frequency-weighted components $N_i'(t)$, the energy of $N_i'(t)$ (i=1,2,…24) can be calculated from the following equation

$$E_i = \int_0^T N'^2_i(t)\mathrm{d}t \tag{16}$$

(4) Calculation of the sound metric SMCBWD. SMCBWD is defined as the summation of the energy of frequency-weighted component $N'_i(t)$

$$SMCBWD = \sum_{i=1}^{24} E_i \tag{17}$$

As can be seen from the computational process of SMCBWD, a bigger value of SMCBWD indicates the more impact components extracted by the leaky integration. Furthermore, a bigger energy of a frequency-weighted component indicates the existence of the more high frequency components. As the high frequency components have greater effects on sound quality (Lee *et al.*, 2010), SMCBWD is suitable to be used to evaluate the sound quality of door-slamming.

4. SOUND QUALITY EVALUATION OF DOOR-SLAMMING BASED ON SMCBWD

To apply SMCBWD in the evaluation of the door-slamming sound quality, 14 passenger cars were selected as sample cars for the acquisition of the door-slamming sound signals, the leaky integration and wavelet decomposition were applied to the sampled door-slamming sound signals.

4.1. Acquisition of Sound Signals of Door-Slamming

The door-slamming sound test of cars was conducted in a free acoustic field and 14 passenger cars (Toyota, Volvo, Chevrolet, SGMW, Foton and so on) with the different door-slamming sound qualities were tested to obtain the corresponding sound signals. The software and equipment used in the test are the test.lab and the front data acquisition equipment developed by the LMS Company. The sound pressure sensor was fixed at the place as far as 500 mm to the B-pole of a car and of 1600 mm high. The parameters of data acquisition were set as follows: sampling frequency is 20480 Hz, analyze frequency is 10240 Hz, spectral line width (the distance between two neighboring spectral lines) is 1 Hz and sampling time is 3s. After the sound signals were acquired, the loudness and sharpness of the sampled sound signals were calculated by using Equations (1) and (2), respectively. As can be seen in Table 4, there are great differences in the loudness and sharpness of these sampled sound signals, which indicates that the door-slamming sound qualities of the 14 sample cars are different from each other remarkably.

Table 4. Loudness and sharpness of the door-slamming sound of 14 sample cars.

Car no.	Loudness (sone)	Sharpness (acum)
1	52.22	1.86
2	47.54	1.84
3	46.21	1.74
4	50.73	1.72
5	64.56	2.18
6	51.20	2.05
7	73.13	2.13
8	64.29	2.06
9	76.63	1.91
10	66.88	1.98
11	47.41	2.09
12	50.00	2.01
13	102.63	2.19
14	120.98	2.25

4.2. Sound Quality Evaluation of Door-Slamming based on SMCBWD

The main steps of the sound quality evaluation of door-slamming based on SMCBWD are as follows

4.2.1. Extraction of the main signal component that affect the door-slamming sound quality

The sampling time was 3s, but the door-slamming happened during 500 ms, so the data within 500 ms were extracted. The main signal component contributing to the door-slamming sound quality of these sample cars was extracted based on the leaky integration. The original door-slamming sound signal of the sample car No.1 is shown in Figure 1 (a) and the extracted signal component contributing to the door-slamming sound quality is shown in Figure 1 (b).

From Figure 1, we can see that the door-slamming sound pressure signal of sample car No.1 shows clear impact characteristics, but it is hard to distinguish the main signal component that affect the door-slamming sound quality in the original sound signal. After the application of leaky integration to the original sound signal, the extracted sound signal not only shows the obvious impact characteristics

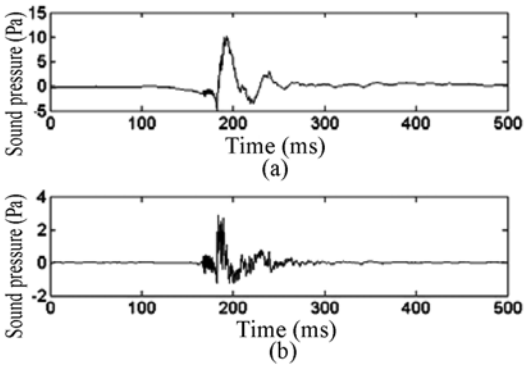

Figure 1. Door-slamming sound pressure signals of sample car No.1: (a) Original sound signal of door-slamming; (b) Sound signal of door-slamming extracted by the leaky integration.

but also shows the fluctuation of the sound pressure. The fluctuation of the sound pressure indicates that the main component contributing to the door-slamming sound quality is extracted from the original door-slamming sound signal.

4.2.2. Wavelet decomposition based on the critical bands
First, the critical-band-based wavelets with the wavelet parameters shown in Table 3 were acquired; and then the extracted door-slamming sound signals of sample cars were decomposed by using of the critical-band-based wavelet decomposition. The critical-band-based wavelet decomposition results of the door-slamming sound signal of sample car No.1 are shown in the Figure 2.

