The subjective evaluation on sound quality for interior noise based on customer satisfaction

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Abstract

Customer satisfaction is proposed to evaluation a product quality whether good or not in the development of market with customer-oriented. In this paper, the importance of the customer requirement is introduced in sound quality evaluation. During the subjective evaluation procedure, the roughness coefficient and average roughness interval are applied to calculate the basic importance of customer requirement. Subsequently, the amending factor set is conducted to correct the basic importance of customer requirement based on the Kano model. As a result, the final importance of customer requirement is obtained, which can transform the customers' subjective requirements to engineering improvement targets. Moreover, the test on noise working condition is carried out. The results indicate effectiveness of the proposed method.

Keywords: Customer Satisfaction; Roughness Coefficient; Average Roughness Interval; Kano Model

1 Introduction

Vehicle interior noise environment can directly reflect the passengers' ride comfort. Therefore, interior noise quality has become a significant factor which can affect the consumer purchasing psychology and market shares of Automobile industry [1-2]. Due to the discrepancy of needs among different types of vehicles, the acoustic quality also varies, and people usually have subjective preference according to their psychological impression and physiological influence. The evaluation index of conventional A weighting sound pressure level neglects the subjective of customers, which couldn't meet customers' pursuit on sound quality, such as, comfortable, pleasure and so on [3]. The customer satisfaction is always as the target of market during the development of vehicle, and it's not allowed to generate noise which can make the customer complaint at any reasonable working condition. So based on the theory of psychological acoustics, overall considering human psychological reaction mechanism and noise perception characters, it can more correctly reflect difference of people's objective feeling on different noise [4].

In the late 20^{th} century, AVL LIST invented a sound quality drawing software which could directly run on PC, and elicited evaluation result through necessary calculations based on the objective parameters. A dozen subjective feelings were summed up to two kinds acoustic evaluation attributes of sport and luxurious feeling by Honda, according to numbers of subjective evaluation tests. Moreover, through the multiple analysis, the relationship between the above two attributes and the main psychological acoustics objective parameters were established [5-6]. In China, Dogxing Mao and Wuzhou Yu of Tongji University evaluated noise samples from two different vehicles, and analyzed the reason of easily occurring the triangular loop situation. Weikang Jiang and Wei Zhang from Shanghai Jiao tong University distinguished the vehicle interior noises using the subjective analysis method of psychological acoustics, and came up with a new Index calculation method on noise annoyance level using the Noise masking equivalent principle. 32 steady interior samples from 8 types of vehicles were tested by the Dengfeng Wang of Jinlin University. It had been established the mathematical model of annoyance level based on the description of loudness and sharpness [7]. However, the large majority of the studies above mainly concentrated on the objective parameters of subjective evaluation, little attention was paid to customer's real requirements. Actually, the research on customer's requirements is more complex than that of objective parameters of subjective evaluation. Moreover, the studies neglected the contribution of the amending factor of Kano model. In truth, the amending factor plays an indispensable role on customer requirement. Additionally, the research on how the importance of customer requirement influences the subjective evaluation of interior noise is scant. Therefore, it is of great importance to study the influence of

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importance of customer requirement on the subjective evaluation of interior noise.

This paper introduced customer satisfaction into the evaluation of sound quality. On the basis of roughness theory, roughness coefficient and average roughness range were put forward to characterize the ambiguity and uncertainty. It can get the basic importance ratings of the customer requirement through the eigenvalue and eigenvector solved from the constructed rough paired comparison matrix. Considering the result of market competitive analysis, it introduced the amending factor of Kano model to modify the basic importance ratings of the customer requirement, and eventually obtained the final importance ratings of the customer requirements.

2 Experimental design of subjective evaluation

It must resolve the problems of three W and one H before the subjective evaluation experiment, namely what, who, where and how. In a word, it's necessary to choose a reasonable method to design 4 factors of people, vehicle, road and environment.

2.1 NOISE SAMPLE

Kano model defines 3 kinds of customer requirements: basic, conventional and interesting. Basic requirements are vital competitive factors at any time. Conventional requirements are requirements that customers expect, and the more expected requirements those enterprises can offer, the more competitive is. While interest requirements essentially are the ones customers not familiar, and have not too much expectation. Therefore, whether the enterprise can meet or not will not arouse customer disappointment or dissatisfaction [8].

