Parametric model for low-frequency index of subjective car interior sound quality

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Abstract: Low-frequency character is one of the most important properties for car interior noise quality, subjective sensation of this kind of sound character is usually expressed in the context of powerful, booming, annoying, and/or even offensive as indicated in some literatures. This study is to establish an index for sound quality focused on subjective perception of car interior noise with low frequency contents. In order to obtain an appropriate verbal descriptor for this feature, questionnaire for verbal description through subjective listening and imaging of sounds are carried out. A verbal expression "Dichen" in Chinese was concluded from statistical analysis of subjective listening data. Jury tests for indicator "Dichen" was performed by using binaurally recorded car interior noise as stimuli; subjective results are analyzed and correlated with objective quantities. Mathematical model for "Dichen" is developed as a function of 1/3 octave sound pressure levels, sharpness and roughness quantities. The proposed model was verified by data collected from sub jective assessment with paired comparison and semantic differential methods. Results indicate a strong correlation between model predicted and subjective data, and therefore proved the developed model an effective index for subjective low-frequency perception.

Key words: sound quality descriptor; low-frequency contents; subjective model; car interior noise

车内噪声品质低沉度参量的数学模型

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摘要：低频成分的噪声是车内噪声的主要特征之一，并对车辆的力度、轰鸣、烦恼等主观听觉感知特征产生影响，本文的研究旨在建立车内低频噪声的主观声品质评价的参量和数学模型。首先采用听音和想象法等词汇描述进行主观问卷调查，通过对调查得到描述词汇的统计分析，得到了描述车内噪声低频特征的中文描述词-低沉。然后采用仿真头双耳记录的车内噪声信号进行实验室主观评价，通过对评价结果的分析得到了影响低沉度感知的主要参量，并由此建立了以1/3倍频程声压级、锐度和粗糙度为变量的低沉度参量的数学模型。采用成对比较法和语义细分法主观评价实验的结果验证了模型的准确性。结果表明，低沉度模型的预测结果与主观评价结果具有很高的相关性，从而证明了所提出模型的有效性。

关键词：声品质参量；低频成分；主观参量模型

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1 INTRODUCTION

For the purpose of evaluating and thereafter improving car interior sound quality, subjective per ception results are required. This is usually acquired through subjective jury test and/or by applying some developed objective sound parameters such as loudness, sharpness, roughness, impulsiveness etc. Bisping[1] concluded that pleasantness and powerfulness are the two most important characteristics of overall sensation of car interior sound quality. While Hashimoto[2] suggested to include noise spectrum property as an addition and thereof proposed the booming index for characterizing acceleration noise. Beside these, many other descriptors are proposed for different perceptual dimension-orientated purposes or specific noise characters.

In order to arrive at a noise descriptor that best represents subjective sensation of a specific kind of noise character, adjective verbals were collected and then a verbal space was built. Two different approaches were used in University of Oldenburg and University of Bochum to reach at German verbal space[3].

Either special sound descriptors or adjective verbal space are dependent on cultural backgrounds. This is because on one hand, consumers on different cultural backgrounds have different psychological anticipations and preference, and on the other hand, the connotation and denotation of an individual word are likely not the exact the same when it is translated from one language to another language. Some research results proved intercultural differences already, such as Brandl[4] reported dif ference between Europe and Japan, and Buss[5] showed this difference even appeared in different European languages.

Noise annoyance is an important subjective factor for car interior noise, and annoyance is described as a function of several other parameters in AVL's Noise Quality Map software[4]. In this software, two parameters, loudness and low frequency content, are used in all four different operating conditions (i. e. Low idle, Stationary operation, Instationary acceleration, and Instationary coast down) to evaluate annoyance index, which demonstrates that low frequency is another important parameter beside loudness in car interior noise quality.

In this paper, an index to represent subjective perception of low frequency content in car interior noise quality is proposed. The quantity expression "Dichen" of subjective sensation to noise with low frequency character in Chinese is first derived through statistical analysis of subjective listening questionnaire, and then jury tests of "Dichen" with car interior noise stimuli were undertaken, finally, mathematical model of "Dichen" as a function of 1/3 octave sound pressure level, sharpness and rough ness is developed and verified by subjective evaluation results with paired comparison and semantic differential methods.

2 EXPRESSION DEVELOPMENT

Because of probably intercultural differences in sound quality descriptors, expressions in Chinese are collected through subjective listening questionnaire approach. Two different processes are applied, namely, imaginary description and listening response. The expression development procedure was applied to not only the low frequency sensation but all sound characters, including roughness, sharpness etc. for the sake of not adding any possible "misleading factor" to jury's perception. (Actually, the word "Dichen" is one of the most frequently selected words we concluded in the entire verbal space which includes different aspects of subjective sensation to car interior noise quality. The meaning of the word "Dichen" represents noise that rich in low frequency and gives a kind of deep, powerful and strong sensation.)

