

Vehicle Interior Sound Quality Analysis by Using Grey Relational Analysis

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ABSTRACT

In this paper, the relationship was investigated between objective psychoacoustic parameters, A-weighted sound pressure level (SPL) and the results of the subjective evaluation by using grey relational analysis (GRA). The sounds were recorded with eight different passenger cars at four different running conditions. The sound quality indices were calculated, including loudness, sharpness, roughness, fluctuation, and A-weighted SPL. Subjective evaluation was performed by thirty subjects using rating scale method. GRA was compared with traditional correlation analysis, and the comparison shows that some hidden information which could not be found in the traditional correlation analysis was revealed. In order to know the further relationship between fluctuation and subjective evaluation, another subjective evaluation was performed by the same 30 subjects. The result demonstrates that the relationship revealed from GRA is correct. Furthermore, some measures were presented to improve the sound quality of vehicle interior noise. Both of the improved measures were applied on one of the test vehicles, and the comparison between the sound quality indices of the original and improve vehicles shows that the sound quality can be improved effectively based on GRA.

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INTRODUCTION

Quiet driving conditions have become available owing to development of noise reduction techniques in automobiles in recent years. Vehicle design has been concentrated on performance improvement because of customers' increasing demand for a quiet and comfortable vehicle interior environment [1]. Numerous vehicle noise sources and excitations including cavity booming, driveline rumble, timing belt whine, gear rattle, intake hiss, exhaust roar, brake judder, wind whistle, brake groan, tire whiz, door closing sound, air conditioning noise, power window noise, etc. are related to numerous perceptual feelings and their properties [2,3,4]. A large research effort related to sound quality of vehicle interior noise has been presented, and human perceptive factors that lead to positive emotional states have been taken into consideration [5,6,7]. There are both evaluation methods including subjective and objective evaluations used for sound quality analysis [8]. Various psychoacoustic indices including A-weighted sound pressure level (SPL), sharpness, loudness, roughness, etc. are commonly used to evaluate interior noise of vehicle [9].

Vehicle sound quality is a wide subject. Gabriella Cerrato [10-11] studied on the sound quality of powertrain, wind noise, road noise, accessories, BSR (Buzz, Squeak and Rattle), brake noise, and door open/close noise. Active noise control methods have been applied to sound quality analysis. Oliveira, et al. [12] evaluated numerically and experimentally, the effect of a feedback controller on the sound quality of a vehicle mockup excited with engine noise. Kuo, et al. [13] studied on several broadband active sound quality control algorithms based on delayed frequency-domain techniques and sub-band adaptive filters, and the algorithm was also simulated in applications requiring high-order adaptive filters. Also, A. Gonzalez, et al. [14] evaluated the ability of active noise control systems to achieve a more pleasant sound throughout sound quality analysis of a real multi-channel active noise controller.

Several correlation analysis methods including graphing method, linear regression, and multiple linear regression, etc. are commonly used [15-16]. Traditional mathematical statistics methods are suitable for large scale samples. However, these

methods often require samples assume a normal distribution. The distribution of data needs to be verified based on mass of samples. The assumption of normal distribution can not be proven when there are few samples, even though it is consistence with the fact.

In the early 1980s, Deng [17-18] proposed a grey relational analysis (GRA) method. GRA is a method for measuring the degree of approximation among the sequences with a grey relational grade. Grey relational analysis theories have attracted various interests among researchers. GRA has been proven to be useful for dealing with incomplete, uncertain, and poor information. In GRA, black represents having no information, white represents having all information, and a grey system has a level of information between black and white. It avoids the inherent shortages of traditional statistical methods, and it only requires limited data to estimate the characteristics of an uncertain system. Also, it can provide efficient solutions to the uncertain, discrete, and multi-input data problems [19].