In the process of noise subjective evaluation, it can classify cavity and rough concrete roads into interesting requirements. From the aspects of cost-cutting and data process, this subjective evaluation is researched mainly based on basic and conventional requirements, so it merely collect the noises of tested vehicles running on smooth asphalt road and high-speed road on different working condition, which can also reduce the influence on vehicle interior noise. The data collection time is selected on 8:00-11:00 AM to 2:00-5:00 PM, and the environment temperature among 17-28ºC. In addition, the distance between to-be-tested vehicles and giant subjects exceeds 20m during the experiment, which can avoids part noise that vehicle radioactive noise reflect through building and walls [9].

The noise data is collected through German head measure system Ⅲ artificial head and SQlab Ⅱ multiple tunnel testing system [10-11], as shown in Fig. 1 That respectively records driver's right ear noise signals on the working conditions of idling (A/C on and off), acceleration (3G WOT 900-3000rpm and 4G WOT 900-3000rpm),constant velocity (60Km/h, 110Km/h, 120Km/h), cruise (60Km/h-110Km/h, wi.th 10Km/h step by step). 28 noise samples with 5 second length eventually are obtained after screening and handling. [12-13].

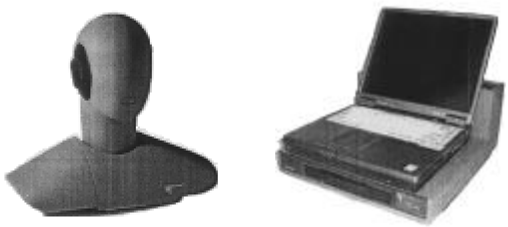

FIGURE 1 Instruments of subjective evaluation

2.2 EVALUATORS

Norm Otto and Scott Amman indicated that 25 to 30 evaluators can carry out the accurate subjective evaluation result about the simple listening mission [8]. While, due to the complexity of vehicle interior noise generated by different parts, the inexperienced evaluators may be unable to make reasonable judgment. Therefore, 30 evaluators are selected in this experiment, including NVH experts, professional test engineers, the people experienced in driving or associated with automotive. Meanwhile, Thirty percent is female, and male occupies the remaining proportion. On account of the orientation to target customers, there are four evaluators aged between 22 and 30, ten between 30 and 39, sixteen over the age of 40. Each evaluator must complete evaluation less than 40 minutes every time in order to avoid low confidence generated because of tired. In addition, it is necessary to make some training on sound sample to reduce some misjudgment for evaluators before evaluation, which aim to obtain a correct and reasonable result [13-14].

2.3 HEARING ENVIRONMENT

A comfortable hearing environment can help evaluators to give a reasonable judgment [8]. In this experiment, a room chosen is located in the school office area. Meanwhile, during the summer vacation time, low environment noise also satisfies the general signal-noise ratio. Moreover, the reverberation effects are small due to using headphones instead of loudspeaker, and temperature in room is appropriate.

2.4 SUBJECTIVE EVALUATION METHODS

There are many commonly subjective evaluation methods, such as semantic differential method, paired comparison method, rating scale method and so on [15]. In this paper, it combines rating scale method and paired comparison method with Rough Set theory from the viewpoint of customer satisfaction on sound preference to make evaluation.

The objective value of rating scale is used to represent the degree of the subjective feeling of evaluators. While paired comparison requires the evaluators to make the choice between two sounds according to individual preference, which can quickly distinguish the subtle differences between two evaluation objects [8]. In this experiment, evaluators according to preference are required to give a score between two given records. Table 1 shows the standard of evaluation, where compared A record with B, it can get corresponding scores with standard as shown in Table 1.

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TABLE 1 Standard of subjective evaluation

Standard of subjective evaluation		Scores
Unacceptable	The basic requirements can't be assured.	1
	The basic requirements are invalid.	2
Unacceptable for a certain requirements	A certain defect occurs repeatedly.	3
	A certain defect occurs accidentally.	4
Dissatisfied	The regular use is badly affected.	5
	The regular use is affected.	6
Acceptable	There are some problems existed, but acceptable.	7
Satisfied	There is no complaint on purpose.	8
	It is able to meet the customer requirements.	9
Perfect	It is beyond the customer expectation	10

3 Rough Set theory

Rough Set theory proposed by the polish scholar Pawlak is a method of processing data, which can effectively analyze and deal with imprecise information. It is widely used not only in discovering the true sense of customers but also in ranking the customer requirements [16]. Based on the Rough Set theory, rough number and rough boundary interval is put forward. Two new concepts can be well able to handle the indistinct and subjective information of subjective evaluation, and keep the objectivity of original data at the same time [16-17].

