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Improvement of impact noise in a passenger car utilizing sound metric based on wavelet transform

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ABSTRACT

A new sound metric for impact sound is developed based on the continuous wavelet transform (CWT), a useful tool for the analysis of non-stationary signals such as impact noise. Together with new metric, two other conventional sound metrics related to sound modulation and fluctuation are also considered. In all, three sound metrics are employed to develop impact sound quality indexes for several specific impact courses on the road. Impact sounds are evaluated subjectively by 25 jurors. The indexes are verified by comparing the correlation between the index output and results of a subjective evaluation based on a jury test. These indexes are successfully applied to an objective evaluation for improvement of the impact sound quality for cases where some parts of the suspension system of the test car are modified.

1. Introduction

Some indexes have been developed in previous studies related to the evaluation of sound quality of diesel knock noise, door lock noise and vehicle interior noise [1–4]. Impact noise is induced when a car is driven on a harsh road or over some bumps, as shown in Fig. 1. This noise causes discomfort to passengers and can be a factor that customers take into account when making a purchase decision. Therefore, it is necessary to develop an impact sound quality index for objective evaluation of the sound quality perception of impact noise. For the impact modulation of diesel knock, sound metrics were developed, but they only considered sound modulation and are not suitable for sound quality analysis of impact noise due to impact bumps [1]. Door lock noise has impact properties but its sound metric is also not related to the impact sound of the bump on the road [2]. Sound quality evaluation for vehicle interior noise is related to the product of loudness model for a non-stationary signal but it's application is limited to a specific signal [3,4] since this model is produced throughout training process based on neural network. The other paper related to the vehicle sound quality has the purpose of the improvement of the audio sound quality based on active noise control [5]. In this paper, a new sound metric, HFEC (high frequency energy contribution) [6], which captures the impulsive characteristics of sound, is developed. HFEC is developed based on the continuous wavelet transform, which is useful for the extraction of the impact information for non-stationary signals [7]. This new metric is used for the development of sound quality indexes for impact noise with other existing sound metrics such as fluctuation strength and roughness. Fluctuation strength and roughness provide measures of human perception regarding the modulated signal of sound at low frequency and high frequency, respectively [8,9]. Sound quality indexes are developed for impact noises occurring inside a car that is driven over four different types of impact bumps. Fig. 2 illustrates the technology applied to the production of the sound index. For this study, impact noises for 15 passenger

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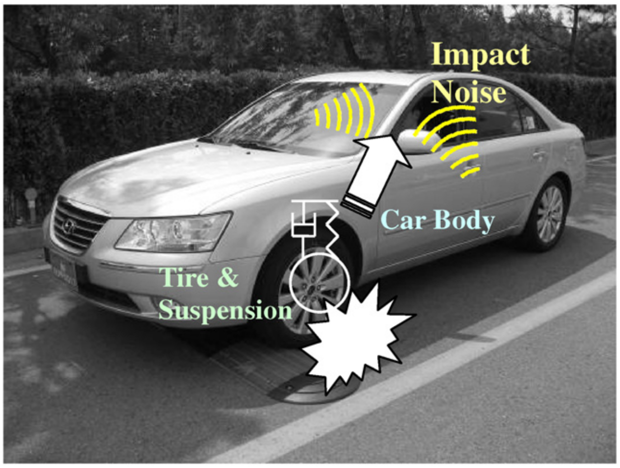

Fig. 1. Impact noise induced by a speed bump on the road.

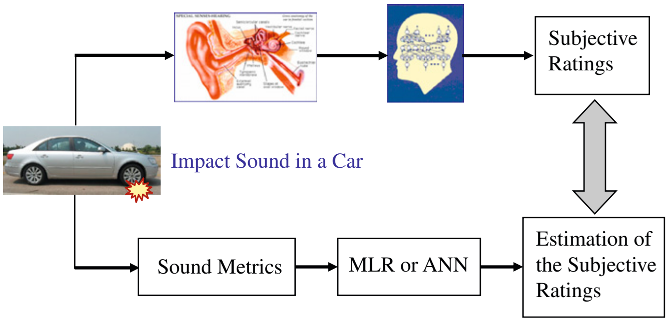

Fig. 2. Process for estimation of the subjective ratings by MLR or ANN.

cars were recorded and 25 participants evaluated the impact sound quality subjectively. An artificial neural network (ANN) [10–13] or multiple linear regressions (MLR) can be applied to the modeling of this subjective evaluation system in order to evaluate the impact noise objectively. In this paper, MLR is used for modeling the evaluation system. The three sound metrics for the impact noise of a passenger car are used as the input of the model and a subjective evaluation for the impact sound is used as the target of the model. Sound metrics for input of the MLR model are HFEC, fluctuation strength, and roughness for each test course. These developed indexes are successfully applied to the objective evaluation for improvement of the impact sound quality for cases where some parts of the suspension system of the test car are changed.

2. Sound recording and jury evaluation

2.1. Recording of impact signals

The impact sounds of 15 test vehicles for four different road conditions were recorded. The four different road conditions are shown in Fig. 3, where each course has different types of obstacles: course 1 has an impact bar, course 2 has a continuous bandy road, course 3 has a broad bump, and course 4 has a narrow bump. A head acoustic HMS III artificial head was employed for recording the impact sounds. Table 1 summarizes the road conditions and vehicle speed on the test course. Note that the driving speed of all vehicles is kept constant on each course. The artificial dummy head is fixed strongly to the seat. The recorded data is saved on a laptop computer.

2.2. Jury evaluation

A jury test was conducted by a rating method for given semantic meanings [14]. The number of participants for the jury test was 25. They graded the given semantic meaning, "impulsiveness", in a range of 4–9 points. Fig. 4 describes the jury test procedure with pictorial explanation. All measured data are storage in the data record memory. It is replayed with specially designed replay system. Twenty-five participants replay the impact sound and rank the sound with rating