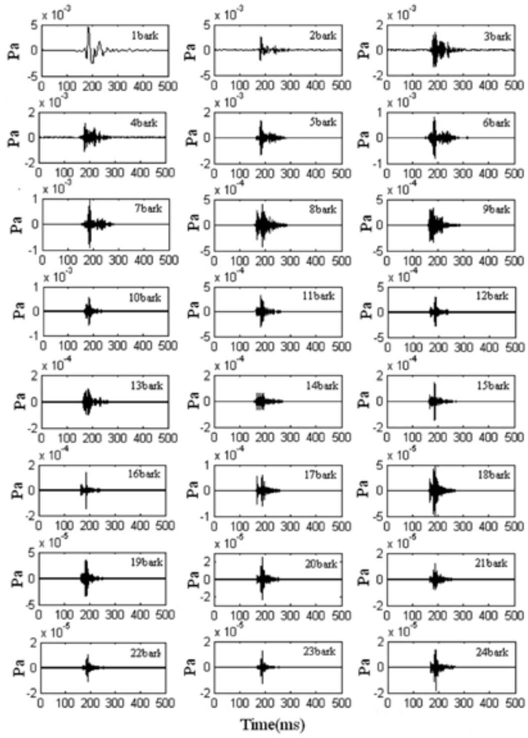

Figure 2. Decomposition results of the door-slamming sound pressure signal of sample car No.1 through critical-band-based wavelets.

Figure 2 indicates that 24 components show obvious impact characteristics. In other words, the door-slamming sound signal was successfully decomposed into 24 impact components by the wavelet decomposition based on the critical bands which are related with the sensitive hearing frequency bands of people.

4.2.3. Calculation of SMCBWD
The SMCBWD values of 14 sample cars were obtained on the basis of Equations (16) and (17) and are listed in table 5.

In Table 5, a higher value of SMCBWD represents the more high frequency components as well as the more frequency components in the door-slamming sound signals. Thus we can infer that the higher value of SMCBWD indicates the worse door-slamming sound quality. According to Table 5, the biggest value of SMCBWD falls on sample car No. 14, which is as big as 24.26. Therefore, the door-slamming sound quality of sample car No. 14 may be the poorest. On the contrary, the door-slamming sound quality of the sample car No.3 may be the best as its SMCBWD is the smallest one. In the next, we will confirm these inferences and investigate the accuracy of SMCBWD for door-slamming sound quality evaluation through subjective evaluation experiments.

5. SUBJECTIVE EVALUATION EXPERIMENT AND CORRELATION ANALYSIS

5.1. Subjective Evaluation Method

The subjective evaluation methods have very high accuracy for sound quality evaluation. Which were often used to evaluate the sound quality in engineering application. The sound quality subjective evaluation methods commonly used are the scoring method, the semantic segmentation method, the amplitude adjustment method, paired comparison method and so on (Mao *et al*., 2005). In this paper, the paired comparison method is used. In order to investigate the accuracy of the SMCBWD for door-slamming sound quality evaluation, the correlation analysis between the door-slamming sound quality evaluation result obtained by SMCBWD and by the paired comparison was done.

In the implement of the paired comparison method, the sound signal samples were divided into pairs, and the evaluation was made by estimators through comparing the each pair of sound samples. The main steps of the paired comparison method for sound quality evaluation are as follows: First, based on the permutation and combination theory, sounds were divided into pairs and the number of pairs is $m = n(n-1)/2$. Second, estimators should choose the better sound from each pair. At last, the chosen probability P_{ij} of i from the pair (i,j) was calculated and the subjective

Table 5. SMCBWD values of the door-slamming sound of 14 sample cars.

Car no.	SMCBWD	Car no.	SMCBWD
1	6.66	8	10.16
2	5.50	9	7.95
3	0.76	10	8.95
4	3.04	11	4.69
5	10.76	12	3.16
6	8.75	13	16.24
7	9.52	14	24.26

Table 6. Subject evaluation results of the fourteen sample cars.

Car no.	Subject rating M_i'	Car no.	Subject rating M_i'
1	-0.8168	8	1.1594
2	-0.9625	9	0.1106
3	-1.8631	10	0.144
4	-1.2465	11	-0.4806
5	0.6262	12	-1.1567
6	0.1734	13	1.7557
7	0.4806	14	2.1014

sound quality preference M_i of sample No. i was calculated

$$M_i = \frac{1}{n}\sum_{i \neq j} \ln\left(\frac{P_{ij}}{P_{ji}}\right) \tag{18}$$

The opposite preference was

$$M_i' = -M_i \tag{19}$$

The higher value of SMCBWD is, the worse sound quality may be. For the convenience of comparison, the M_i' was chosen to be the subject sound quality performance.