Supposing the universe of discourse U is non-empty finite set, *Y* is any object of *U*. There are n divisions of any object of *U*. Depending on above two hypotheses, the set *R* of *U* is defined by $R = \{C_1, C_2, \cdots, C_n\}$. Where any division belongs to set *R* with $C_1 \in R$, $1 \le i \le n$, $C_1 < C_2 < C_3 < \cdots < C_N$, the upper and lower limit of rough approximation set are given by equation[17]

$$\underline{Apr}(C_i) = \cup\left\{Y \in \frac{U}{R(Y)} \le C_i\right\} \quad (1)$$

$$\overline{Apr}(C_i) = \cup\left\{Y \in \frac{U}{R(Y)} \ge C_i\right\} \quad (2)$$

The boundary region is correspondingly given by equation

$$\begin{aligned} Bnd(C_i) &= \cup\left\{Y \in \frac{U}{R(Y)} \ne C_i\right\} \\ &= \left\{Y \in \frac{U}{R(Y)} > C_i\right\} \cup \left\{Y \in \frac{U}{R(Y)} < C_i\right\} \end{aligned} \quad (3)$$

According to above formulas, any divisions C_i of U can be indicated with rough number which is composed of the upper limit $\underline{Lim}(C_i)$ and lower limit $\overline{Lim}(C_i)$ of rough set. The mathematical expression of is as follows:

$$\underline{Lim}(C_i) = \frac{1}{M_L}\sum\left(R(Y) \mid Y \in \underline{Apr}(C_i)\right) \quad (4)$$

Where M_L is the number of objects that the lower approximation set contains.

Similarly,

$$\overline{Lim}(C_i) = \frac{1}{M_U}\sum\left(R(Y) \mid Y \in \overline{Apr}(C_i)\right) \quad (5)$$

Where M_U is the number of objects that the upper approximation set contains.

Therefore, interval between upper and lower makes up the boundary interval $RBnd(C_i)$ which is given by equation

$$RBnd(C_i) = \overline{Lim}(C_i) - \underline{Lim}(C_i) \quad (6)$$

Based on the definition of $\overline{Lim}(C_i)$ and $\underline{Lim}(C_i)$ any fuzzy division can be expressed by the rough numbers which contains upper and lower limit. The function $\underline{Lim}(C_i)$, $\overline{Lim}(C_i)$ and $RN(C_i)$in equation 7 is given by equation

$$RN(C_i) = \left[\underline{Lim}(C_i), \overline{Lim}(C_i)\right] \quad (7)$$

Obviously, the boundary interval describes vagueness of discussed division and indicated the larger of the rough boundary interval, the more vagueness of a certain division. Moreover, according to above calculation process, the solving rough number considers all objects of upper and lower approximation sets. While these objects correspond to a certain evaluation value of customers participated in the survey. It is suggested that the rough number can not only reflect the individual customer evaluation for a certain requirement, but also consider opinion of other customers. The customers requirement reflected in forms of rough boundary interval is the whole cognition of surveyed customers for a certain requirement, and the result is more integral and reliable [17-18].

4 Subjective evaluation results analysis

4.1 CALCULATING THE BASIC IMPORTANCE OF CUSTOMER REQUIREMENTS

Subjective evaluation on a particular vehicle, the weight between two sound samples a_{ij} and a_{ji} is measured according to the scales in TABLE 1. Besides, there is the following equation of *i* factor relative to *j* factor [19, 20].

$$a_{ij} = \frac{1}{a_{ji}} \tag{8}$$

Thirty groups upper triangular paired comparison matrix is obtained from the subjective evaluation results and Formula.8. During evaluation process on sound quality, evaluators lacking concentration or other reasons may lead to faulty judgement, and also probably cause the results from the accuracy. So, all evaluation results must be checked using the triangle loop misjudgement method [21-22] which makes twenty-six evaluators remained with the Kendall coefficient more than 0.7. Moreover, two evaluators with lower Speaman correlation coefficient are removed [23], and finally twenty-four groups rough decision matrix transformed from upper triangular paired comparison matrix are presented in forms as follows through the above two data processing [17-18]:

$$A^* = \begin{bmatrix} 1 & X_{12}^* & \cdots & X_{1n}^* \\ X_{21}^* & 1 & \cdots & X_{2n}^* \\ \vdots & \vdots & \vdots & \vdots \\ X_{n1}^* & X_{n2}^* & \cdots & 1 \end{bmatrix} \tag{9}$$

$$X_{12}^* = \left\{x_{12}^1, x_{12}^2, \cdots, x_{12}^s\right\} \tag{10}$$

Where *n*=28, *s*=24 is the number of sound samples and the evaluators, respectively. X_{12}^*, X_{1n}^*, X_{21}^*, X_{2n}^*, X_{n1}^*, X_{n2}^*, represent a universe of discourse. Taking X_{12}^* for example, it can calculate its rough number RN_{12}^i and the rough boundary interval $RN\left(X_{12}^*\right)$as shown in equation 11-12 that corresponds to the evaluation data from *s* customers according to the equation 1-7.