Imaginary description: In this part of questionnaire, firstly, a description of the situation which had an apparently property of commonly accepted sound quality metrics is given, such as for "powerfulness", questioners were asked to image the situation hearing sound from a sports car race, and sound from cars pass through crossroad quickly when lights turn green. Several hint adjective words for describing this sound character were given, questioners were asked to select one or more from them and to add or suggest words that he/she felt more suitable for describing this sound, and furthermore, suitability of using all those words was evaluated. Secondly, a more comprehensive words list which covering all aspects of car sound was given, and questioners were asked to select words that can be used to describe car sounds.

Listening response: This part of questionnaire is more metric orientated. Firstly, sound stimuli reflecting change mainly in one designated sound quality metric were synthesized, as an example, for sharpness, sounds change from 0.4acum to 7acum were synthesized. Questioners were asked to listen to synthesized sounds and give an adjective word that best describes the changed character of sounds. Furthermore, similar procedure in imaginary description process was undertaken, besides not imaging but hearing sounds of different driving conditions to get a more comprehensive words list covering all aspects of car sound perception.

After the subjective questionnaire procedure, the data were statistically analyzed, and those words that had been high frequently selected were chosen to build the final Chinese verbal space for car interior sound quality[6]. "Dichen" is one of the descriptor in the verbal space which shows apparently low frequency content and a deep powerful sensation.

3 JURY TEST EXPERIMENT

Sound stimuli are car interior noise events recorded binaurally with HEAD Acoustics digital artificial head. Sound database are 40 stimuli recorded in 3 types of car from local manufactures running on normal asphalt road surface. Driving conditions are cruise at 30km/h, 50km/h, 80km/h, 100km/h, from 2nd-5th gear.

Original recorded sound stimuli were pre-processed before subjective evaluation, including length adjusting of the stimuli for better presentation to juror, and equal-loudness editing according to averaged loudness of two ear channels[7] for eliminating influence of loudness. Meanwhile, a systematic training procedure for jurors had been undertaken before final jury test.

Two different subjective test methods, namely, semantic differential (SD) and grouped pair-wise comparison (GPC)[8] method are adopted for subjective jury test. The assessed sound quality descriptor is "Dichen" (low-frequency), and 26 normal hearing graduate students from 22-28 years old had taken part in the test. Same sound stimuli and test persons were used in different listening test methods. For pair-wise comparison method, the weight factor of consistency[9] is adopted as criterion to judge the credibility of subjective data. Meanwhile, for semantic differential method, Pearson correlation coefficient between scores from individual person and geometrical mean scores of the entire jury was applied as criterion of credibility. Around 10% of data from poorly performed jurors were removed at final statistical analysis of sound quality properties.

4 DERIVING OF LOW FREQUENCY MODEL

For the development of a model representing low frequency content of car interior sound which is depicted by Chinese word "Dichen", analysis of objective quantities was first carried out to decide proper parameters, then relationship between "Dichen" and those selected parameters was established, and finally the developed model was verified by subjective test results. These procedures are introduced in more detail in the following sections.

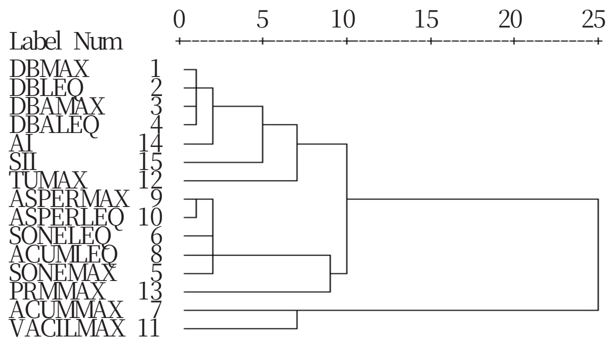
4.1 Analysis of objective quantities

The goal of objective quantities analysis was to reveal similarity and relations underlying them and then to get a reduced number of quantities for best describing the low frequency metric.