The subjective evaluation experiments on 14 sample cars were made by the paired comparison method. The sound diagnosis module of Test. Lab software of the LMS Company was used to playback the door-slam sounds. There were 24 male and 6 female estimators. They were postgraduate students. The results of evaluation were listed in Table 6. In Table 6, the higher value is, the worse of the sound quality is. According to the comparison between Table 5 and Table 6, we can come to the conclusion that the higher of the subject sound quality performance is, the higher of SMCBWD is. Therefore, the effectiveness of SMCBWD for the sound quality evaluation of door-slamming has been verified.

5.2. Correlation Analysis

In order to further verify the effectiveness of SMCBWD,

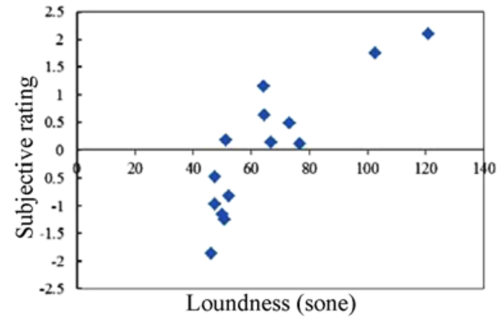

Figure 3. Scatter diagram of loudness and subject rating of 14 passenger cars.

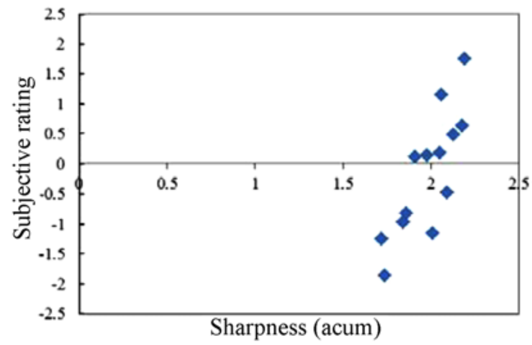

Figure 4. Scatter diagram of sharpness and subject rating of 14 passenger cars.

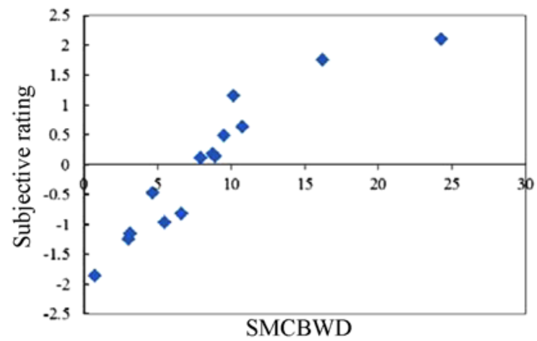

Figure 5. Scatter diagram of SMCBWD and subject rating of 14 passenger cars.

the correlation coefficients between the new sound metric and the subjective sound quality performance value of door-slamming, as well as between the traditional sound metrics (loudness, sharpness) and the subjective sound quality performance value of door-slamming have been calculated, respectively. The formula to calculate the

Table 7. Correlation coefficients.

	Loudness	Sharpness	SMCBWD
Correlation coefficient	0.8588	0.8477	0.9301

correlation coefficient is

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (20)$$

Where r_{xy} was the correlation coefficient between the vector **x** and the vector **y**; x_i and y_i were the elements of the vector **x** and the vector **y**; $\bar{x}$ and $\bar{y}$ were the average values of the elements in the vectors **x** and **y**; n was the number of the samples.

Figure 3 to 5 are the scatter diagrams of loudness, sharpness, SMCBWD and subject performance. The correlation coefficients are shown in Table 7.

From Figures 3 to 5, we can see that the points in Figure 5 were more close to a line when compared with the points shown in Figures 3 and 4. The results listed in Table 7 show that the correlation coefficient between SMCBWD and the subjective sound quality performance was higher than the correlation coefficients between the traditional sound metric (loudness, sharpness) and the subjective sound quality performance. As a result, the new sound metric, SMCBWD, can be used to evaluate the sound quality of door-slamming of a car more effectively compared with the traditional sound metrics.

6. CONCLUSION

For the sound quality evaluation of door-slamming of cars, a new sound metric, named as SMCBWD, is developed. The main conclusions of the research were

(1) Based on the leaky integration and the wavelet decomposition method based on the critical bands, a new sound metric, SMCBWD was established. It can be used to evaluate the door-slamming sound quality of a car. The higher value of SMCBWD indicates the worse sound quality.

(2) The results of correlation analysis show that the correlation coefficient between SMCBWD and the subjective sound quality performance was higher than the correlation coefficients between the traditional sound metric (loudness, sharpness) and the subjective sound quality performance. Therefore, SMCBWD can be used to evaluate the door-slamming sound quality of a car more effectively when compared with the traditional sound metrics.

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