GRA is an effective method analyzing the relationship between sequences with grey information. It has been applied in numerous fields [20,21,22]. Zheng, et al. [23] applied improved grey relational projection method to evaluate sustainable building envelop. Tseng [24] proposed a combined fuzzy grey relational analysis method to evaluate the environmental knowledge management capacity. Du, et al. [25] presented the portable hand motion classifier for multi-channel surface electromyography recognition using GLA. Optimization methods are also combined with GLA to deal with complicated problems [26,27,28]. Artificial neural network are also used together with GRA. Lai, et al. [29] designed the product image using GRA and neural network models.

In this research, the grey relational analysis was performed between objective psychoacoustic parameters, A-weighted SPL and results of the subjective evaluation. Some hidden information which can not be found in traditional analysis was revealed. Eventually, some improved measures for sound quality was presented.

GREY RELATIONAL ANALYSIS

Data Processing

In the grey relational analysis, the function of factors can be neglected when the range of the sequence is large or the standard value is numerous. However, incorrect results might be caused using grey relational analysis if the factors goals and directions are different. Thus, the data which are relevance to a group of sequences called "grey relational generation" have to be preprocessed [17-18].

Initializing operator is usually used for data normalization. The original sequences can be normalized with the simplest method of initializing operator that is all the values of the original sequence could be divided by the first value of the sequence. The normalized sequence can be written as

$$x_i^*(k) = \frac{x_i^{(o)}(k)}{x_i^{(o)}(1)} \quad (1)$$

where $x_i^{(o)}(k)$ is the original sequence of subjective evaluation values and sound quality indices, $x_i^*(k)$ is the sequence after the data normalization, where, $i = 1, 2, \dots, m$ and $k = 1, 2, \dots, n$.

Grey Relational Coefficient and Grey Relational Grade

A grey relational coefficient can be computed with the preprocessed sequences, after data processing is performed.

The grey relational coefficient [26] can be expressed as

$$\gamma(x_o^*(k), x_i^*(k)) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{oi}(k) + \zeta \Delta_{max}} \quad (2)$$

where $\Delta_{oi}(k)$ is the deviation sequence of the reference sequence $\Delta_o^*(k)$ and the comparability $\Delta_i^*(k)$, for example, $\Delta_{oi}(k) = |\Delta_o^*(k) - \Delta_i^*(k)|$ is the absolute value of the difference between $\Delta_i^*(k)$ and $\Delta_o^*(k)$, ζ is distinguishing coefficient, $\zeta \in [0, 1]$,

$$\Delta_{min} = \min_{\forall i} \min_{\forall k} \Delta_{oi}(k), \Delta_{max} = \max_{\forall i} \max_{\forall k} \Delta_{oi}(k).$$

The purpose of defining the relational coefficient is to show the relational degree between $x_o^*(k)$ and $x_i^*(k)$. The grey relational grade is an average value of the grey relational coefficients, and it is expressed as

$$\Gamma(x_o^*, x_i^*) = \frac{1}{n} \sum_{k=1}^n \gamma(x_o^*(k), x_i^*(k)) \quad (3)$$

The grey relational grade $\Gamma(x_o^*, x_i^*)$ is the level of correlation between the reference sequence and the comparability sequence. The values of grey relational grades are equal to 1 if two sequences are coincidence. Also, the grey relational grade means the degree of influence that the comparability sequences can exert on the reference sequence. Thus, if some comparability sequence is less important than the other comparability sequence to the reference sequence, then, the grey relational grade for the first comparability sequence will be smaller than the other grey relational grade. Actually, GRA is

an absolute value measurement of data difference between sequences, and it can be applied to measure approximate correlation between sequences.