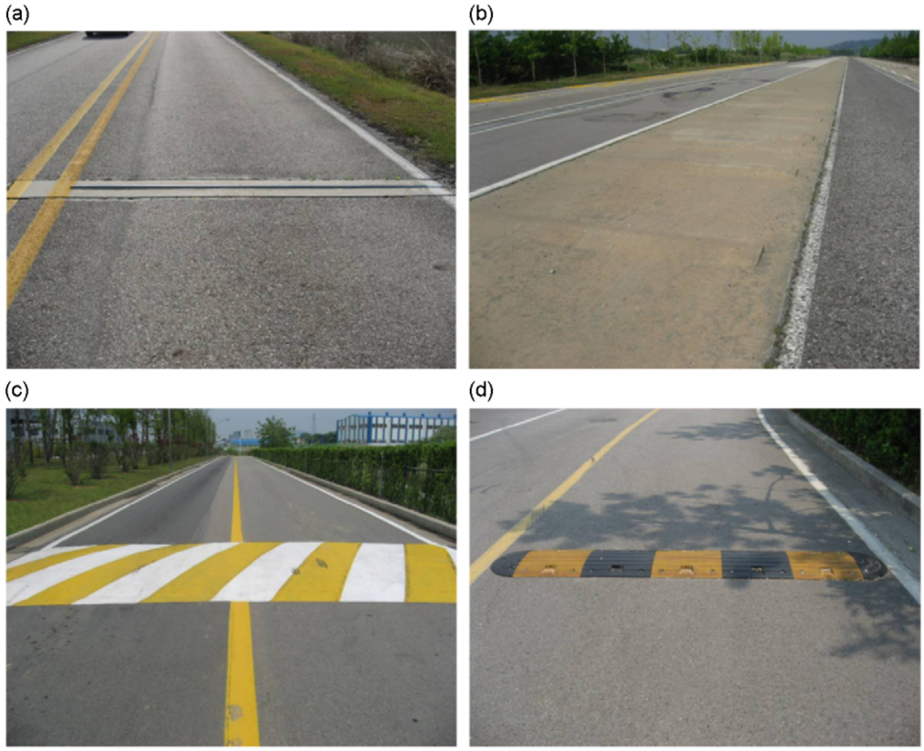

Fig. 3. Photographs of the test courses. (a) Course 1: impact bar, (b) course 2: continuous bandy road, (c) course 3: broad bump, (d) course 4: narrow bump.

Table 1
Test conditions for each course.

Course no.	Course type	Car speed (km/hour)
Course 1	Impact bar	30
Course 2	Continuous bandy road	20
Course 3	Broad bump	35
Course 4	Narrow bump	25

method subjectively. Fig. 5 shows the subjective testing results and 95% confidence interval for the impulsiveness. First, data with less than a 75% correlation with the mean rating of the evaluators is removed. The subjective rating is then obtained by averaging the results in the confidence interval. The same procedure was applied to all four test courses, and the subjective ratings of each course are summarized in Table 2.

3. Sound metrics for impact noise index

The impact noise is induced by road courses having an impact bar, speed bumps, etc. The impact noise contains impulsive and fluctuating characteristics due to vibration of the suspension and shock absorber. Therefore, the fluctuation strength, roughness, and HFEC are considered as sound metrics of impact noise in this study.

3.1. Fluctuation strength

Fluctuation strength is the auditory perception character related to amplitude modulation and frequency modulation for sound with frequency modulation at lower frequency around 4 Hz. Fastl and Zwicker [8] proposed a calculation model for the fluctuation strength of sound. The unit of fluctuation strength is vacil, where one vacil is the fluctuation strength for pure tone sound with an amplitude of 60 dB at 1 kHz, which is 100% modulated in amplitude at a modulation frequency of

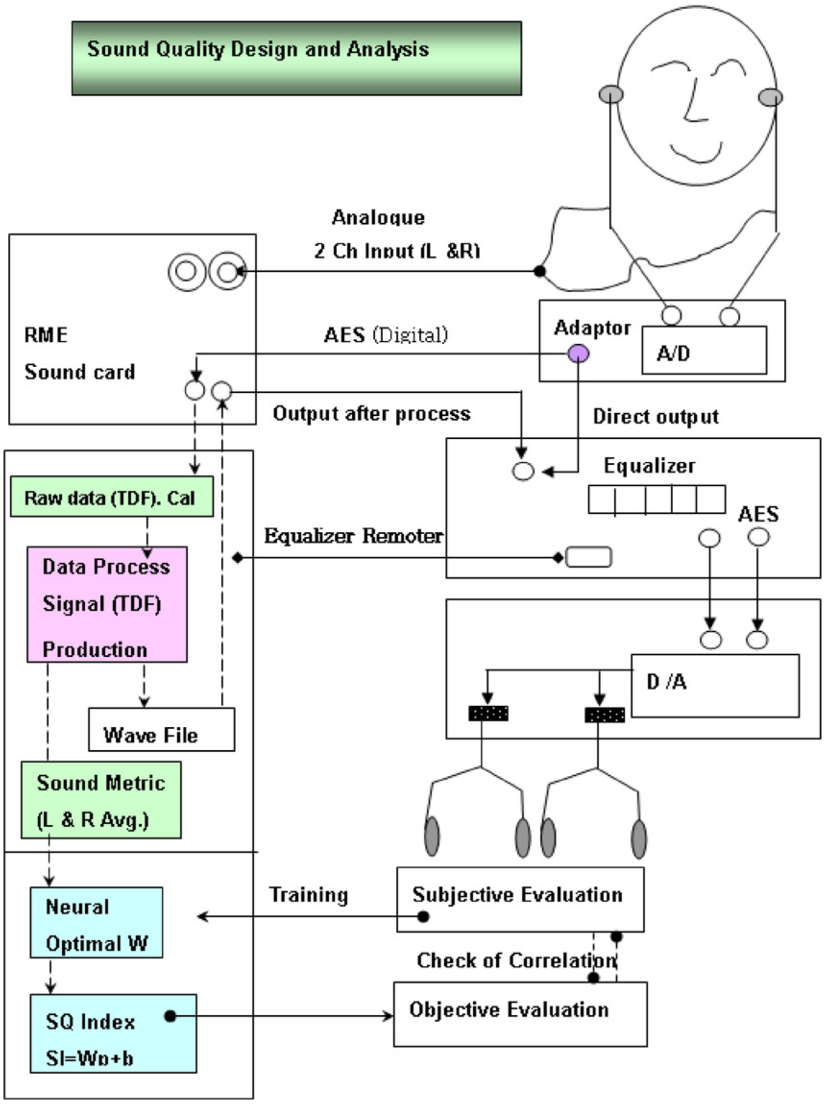

Fig. 4. Experimental set-ups for the subjective evaluation of the impact sound of a passenger car.

4 Hz. Fig. 6 shows the fluctuation strength measured for 15 impact sounds of four courses. From the graph, the fluctuation strength has a relationship with human perception of impact noise in some courses, as shown in Fig. 6.

3.2. Roughness

Roughness is the auditory perception characteristic related to the amplitude modulation and frequency modulation for sound with frequency modulation at a middle frequency around 70 Hz. It is related to high frequency modulation of the sound. Aures [9] introduced asper, a calculation model of roughness for sound. One asper is the roughness of a pure tone sound with an amplitude of 60 dB at 1 kHz, which is 100% modulated in amplitude at a modulation frequency of 70 Hz. Fig. 7 shows the roughness measured for 15 impact noises from the four courses. It is concluded from the graph that there is some relationship between roughness and human perception for impact noise in course 4.