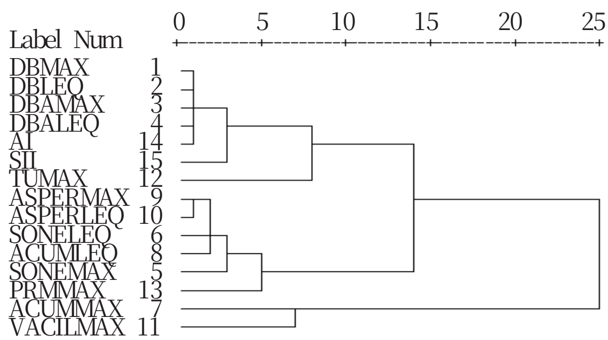
15 quantities have been selected for the analysis, they are maximum and equivalent sound level (dB Max, dB Leq), A-weighted maximum and equivalent sound level (dBA Max, dBA Leq), maximum and equivalent loudness (Sone Max, Sone Leq), maximum and equivalent sharpness (Acum Max, Acum Leq), maximum and equivalent roughness (Asper Max, Asper Leq), maximum fluctuation strength, tonality and prominence ratio (Vacil Max, Tu Max, Prm Max), Articulation index (AI), and Speech intelligibility index (SII).

Results of hierarchical cluster analysis with squared Euclidean distance measure of all 15 quantities are shown in Fig.1, where only analysis results by applying the nearest neighbor and within-groups linkage method are shown. Similar results were obtained when applying other methods in hierarchical analysis. It can be concluded that 15 quantities may be classified into 3 clusters minimally. Where dB Max, dB Leq, dBA Max, dBA Leq, AI, SII and Tu Max belong to the first cluster; Asper Max, Asper Leq, Acum Leq, Acum Leq, Sone Max and Prm Max belong to the second cluster; Acum Max and Vacil Max belong to the third cluster. ALSCAL multidimensional scaling with Euclidean distance results is shown in Fig.2, where 2-dimensional solution is derived. From cluster analysis and ALSCAL scaling, 2 quantities could be chosen from each cluster, and totally 6 quantities were selected to describe sound character of the noise, without having apparent influence to the representation with original 15 quantities.

In deciding which quantities should be included in describing low-frequency sensation (expressed by the Chinese word "Dichen"), Pearson correlation between Dichen and 15 quantities is conducted, and the results are shown in Table.1. Correlation data show there are three quantities (Acum Max, Vacil Max, Prm Max) which do not have strong correlation with Dichen. Suppressing those three quantities, partial correlation result with 12 remaining quantities is shown in Table 2. Data shows, the impact of dB Max and dB Leq to Dichen is similar, and either one of them could been taken as fully represent of the two quantities in Dichen. It's the same situation for Sone Max and Sone Leq; Asper Leq and Asper Max. Therefore, totally 12 quantities could be reduced to 9 quantities: dB Leq, Sone Leq, Asper Leq, Vacil Max, Tu Max, Prm Max, AI and SII.



(a) Nearest neighbour method



(b) Within groups-linkage method

Fig.1 Hierarchical cluster analysis of 15 quantities

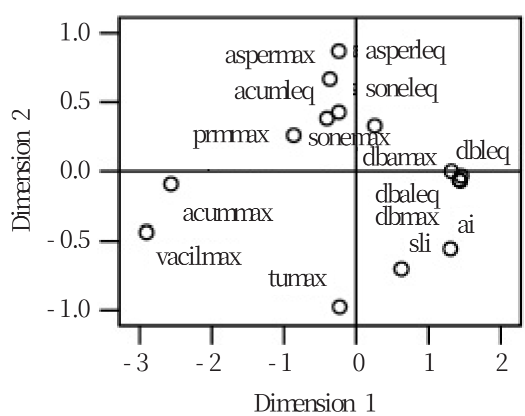


Fig.2 ALSCAL 2 dimensional scaling of 15 quantities

Table 1 Pearson correlation between Dichen and 15 quantities

Quantity	Dichen	Quantity	Dichen
dB Max	- 0.484**	Asper Max	- 0.764**
dB Leq	- 0.541**	Asper Leq	- 0.779**
dBA Max	- 0.698**	Vacil Max	0.107
dBA Leq	- 0.704**	Tu Max	0.556**
Sone Max	- 0.697**	Prm Max	- 0.140
Sone Leq	- 0.735**	AI	0.913**
Acum Max	- 0.238	SII	0.932**
Acum Leq	- 0.751**	**Correlation is significant at the 0.01 level (2-tailed).	