Table 1. Sound quality indices of the 32 different samples

Sample NO.	Loudness (sone)	Sharpness (acum)	Roughness (asper)	Fluctuation (vacil)	SPL (dB(A))
01	41.223	0.9641	1.0811	0.4744	72.7
02	30.155	0.8703	0.4857	0.2078	63.0
03	33.232	0.9809	0.9728	0.5707	66.4
04	54.29	1.0781	1.5348	0.2344	76.5
05	52.859	1.0706	1.2736	0.3483	75.9
06	49.400	1.3116	2.0941	0.2391	73.4
07	17.415	0.9546	0.4719	0.3414	57.8
08	53.069	1.0326	1.4339	0.1722	75.4
09	22.302	0.9863	0.5467	0.3736	55.8
10	39.672	0.9651	0.8231	0.4896	75.3
11	38.869	1.1034	1.7631	0.4186	66.5
12	24.029	0.7578	0.5762	0.1892	60.8
13	36.506	1.0763	0.8019	0.5309	65.1
14	29.896	0.9785	1.2820	0.4563	58.7
15	18.301	0.9659	0.6931	0.3007	59.4
16	51.893	1.2357	2.1764	0.2038	71.7
17	42.764	1.1082	1.4974	0.4735	65.4
18	20.58	0.9803	0.8335	0.3667	56.4
19	44.357	1.097	2.1024	0.3871	72.2
20	19.486	0.7934	0.5647	0.1972	55.6
21	41.885	0.9537	1.7023	0.5364	63.9
22	32.134	0.8867	1.1753	0.4380	60.6
23	45.067	1.1875	1.8670	0.3896	71.1
24	27.401	0.9862	0.6318	0.2674	57.7
25	36.423	1.0676	1.5045	0.5212	75.1
26	38.229	1.0778	1.6523	0.4955	66.6
27	30.367	0.9345	1.2046	0.3934	73.3
28	25.972	0.8984	0.6097	0.2894	61.6
29	43.079	1.2045	1.6637	0.2767	74.7
30	35.605	0.9578	1.4780	0.5567	78.2
31	25.855	0.7819	0.4625	0.2183	63.8
32	44.503	0.9906	1.2560	0.5033	71.1

SOUND RECORDING AND SUBJECTIVE EVALUATION

Sound Recording

Vehicle interior noises from eight vehicles of several different brands were recorded at four different conditions. Binaural recording was performed using an artificial head (Bruel and Kjaer 4133) placed on the second pilot seat, on an asphalt road. The artificial head was adjusted until its microphones were in ear positions for an average passenger. The recording differs depending on whether the accessories such as air conditioning, audio set, etc. are on or off. In order to acquire the sounds including powertrain noise, transmission noise, intake noise, exhaust noise, road noise, and wind noise, all accessories were closed during the process of the sound recording. All the recordings were edited for later analysis, obtaining sound files of 5 seconds duration. If the sounds are too long, the subjects will be bored, if they are too short, the subjects will not perceive the sound characteristics.

Sound Quality Indices

Generally, several sound quality indices [30] are usually used, including sound pressure level (SPL)-A level, loudness, sharpness, roughness, and fluctuation. The sound quality indices of 32 different sound samples were calculated respectively, and they are shown in [Table 1](#).

Subjective Evaluation

The interior noise recorded was evaluated by using the rating scale method [31], which evaluates sound quality on a given rating scale as numbers. Thirty-two sound samples, which were comprised of all of recorded sounds, were evaluated. All sound samples in the listening test were arranged in random order, and one of the sounds was used to be a reference sound. Thirty subjects participated in the listening test. Subjects were composed of students studying NVH performance of vehicle, professors researching on automobile, drivers, NVH staffs of a vehicle producer. The age composition of subjects was 18 subjects in 20s, 8 subjects in 30s, and 4 in 40s. Meanwhile, the sex composition of subjects was 20 males and 10 females. Twenty-scaled rating was adopted, and the rating scale was shown in [Table 2](#). Scale '1' means 'not annoying', scale '20' indicates 'very annoying', the interior noise becomes more and more annoying as the scale increases. The results of the subjective evaluation are shown in [Table 3](#).