3.3. HFEC

CWT is an effective time-scaling analysis tool for the impact noise signal induced by road courses having an impact bar [7]. CWT is applied to the development of a sound metric for impact noise [6]. The development process of the sound

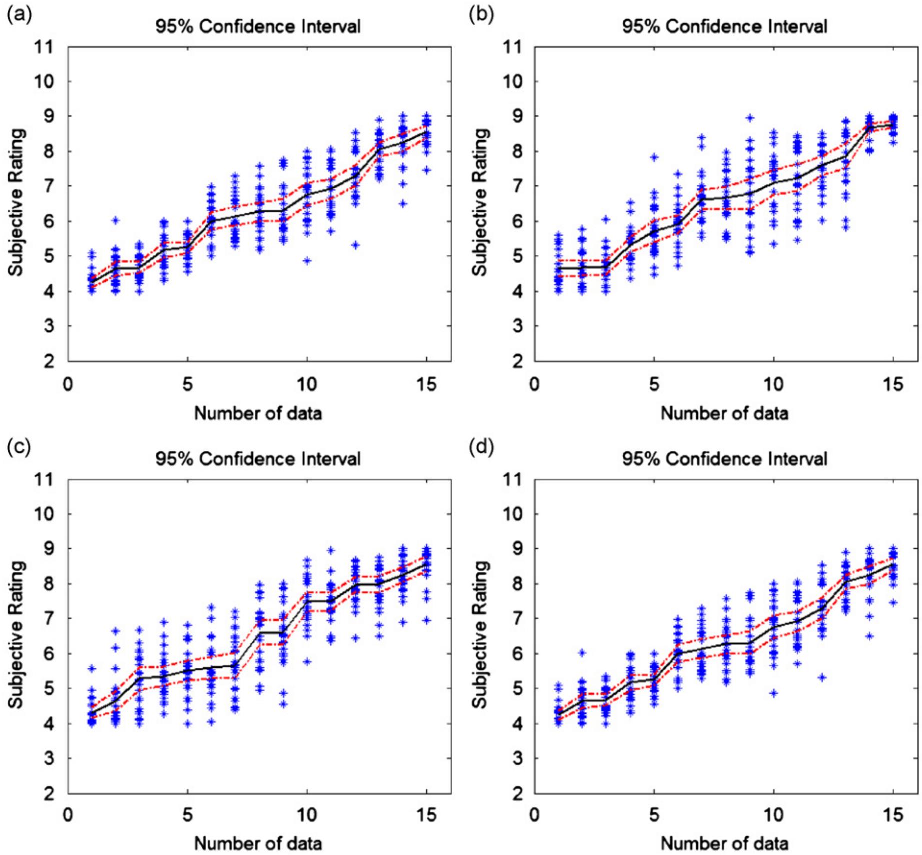

Fig. 5. Subjective ratings (*) and the mean values (——) and its 95% confidence interval (– · –) for (a) course 1, (b) course 2, (c) course 3, (d) course 4.

Table 2
Mean subjective ratings for each car and course (lowly-impulsive: rating of 4, highly-impulsive: rating of 9).

Car no.	Course 1	Course 2	Course 3	Course 4
1	7.96	7.59	6.62	8.04
2	8.32	8.66	7.49	8.56
3	7.90	4.65	8.56	4.24
4	6.53	4.64	5.35	6.76
5	5.07	6.66	5.59	6.14
6	4.25	4.66	4.63	4.67
7	7.14	5.32	4.30	5.24
8	5.14	5.90	7.97	4.64
9	8.30	6.77	6.59	7.29
10	7.41	7.24	5.50	6.31
11	8.79	8.76	7.48	8.26
12	6.59	7.10	7.98	5.99
13	6.02	7.86	5.65	6.92
14	5.97	6.61	8.25	6.26
15	6.08	5.71	5.27	5.16

metric based on CWT is explained as follows:

(1) *CWT for A-weighting impact noise signal*: Obtain an M by N wavelet coefficients matrix from the CWT for the A-weighted impact noise signal. The CWT for A-weighted impact noise signal $s(t)$ is defined by [15],

$$W(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} s(t)\psi^*\left(\frac{t-b}{a}\right) dt, \quad a \neq 0 \tag{1}$$

where $\psi(t)$ is the mother wavelet, a is called a scaling parameter, and b is the translation parameter. The parameter a represents the scale index, determining the center frequency of function $\psi(a^{-1}(t-b))$. The parameter b indicates the time shift. Suppose that $\psi(t)$ is centered at t=0 and its Fourier transform $\Psi(\omega)$ is concentrated at $\omega = \omega_0$. The center frequency of the function $\psi(t)$ is ω_0

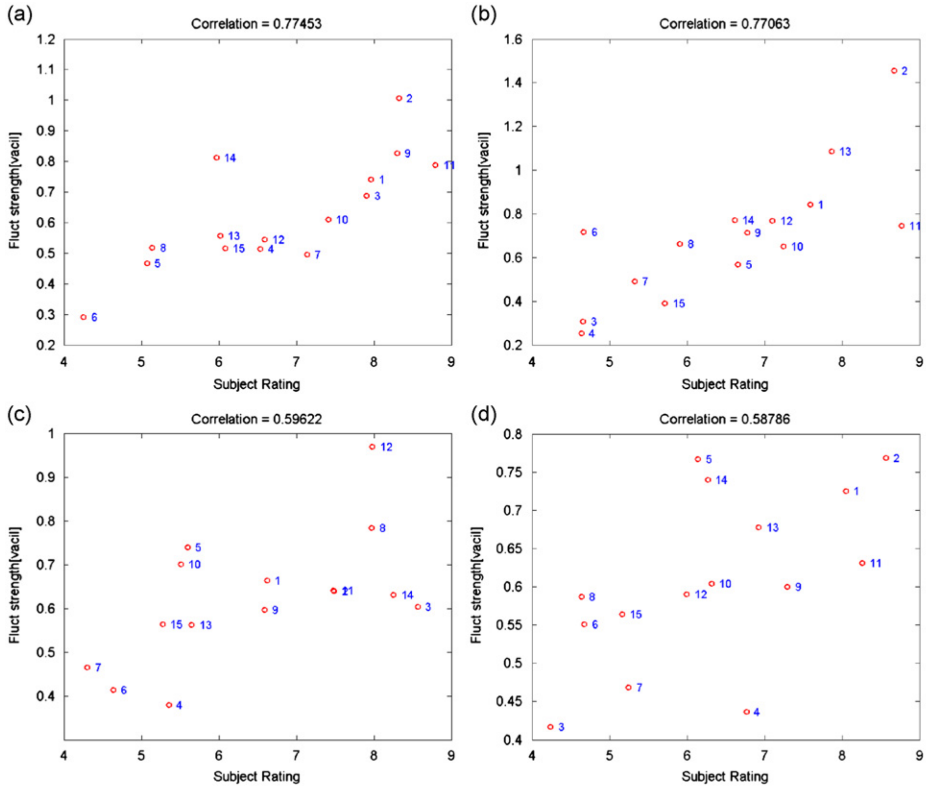

Fig. 6. Fluctuation strength and the subjective rating of 15 passenger cars for four impact courses (a) course 1, (b) course 2, (c) course 3, (d) course 4.