Table 2 Partial correlation between Dichen and 12 quantities by controlling 3 quantities

Quantity	Dichen	Quantity	Dichen
dB Max	- 0.4275	Acum Leq	- 0.7342
dB Leq	- 0.4896	Asper Max	- 0.7895
dBA Max	- 0.6996	Asper Leq	- 0.8111
dBA Leq	- 0.7156	Tu Max	0.5289
Sone Max	- 0.6863	AI	0.9084
Sone Leq	- 0.7724	SII	0.9281

Again, Pearson correlation between Dichen and 9 reduced quantities is carried out as shown in Table.3. The data reveal that tonality, fluctuation strength and proximity ratio have only weak corre lation with Dichen, and these three quantities can be further removed.

Table 3 Pearson correlation between Dichen and 9 reduced quantities

Quantity	Dichen	Quantity	Dichen
Sound Level	0.415	Fluctu. Strength	- 0.047
Loudness	- 0.490	Articulation Index	0.913
Sharpness	- 0.883	SII	0.932
Roughness	- 0.720	Proximity ratio	- 0.140
Tonality	0.181	-----	-----

With the final 6 quantities reflecting low-frequency character of car interior noise, factor analysis with relation to subjective results of "Dichen" was conducted. Factor analysis result is listed in Table.4, shown 3 components explain about 94.5% of total variance.

Table 4 Total variance explained

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	4.015	66.924	66.924
2	1.013	16.889	83.812
3	.644	10.737	94.549
4	.271	4.509	99.058
5	.040	.660	99.718
6	.017	.282	100.000

From the results of objective quantity analysis, and results of some other researches on car interior noise quality, such as Brandl[4], three parameters are finally determined to construct mathematical model for "Dichen". They are 1/3 Octave sound pressure level, sharpness and roughness.

4.2 Model development

Sound has a strong "Dichen" sensation means it is rich in low frequency content, therefore frequency spectrum is taken as part of the model. For simplicity, 1/3 octave sound pressure level was used to describe frequency dependent character of sound, and meanwhile a weighting function that can represent special attention to low frequency content is added to the spectrum.

With reference of other sound quality models, such as roughness and booming level index, an effective attenuation up to 70Hz of SPL would be better anticipated. Consequently, an exponential decay curve is adopted as shown in Fig.3.

Therefore, when taking into account frequency character, model of "Dichen" can be expressed in form as follows,

$$D \propto k \times \frac{\sum L_p(F_c i) \times e^{-10/\sqrt{2} \times X(F_c i)}}{n^2} \qquad (1)$$

where $F_c i$ denotes 1/3 octave center frequency from 20Hz to 20kHz, and $L_p(F_c i)$ the corresponding sound pressure level; $X(F_c i)$ is serial number of 1/3 octave center frequency with X(20)=1, X(25)=2, ...X(20k)=31; n is total number of frequency bands, and k is an arbitrary coefficient.

The next step is to setup relation of "Dichen"

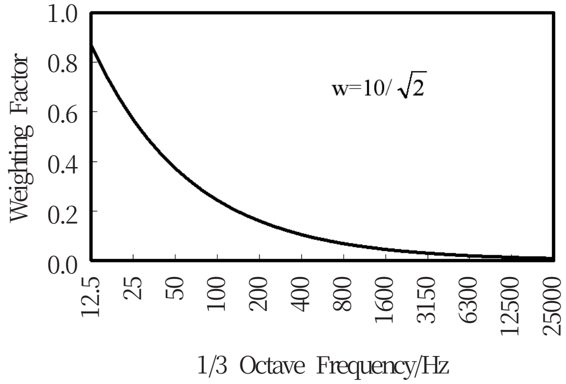


Fig.3 Decay curve of weighting function

to sharpness and roughness, subjective results shown that "Dichen" has a negative relation to sharpness and roughness, and sharpness is a more influencing parameter than roughness. For this reason, a weighting factor 2 was appointed to sharpness, and then the relation could be expressed as,

$$D \propto B-2S-R \tag{2}$$

where S is sharpness in Acum, R is roughness in Asper, and B is constant applied to adjust value range of the model, and when B=8 would make the results more rational for car interior noise.

By combining Eq.(1) and (2), we can get,

$$D=k\times\frac{\sum L_p(F_c i)\times e^{-10/\sqrt{2}\times X(F_c i)}}{n^2}\times(8-2S-R) \tag{3}$$

Now we can define the reference value of "Dichen" with a similar procedure as used in other metrics such as roughness and sharpness. Defining a white noise with 60dB sound pressure lelvel in all 1/3 octave frequency bands has a "Dichen" of 1 (D=1), then we can get k=1/1.72. Therefore, model for metric "Dichen" could finally be written as,

$$D=\frac{\sum L_p(F_c i)\times e^{-10/\sqrt{2}\times X(F_c i)}}{1.72n^2}\times(8-2S-R) \tag{4}$$