Table 2. Rating scale of the subjective evaluation

Rating	Annoying																			
	No				A little				Even				More				Very			
Scale	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Table 3. Results of the subjective evaluation

Sequence NO.	1	2	3	4	5	6	7	8
Sample NO.	12	20	02	31	24	15	28	07
Rating Scale	2.79	3.22	3.59	4.07	4.54	4.63	4.97	5.55
Sequence NO.	9	10	11	12	13	14	15	16
Sample NO.	18	09	27	22	14	30	03	26
Rating Scale	5.70	5.99	6.36	6.55	7.02	7.37	7.50	7.72
Sequence NO.	17	18	19	20	21	22	23	24
Sample NO.	25	10	32	17	21	01	13	23
Rating Scale	8.01	8.24	8.36	8.61	8.81	9.32	9.97	10.25
Sequence NO.	25	26	27	28	29	30	31	32
Sample NO.	11	16	29	19	05	08	04	06
Rating Scale	10.86	11.38	11.83	12.14	12.82	13.09	13.27	14.91

GREY RELATIONAL ANALYSIS BETWEEN SUBJECTIVE EVALUATION AND SOUND QUALITY INDICES

Grey Description of the Experiment Results

Grey system is described by grey number, grey equation, grey sequence, etc. According to grey system theory, grey number is the number which is uncertain and in a limited scope. Also, it is the basic unit or cell in grey systems. In traditional statistics research, samples are usually small under the constraint of some objective conditions. The mean value of the statistical data can not be assigned as central value, and the variance of the data also can not represent the right distribution characteristic in the meaning of statistics. However, variation regularity can be found based on the digging up, arrangement and in-depth analysis of the raw data using grey system principle, which is a way of seeking objective regularity through raw data. The mean value of the grey system theory can represent grey number which is called white value of the corresponding grey number.

Correlation analysis is widely used between sound subjective evaluation and objective psychoacoustic parameters. As far as author's knowledge, grey system theory used in correlation analysis of sound quality has not been found. In this research, there are 32 samples, which is suitable for the definition of grey number. Thus, the correlation analysis between subjective evaluation and objective psychoacoustic parameters can be performed using grey system theory. A group of white numbers can be obtained during the process of researching the characteristic of system, and they can be assigned as white values of grey process which are called grey sequence.

The results of subjective evaluation were regarded as primary sequence, which can be expressed as

$$x_0(j), j = 1, 2, \dots, n \quad (4)$$

The objective psychoacoustic parameters were regarded as secondary sequence, which can be written as

$$X = \begin{bmatrix} x_1(1) & x_1(2) & \cdots & x_1(n) \\ x_2(1) & x_2(2) & \cdots & x_2(n) \\ \vdots & \vdots & \ddots & \vdots \\ x_m(1) & x_m(2) & \cdots & x_m(n) \end{bmatrix} \quad (5)$$

where, m is the number of the samples, n is the number of the sound quality indices. In this research, m and n are set as 32 and 5, respectively.

The curve of the primary grey sequence is shown in Fig. 1, and the curves of the secondary sequences are shown in Fig. 2.

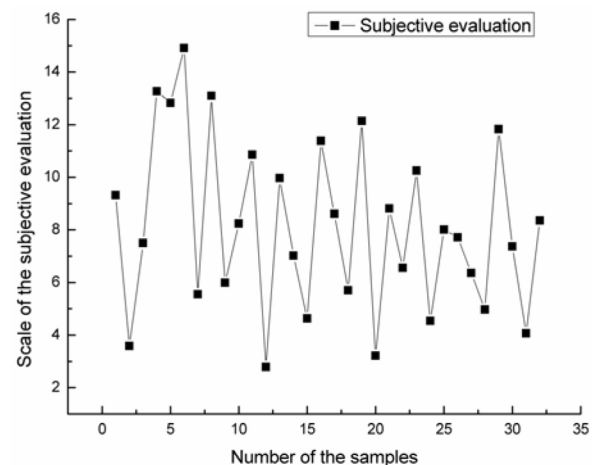


Fig. 1. Curve of primary grey sequence