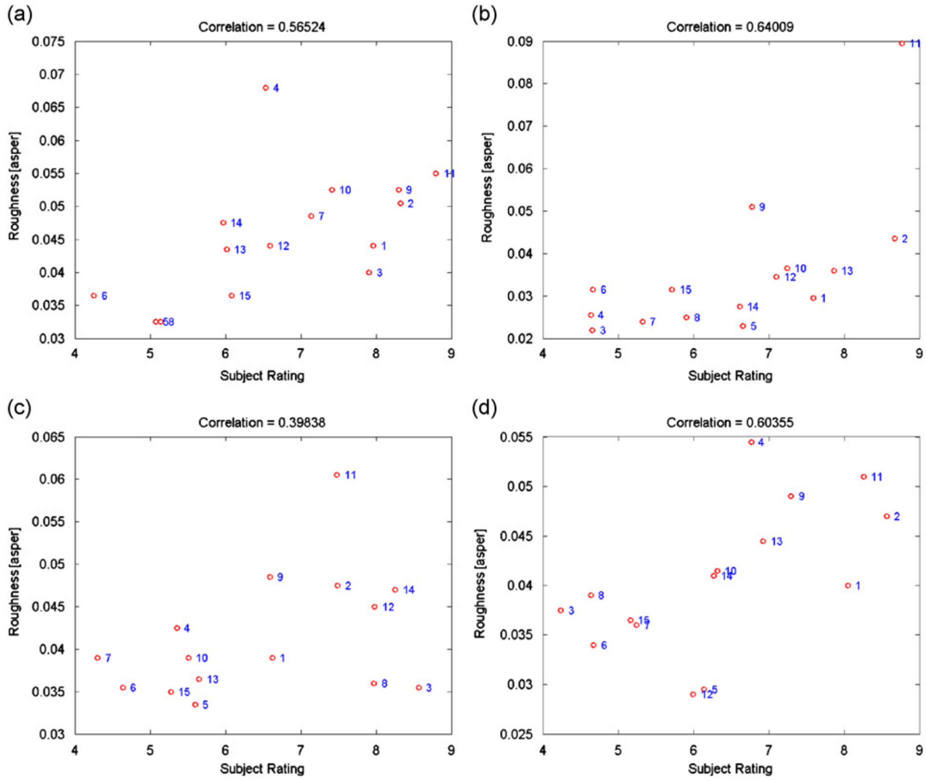

Fig. 7. Roughness and the subjective rating of 15 passenger cars for four impact courses: (a) course 1, (b) course 2, (c) course 3, (d) course 4.

and the center frequencies of its time-scaled version $\psi(t/a)$ will become a scale ω_0/a; that is, $\omega=\omega_0/a$. The time and frequency center of its dilated and translated version $\psi(a^{-1}(t-b))$ are b and $\omega=\omega_0/a$, respectively. Hence, the quantity *CWT* (a,b), the inner product of $s(t)$ and $\psi(a^{-1}(t-b))$, can be considered as quantities measure of signal's behavior in the vicinity of (b, ω_0/a).

$$CWT(a,b)|_{a=\omega_0/\omega, b=t} = CWT_{m,n} \tag{2}$$

where m is the m-th scaled frequency and n is the n-th time shift. Therefore the scaling parameter a is inversely proportional to the frequency. The CWT is a kind of the $1/n$ octave filters [16]. After transform, we obtain the M by N matrix from the CWT. M is the number of scaled frequency and N is the number of time shift.

(2) *Extraction of the impact parts from the signal*: Set the threshold at a high level that can extract only the impact parts according to the condition of the signal. The CWT for a raw impact noise signal includes the engine harmonic noise parts as shown in Fig. 8(a). The dot line means the m-th scaled frequency in CWT. The engine harmonic noise signals are sinusoidal and exist at low frequency. Fig. 8(b) shows a part of impact noise filtered by the m-th scaled frequency band filter of CWT. The impact noise signal has high energy level and is still interfered with engine noise. In order to extract only the impact noise part with high energy from CWT for a raw signal, A-weighting was given to a raw signal in the first step and the threshold level is selected in this step throughout iteration process as shown in Fig. 8(c). The y_i in this iteration process is a subjective rating. The iteration proceeds until the correlation arrives to a max value above 0.7. In this step, a new M by N matrix for wavelet coefficients, whose values are zero if under the threshold, is obtained.

(3) *Frequency-weighting $Freq_{m,n}$ for the impact parts*: Multiply the frequency values to the power of the extracted wavelet coefficients. This operation increases the contribution of high frequencies. The abrupt change in frequency is in most cases correlated with an audible click so that the just-noticeable variations in frequency (JNVF) are measured using frequency modulation. Our hearing system is relatively insensitive for changes in frequency modulation in low frequency range but is very sensitive to frequency variation in high frequency range [8]. Therefore, in the JNVF curves, the frequency resolution increases nearly in proportion to frequency. In the perception analysis of an audio signal, many various signal processing tools are used. These tools are designed by considering the JNVF curve. According to our previous results [17], the frequency resolution of CWT filter very well corresponds with JNVF curve as shown in Fig. 9. The frequency resolution in CWT filter is controlled by scaling parameter a, which in inversely proportion to the frequency. Therefore, in this step, by considering the perception characteristics for impact noise in human hearing system, the $CWT_{m,n}$ for impact noise is multiplied by frequency weighting $Freq_{m,n}$ which is an inversely proportion function according to relationship between scaling parameter a and frequency ω; that is, $\omega=\omega_0/a$.

(4) *Final equation for the sound metric*: Divide the power of the extracted coefficients by the power of the coefficients of the original CWT so as to normalize the magnitude of the coefficients and summate the normalized coefficients matrix.

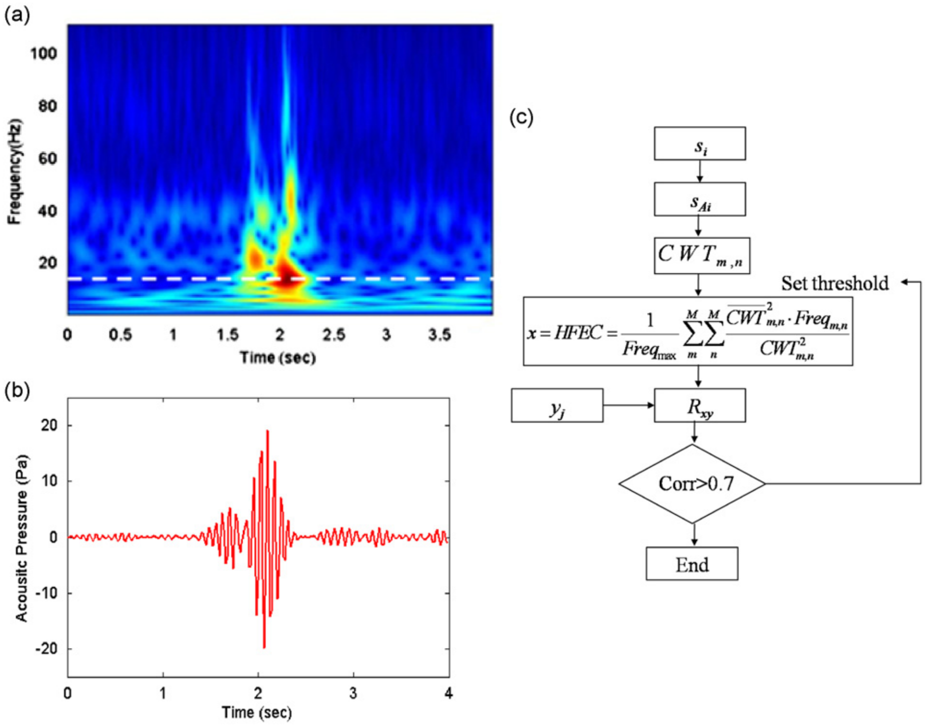

Fig. 8. Algorithm for FFEC development and set of threshold for extraction of impact part from CWT for the impact noise. (a) Image map for wavelet coefficients, (b) wavelet coefficient used for a set of thresholds, (c) extraction process of a sound metric, HFEC.