4.3 Model verification

The developed model is compared with results of subjective test on "Dichen". Subjective test procedures have been introduced in former session. Fig.4 and 5 show calculated results with developed model in comparison with semantic differential (SD) and grouped pair-wise comparison method of 40

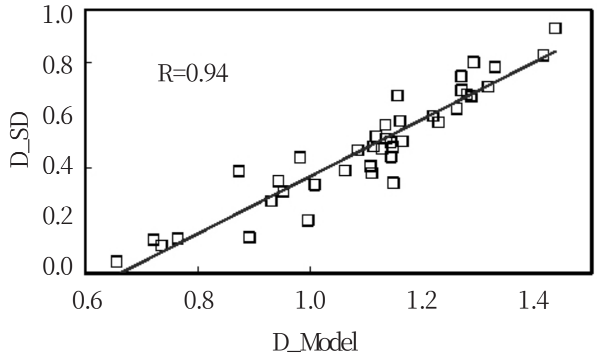


Fig.4 Comparison of model results to subjective SD results of 40 stimuli

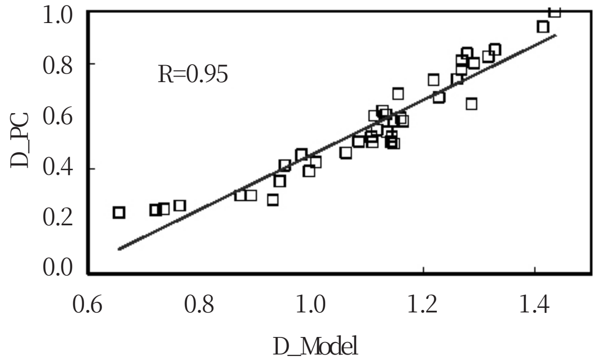


Fig. 5 Comparison of model results to subjective GPC results of 40 stimuli

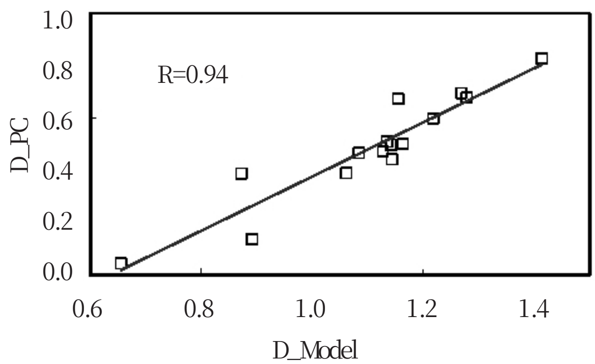


Fig. 6 Comparison of model results to subjective SD results of 15 stimuli

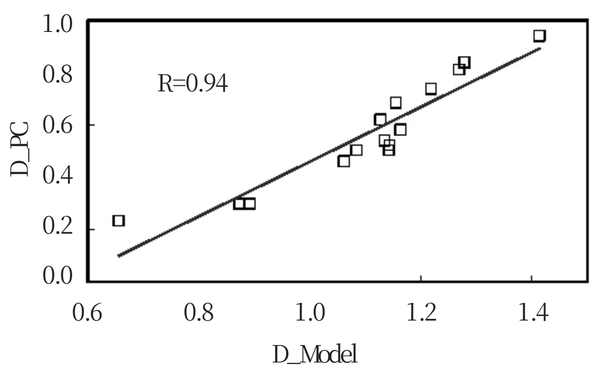


Fig.7 Comparison of model results to subjective GPC results of 15 stimuli

stimuli respectively, and Fig.6 and 7 show results of 15 stimuli. In all the figures the ordinate are calculated results with the model, and abscissa are subjective merit values derived with Bradley Terry model[10].

Comparison of calculated results with the developed model to subjective test results of car interior noise shows a high correlation coefficient of 0.94. Good agreement between two results proved that the low frequency model proposed can predict the subjective "Dichen" perception of car interior noise satisfactorily.

5 CONCLUSIONS

For the description of subjective perception on low frequency content in car interior noise, a Chinese word "Dichen" was colleted through imaginary description and listening response procedures. Statistical analysis methods were used to reveal relationship among 15 subjective quantities, and 3 reduced quantities are finally reached to represent low frequency characters. Thereafter, mathematical model for predicting subjective "Dichen" perception is developed as a function of weighted 1/3 octave sound level, sharpness and roughness. Proposed model was verified through subjective test with semantic differential and grouped pair-wise methods on 40 and 15 binaurally recorded car interior sound stimuli, good agreement between predicted and subjective results is reached.

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