$$RN_{12}^i = \left[x_{12}^{i-}, x_{12}^{+}\right] \tag{11}$$

$$RN\left(X_{12}^*\right) = \left\{\left[x_{12}^{1-}, x_{12}^{+}\right], \left[x_{12}^{2-}, x_{12}^{2}\right], \cdots, \left[x_{12}^{s-}, x_{12}^{s+}\right]\right\} \tag{12}$$

Where x_{12}^{i-}, x_{12}^{i+} is the lower and upper limit of Rough Set, with $i \in [1, s]$. It is important to note that the algorithms of Rough Set are similar to those of vector. Based on the algorithms of vector, the average rough boundary interval (for example $RN(X_{12})$), is given by

$$RN(X_{12}) = \left[x_{12}^-, x_{12}^+\right] \tag{13}$$

$$X_{12}^- = \left(x_{12}^{1-} + x_{12}^{2-} + \cdots + x_{12}^{5-}\right)/S \tag{14}$$

$$X_{12}^+ = \left(x_{12}^{1+} + x_{12}^{2+} + \cdots + x_{12}^{5+}\right)/S \tag{15}$$

Where $\left[x_{12}^-, x_{12}^+\right]$ is one rough number and x_{12}^-, x_{12}^+ is respectively the lower and upper limit.

After calculating the rough numbers and average boundary interval of rough decision matrix, the rough paired comparison matrix X, which is divided into lower rough boundary matrix X^- and upper rough boundary matrix X^+, is given by

$$X = \begin{vmatrix} [1,1] & \left[X_{12}^-, X_{12}^+\right] & \cdots & \left[X_{1n}^-, X_{1n}^+\right] \\ \left[X_{21}^-, X_{21}^+\right] & [1,1] & \cdots & \left[X_{2n}^-, X_{2n}^+\right] \\ \vdots & \vdots & \cdots & \vdots \\ \left[X_{n1}^-, X_{n1}^+\right] & \left[X_{n2}^-, X_{n2}^+\right] & \cdots & [1,1] \end{vmatrix} \tag{16}$$

$$X^- = \begin{bmatrix} 1 & X_{12}^- & \cdots & X_{1n}^- \\ X_{21}^- & 1 & \cdots & X_{2n}^- \\ \vdots & \vdots & \vdots & \vdots \\ X_{n1}^- & X_{n2}^- & \cdots & 1 \end{bmatrix} \tag{17}$$

$$X^- = \begin{bmatrix} 1 & X_{12}^- & \cdots & X_{1n}^- \\ X_{21}^- & 1 & \cdots & X_{2n}^- \\ \vdots & \vdots & \vdots & \vdots \\ X_{n1}^- & X_{n2}^- & \cdots & 1 \end{bmatrix} \tag{18}$$

Depending on using the equation 16, 17 and 18 respectively to calculate the eigenvalue and eigenvector of X^- and X^+, the basic importance of customer requirements $f^*(CR_i)$ can be calculated as follows:

$$f_i^- = w_i^- / \textstyle\sum_{i=1}^{n} w_i^- \tag{19}$$

$$f_i^+ = w_i^+ / \textstyle\sum_{i=1}^{n} w_i^+ \tag{20}$$

$$f^*(CR_i) = \left(\left|f_i\right| + \left|f_i^+\right|\right)/2 \tag{21}$$

Where f_i^- *and* f_i^+ are the standardization of eigenvector, and w_i^- and w_i^+ are each value of those.