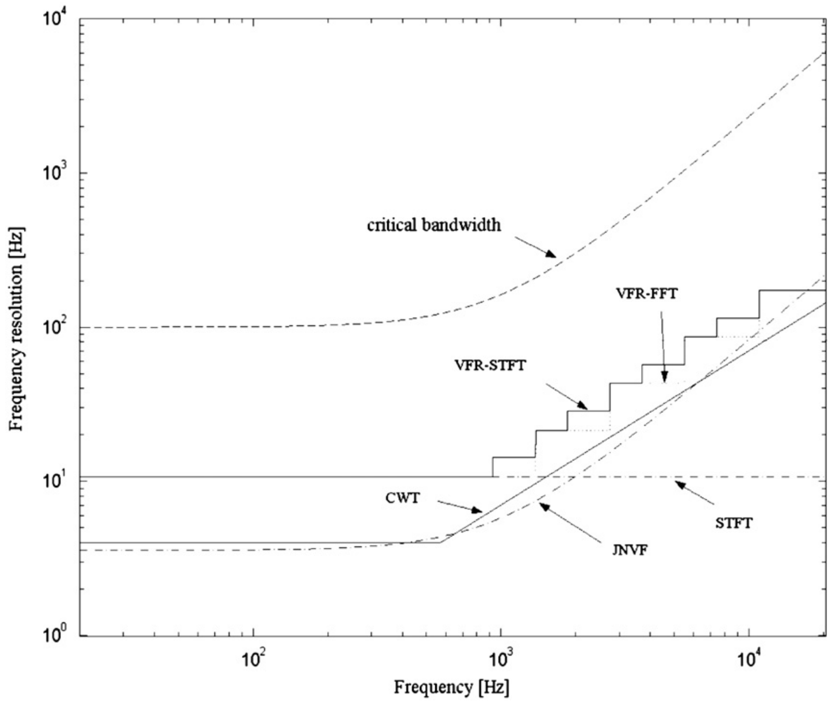

Fig. 9. JNVF and critical bandwidth as a function of frequency. VFR-STFT (variable frequency resolution-STFT), VFR-FFT (variable frequency resolution Fourier transform), STFT (short Fourier transform), CWT (continuous wavelet transform), JNVF (just-noticeable variation in frequency theory).

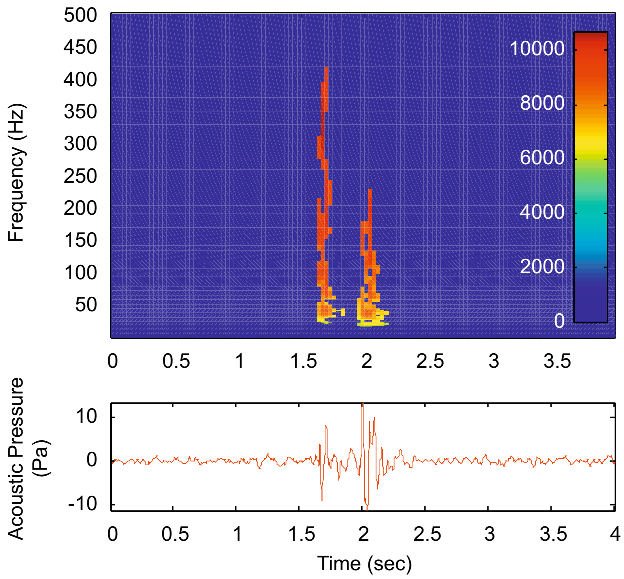

Fig. 10. Wavelet coefficients with frequency weighting for impact noise after frequency weighting.

Finally, divide the calculated value by the maximum frequency. The outcome value is dimensionless. This metric, HFEC (high frequency energy contribution), can be expressed by the following equation:

$$HFEC = \frac{1}{Freq_{\max}} \sum_{m}^{M} \sum_{n}^{N} \frac{\overline{CWT}_{m,n}^{2} \cdot Freq_{m,n}}{CWT_{m,n}^{2}}, \quad \overline{CWT}_{m,n} : \text{extracted CWT of high level} \tag{3}$$

where $CWT_{m,n}$ is the wavelet coefficient, $\overline{CWT}_{m,n}$ is the wavelet coefficient above the threshold, and $Freq_{m,n}$ is the frequency weight at the impact time. The frequency weighting is given because the impact noise contains the high frequency components. Fig. 10 presents the extracted and the frequency-weighted coefficients matrix. The acceptability of the HFEC

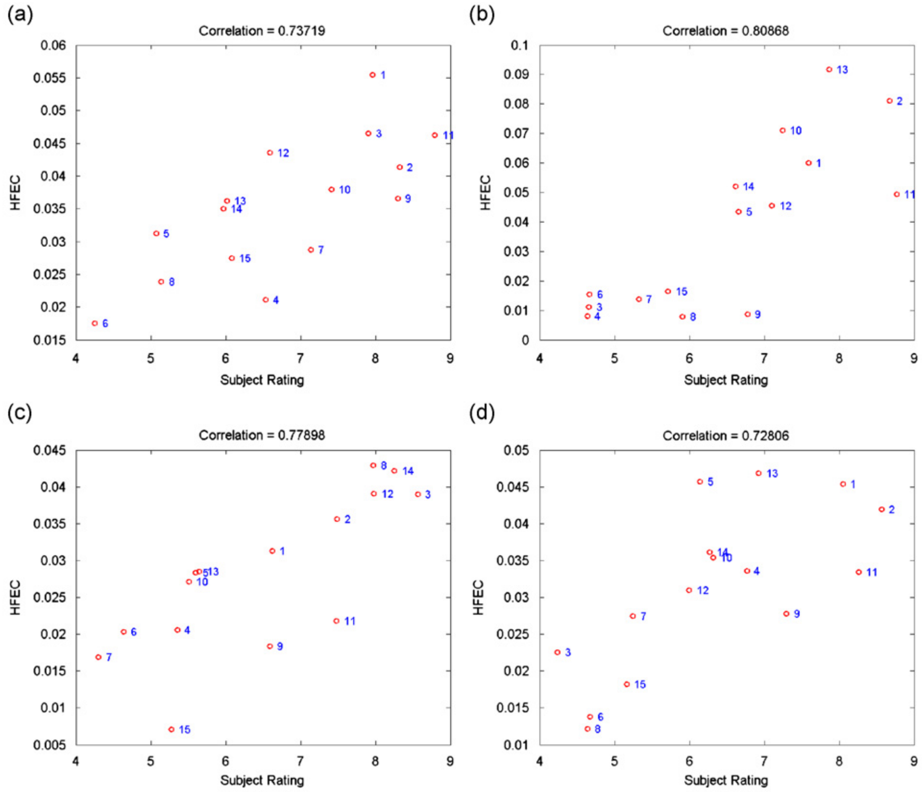

Fig. 11. HFEC and the subjective rating of 15 passenger cars for four impact courses: (a) course 1, (b) course 2, (c) course 3, (d) course 4.

Table 3
Correlation between sound metrics and subject rating at each course.

Course no.	First	Second
Course 1	Fluctuation strength 0.7745	HFEC 0.7372
Course 2	HFEC 0.8087	Fluctuation strength 0.7706
Course 3	HFEC 0.7790	Fluctuation strength 0.5962
Course 4	HFEC 0.7281	Roughness 0.6036

is examined by comparing its correlation with the subjective rating in the paper [6]. Fig. 11 shows the HFEC values measured for 15 passenger cars on four test courses.

The sound metrics chosen for each course are respectively summarized in Table 3. Among the three major sound metrics discussed in this section, two metrics having high correlation for each course are selected for each course as the input of the MLR model in order to develop the sound indexes, because the sound metric having a low correlation with the subjective rating does not affect the sound index significantly. Therefore, the third correlated metric was not used in the development of the sound index, since it has low correlation and thus only the two high correlated metrics were used in the development of sound metrics.

4. Development of impact sound indexes

MRL and the ANN are two methods for modeling the sound quality index. The ANN is a useful tool for the presentation of a nonlinear model but demands many data for training the model. On the other hand, the MLR requires not only a relatively small number of data, but also can make reasonable outputs even through simple calculations. Therefore, in this research, the multiple regression method is used, since the number of sounds of the sample car is only 15 for each course.

The mathematical expression of multiple regressions is given by

$$Y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \varepsilon \tag{4}$$

where Y_i is the sound index for 15 impact sounds, $i = 1,2,3,\ldots,n$, β is the weighting coefficient to be determined throughout multiple regression, β_0 is the y-axis intercept, and x is the related input sound metrics. The determined weighting values for each course are summarized in Table 4. Therefore, these weighting values can be used for the sound quality index for the 15 impact sounds of the passenger cars. β_0 and β_i (i=1,2,…,k) are unknowns, which have to be estimated from Y_i and x_i. When the estimated unknowns are b_0 and b_i (i=1,2,…,k), the estimated equation for multiple regressions can be expressed as

$$\hat{y}_i = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_k x_k \tag{5}$$

When two sound metrics are used, Eq. (3) can be rewritten as

$$\hat{y}_i = b_0 + b_1 x_1 + b_2 x_2 \tag{6}$$

Table 4 shows the y-axis intercept b_0, the weighting coefficient b_k, and the sound metric x_k used for developing the sound quality index for 15 sounds of four courses. Finally, the subjective ratings can be estimated through Eq. (6). Fig. 12 shows

Table 4
Factors of sound quality index for impulsiveness at each course by using two sound metrics listed in Table 1.

Course no.	b_0	b_1	b_2
Course 1	−0.8020529	0.4814040	0.7641221
Course 2	−0.3019698	0.5695469	−7.6625514
Course 3	−2.5269508	0.5405098	10.1133477
Course 4	−1.7994997	0.5476082	−2.0975628

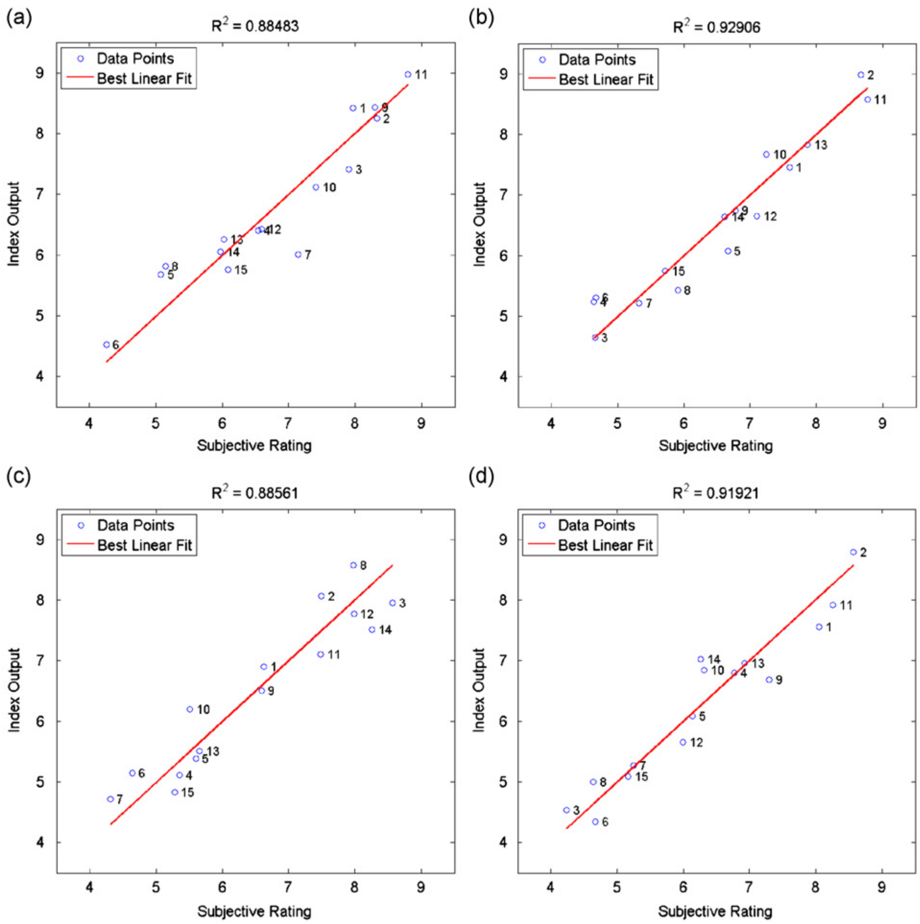

Fig. 12. Index outputs and subjective ratings of 15 passenger cars for four impact courses: (a) course 1, (b) course 2, (c) course 3, (d) course 4.

the correlation between the subject evaluation and sound quality index output for the 15 sounds of each course. The vertical axis is the index output and the horizontal axis is the subjective rating for the 15 impact sounds. The sound quality index for each sound is developed by multiple regressions. The square of the correlation between the index output and subjective evaluation is greater than 0.88.

5. Applications of sound quality index

The impact sound quality index is made by using three sound metrics for each course. In this section, the reliability of the index is confirmed by examining the impact sound generated when some parts of a car are modified.

5.1. Modification of suspension components for improvement of sound quality

The reliability of the given indexes is verified by a new impact noise, which was recorded after the suspension component of one of the test cars was modified. Five parts of the suspension were substituted, and the substituted parts are shown in Fig. 13. The specific information for the modifications is summarized in Table 5. Case 1 (increasing of tire pressure), case 2 (increasing of stiffness for insulator), and case 5 (removal of void for trailing arm bushing) show high value of subjective rating, as predicted. It is also expected that case 3 (low damping of shock absorber) has a low subjective rating. In case 4, the length of the bumper stopper is reduced with the expectation that its stiffness will be modified. Additionally, the impact noise of a car where no parts were replaced was recorded as a reference.

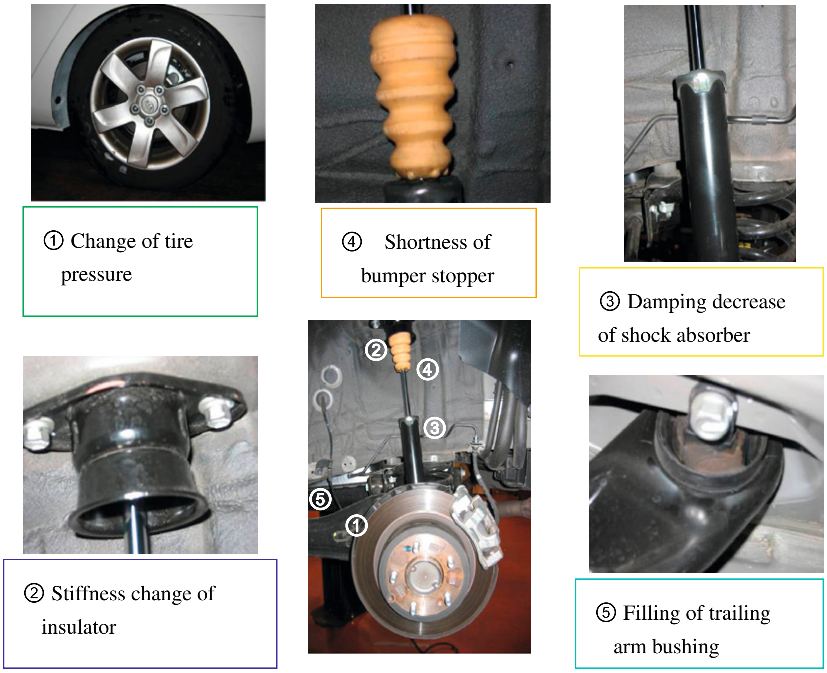

Fig. 13. Modification of components of the suspension system of the test car.

Table 5
List of the modification of the suspension system.

No.	Modified conditions
1	Tire pressure: 40 psi (reference: 33 psi)
2	Stiffness of insulator: HS65 (reference: HS55)
3	Decrease of damping for shock absorber
4	Shortening in the length of bump stopper
5	Filling of trailing arm bushing

5.2. Evaluation of impact sound quality

Provided an appropriate sound quality index is given, it is possible to predict the subjective ratings without a jury test. In the previous section, four sound indexes were produced for four courses that induce impact sound. Fig. 14 shows the estimated subjective ratings for the four different courses obtained by using these sound quality indexes. High tire pressure increases the impact force, when the tire contacts the impact bump it may increase the impact noise, since the vibration damping of the tire is decreased (case 1). Also, high stiffness of an insulator in the suspension system increases the transmission of the impact vibration from the suspension system to the car body. This becomes a source of impact noise (case 2). In the same manner, the removal of a void in a trailing arm bushing increases the stiffness of the bushing rubber and increases the transmission of impact vibration (case 5). Therefore, the subjective rating of impact noise for these three cases is high at each course, as shown in Fig. 14. On the other hand, case 3 shows a low subjective rating value for impact noise, because the impact vibration is absorbed as the damping of the shock absorber is increased. Fig. 14 shows that the subjective rating of impact noise for case 4 is not significantly different from that of the reference case. This indicates that the length of the bump stopper does not affect the quality of impact noise. These results demonstrate that the developed sound indexes are very useful for objective evaluation of impact noise induced when the passenger car is driven over the impact system on the road, without requiring subjective jury test. For the validation of these results, the impact noises are evaluated subjectively by the participants for a jury test. The results are compared with the index outputs. Fig. 15 shows the comparison between the index outputs and subjective ratings, indicating good correlation. Therefore, the developed impact sound indexes can be useful for improving impact sound quality in automotive engineering.

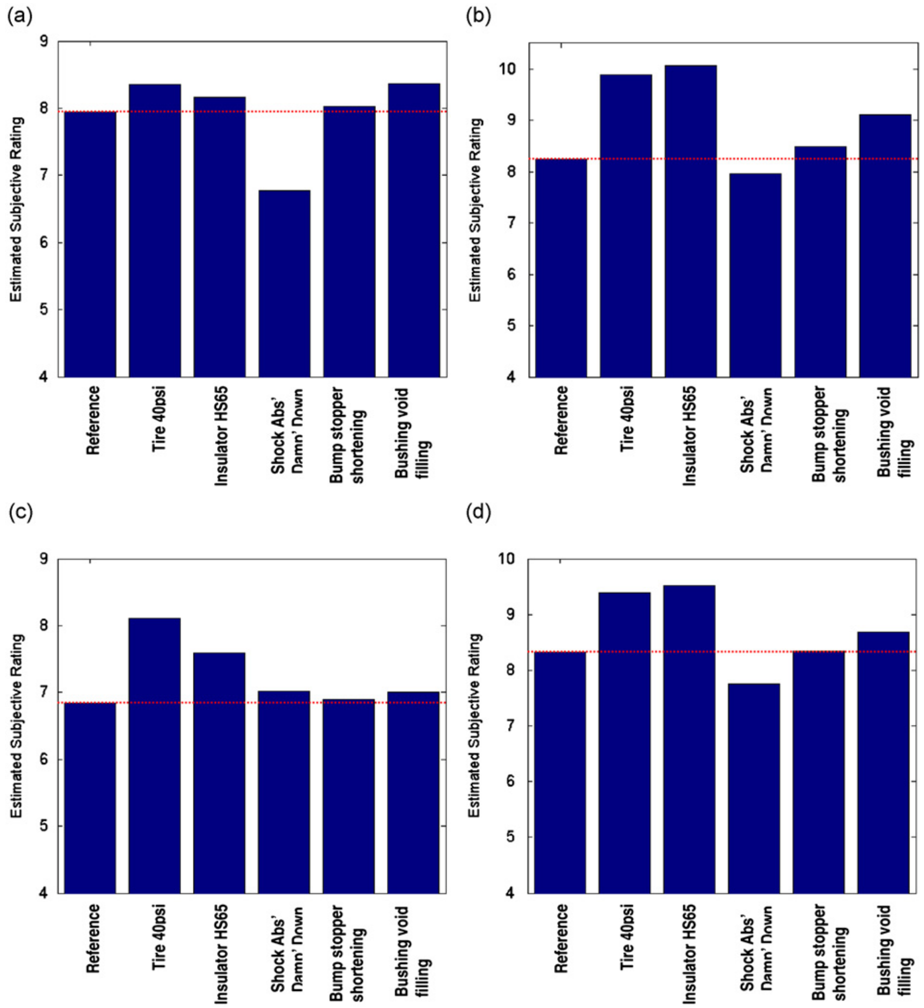

Fig. 14. Estimated subjective ratings for impact noise induced by modification of components of the suspension system (dashed line: reference rating): (a) course 1, (b) course 2, (c) course 3, (d) course 4.

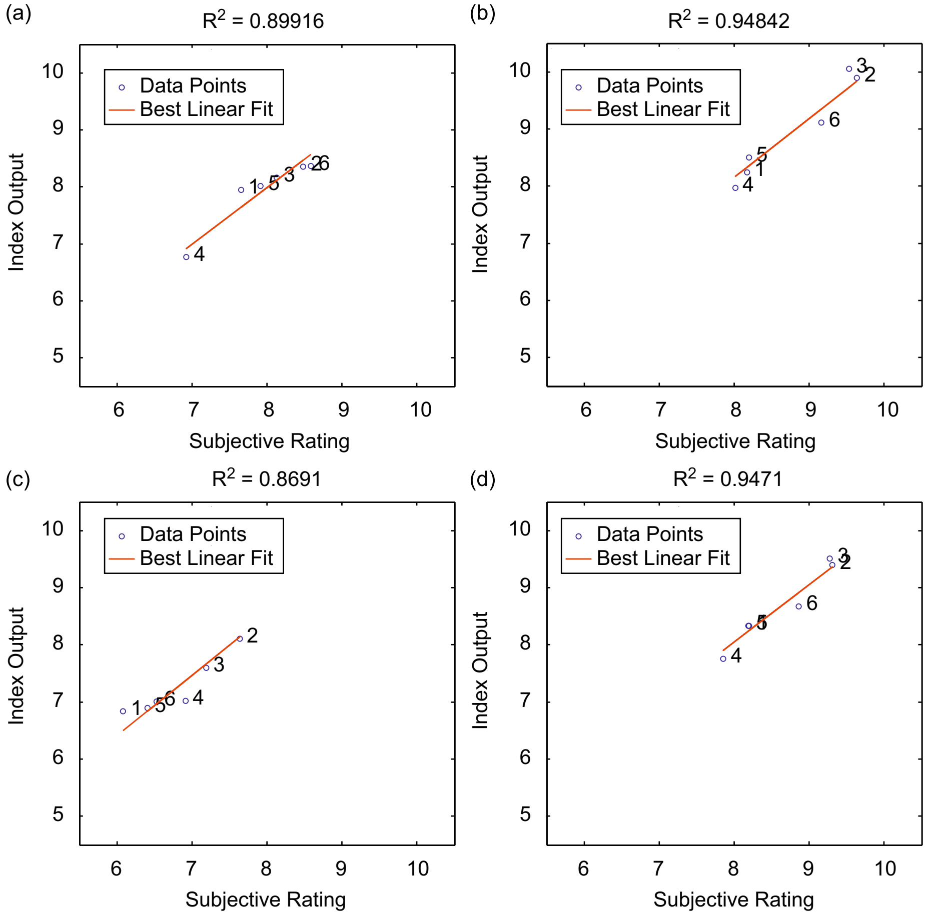

Fig. 15. Comparison between index outputs and subjective ratings for impact noise induced by modification of components of the suspension system: (a) course 1, (b) course 2, (c) course 3, (d) course 4.

6. Summary and conclusions

Impact sound indexes are developed based on sound metrics and a subjective test for impact noise. A new sound metric is based on a wavelet transform with consideration of human perception for impact sound. Four sound indexes were made for an objective sound quality evaluation of impact noise corresponding to four different impact courses on the specific road. The sound quality indexes could estimate the subjective evaluations without any jury test. The square value of correlations between the estimated subjective values (index output) and the real subjective ratings exceeded 0.88 for all the courses. Finally, the sound quality index was successfully applied to an objective evaluation for impact noise induced when the suspension components of the test car were modified for improvement of the impact sound quality.

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References

[1] D. Hamilton, Sound quality of impulsive noises: an applied study of automobile door closing sounds, in: Proceedings of the 1999 SAE Noise and Vibration Conference, Traverse City, Michigan, USA, 1999, SAE paper 1999-01-1684, Society of Automotive Engineers, New York.

[2] P. Sellerbeck, C. Nettlebeck, R. Heinrichs, T. Abels, Improving diesel sound quality on engine level and vehicle level—a holistic approach, in: Proceedings of the 2007 SAE Noise and Vibration Conference, Chicago, Illinois, USA, 2007, SAE paper 2007-01-2372, Society of Automotive Engineers, New York.

[3] S.K. Lee, H.C. Chae, The application of artificial neural networks to the characterization of interior noise booming in passenger car, *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 218 (1) (2004) 33–42.

[4] Y.S. Wang, J.M. Lee, D.G. Kim, Y. Xu, Sound quality prediction for nonstationary vehicle interior noise based on wavelet pre-processing neural network model, *Journal of Sound and Vibration* 299 (2007) 933–947.
[5] D. Vastfjall, M.A. Gulbol, M. Klieiner, T. Garling, Affective evaluation of reactions to exterior and interior vehicle auditory quality, *Journal of Sound and Vibration* 255 (3) (2002) 501–518.
[6] H.W. Kim, S.K. Lee, Impact sound quality analysis of passenger vehicle, in: Proceeding of the Sixteenth International Congress on Sound and Vibration (ICSV16), Krakow, Poland, 5–9 July, 2009.
[7] S.K. Lee, P.R. White, Application of wavelet analysis to the impact harshness of a vehicle, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 214 (C11) (2000) 1331–1338.
[8] E. Zwicker, H. Fastl, *Psychoacoustics: Facts and Models*, second ed., Springer-Verlag, Berlin, 1999.
[9] W.A. Aures, The sensory euphony as a function of auditory sensations, *Acoustica* 58 (1985) 282–290.
[10] W.R. Dillon, M. Goldstein, *Multivariate Analysis: Methods and Applications*, John Wiley & Sons, New York, 1984.
[11] S.K. Lee, Objective evaluation of interior sound quality in passenger cars during acceleration, *Journal of Sound and Vibration* 310 (2008) 149–168.
[12] H. Matrn, *Neural Network Design*, PWS Publishing Company, New York, 1996.
[13] S.K. Lee, T.G. Kim, J.T. Lim, Characterization of an axle-gear whine sound in a sport utility vehicle and its objective evaluation based on synthetic sound technology and an artificial neural network, *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 222 (3) (2008) 383–396.
[14] N. Otto, S. Amman, C. Eaton, S. Lake, Guidelines for jury evaluations of automotive sounds, *Journal of Sound and Vibration* 35 (2001) 24–47.
[15] S. Qian, *Introduction to Time-Frequency and Wavelet Transforms*, Prentice Hall, New Jersey, 2002.
[16] S.K. Lee, An acoustic decay measurement based on time-frequency analysis using wavelet transform, *Journal of Sound and Vibration* 252 (1) (2002) 141–152.
[17] S.K. Lee, K.S. Park, J.S. Suh, Modeling of the time-frequency auditory perception characteristics using continuous wavelet transform, *Journal of the Acoustical Society of Korea* 20 (8) (2001) 1–7.