4.2 AMENDING THE IMPORTANCE OF CUSTOMER REQUIREMENT BASED ON KANO MODEL

During the subjective evaluation process on the interior noise, the competitiveness of the enterprises or the products in the market isn't taken into consideration. Therefore, to gain a more accurate rank of the customer requirements, a competition value in digital scale is introduced in this paper. Using the Kano Model to classify the type of customer requirements, it is necessary to extend the evaluation process into the product competition by equation 22 and 23 [24].

$$SR_i = \frac{CS_i^1}{CS_{i1}} \tag{22}$$

$$IR_i = (SR_i)^{l_i} \tag{23}$$

Where SR_i is the improvement ratio of a certain customer requirement, which is affected by competitive evaluation value CS_i^1 and the improvement target CS_{1i}. IR_i is a representation of improvement ratio of customer requirements having been evaluated on competition. The higher IR_i is, the more important the corresponding customer requirement is in the enterprise products or the service. l_i is the important coefficient of customer requirements in the Kano model, which varies with the different types of customers' requirements. The value of l_i is workable only if the chosen value can reflect the natural of actual relation, while which is often collected based on the empirical formula in normal condition [17-18]. In this paper, choosing 2.0, 1.0, 0.8 respectively is on behalf of basic, conventional and interesting customer requirements. When taken the market competition into consideration, only considering its competitive value is far from enough, but also combing with marketing hot issues noted as SP_i. As usual, 1.5, 1.2, 1.0 is generally used to represent the value of marketing hot issues with three levels from high to low [24].

Based on above analysis, the amending factor set R of basic importance of customer requirements, with $i \in (1, n)$, can be gained by [18, 24]

$$R_i = IR_i \times SP_i = (SR_i)^{L_i} \times SP_i \quad (24)$$

$$R = (R_1, R_2, \cdots, R_n) \quad (25)$$

4.3 CALCULATING THE FINAL IMPORTANCE OF CUSTOMER REQUIREMENTS

Twenty-eight groups of the sound samples are classified based on the Kano Model theory. It was found that there are fourteen groups of basic customer requirements, eight groups of conventional type and six groups of interest. Combing with the marketing analysis, the final importance of customer requirements $fid(CR_i)$ and its standardization $FID(CR_i)$ is calculated based on the amending factor set according to equation 27 [24].

$$fid(CR_i) = f^*(CR_i) \times R \quad (25)$$

$$FID(CR_i) = \frac{fid(CR_i)}{\sum_{i=1}^{s} fid(CR_i)} \times 100\% \quad (26)$$

Table 2 shows the parameters in the process of solving the importance of customer requirements.

It is clear that the importance of customer requirements on sound samples A4, A10, A15, A19, A22, A25 is lower as shown in Table 2. While through analysis of six samples and summarization of the description from evaluators on interior sound environment, those annoyed sounds are mostly derived from acceleration condition, and a few from wind noise generated because of high speed.

TABLE 2 The importance of customer requirements

Sound samples	$f^*(CR_i)$	IR_i	SP_i	$fid(CR_i)$	$FID(CR_i)$
A1	0.2415	1.3500	1.2000	0.3912	2.0557
A2	0.5679	1.0000	1.2000	0.6815	3.5809
A3	0.4986	1.3500	1.0000	0.6731	3.5369
A4	0.2027	1.3500	1.0000	0.2736	1.4379
A5	0.5521	1.6500	1.0000	0.9110	4.7867
A6	0.5937	1.0000	1.5000	0.8906	4.6794
A7	0.6721	1.0000	1.2000	0.8065	4.2379
A8	0.6209	1.0000	1.2000	0.7451	3.9151
A9	0.7917	1.3500	1.0000	1.0688	5.6160
A10	0.7543	1.0000	1.2000	0.9052	4.7562
A11	0.2281	1.0000	1.2000	0.2737	1.4383
A12	0.5308	1.3500	1.0000	0.7166	3.7653
A13	0.4756	1.0000	1.5000	0.7134	3.7486
A14	0.6952	1.3500	1.0000	0.9385	4.9315
A15	0.2302	1.0000	1.2000	0.2762	1.4515
A16	0.5632	1.0000	1.2000	0.6758	3.5512
A17	0.7081	1.3500	1.0000	0.9559	5.0230
A18	0.4586	1.0000	1.5000	0.6879	3.6146
A19	0.1962	1.0000	1.0000	0.1962	1.0309
A20	0.6657	1.0000	1.2000	0.7988	4.1976
A21	0.5099	1.0000	1.5000	0.7649	4.0189
A22	0.1846	1.0000	1.2000	0.2215	1.1640
A23	0.6691	1.3500	1.0000	0.9033	4.7464
A24	0.7715	1.0000	1.2000	0.9258	4.8647
A25	0.2107	1.0000	1.0000	0.2107	1.1071
A26	0.5811	1.0000	1.5000	0.8717	4.5801
A27	0.6729	1.0000	1.2000	0.8075	4.2430
A28	0.4974	1.0000	1.5000	0.7461	3.9204

Especially, it is easy to generate the noise from engine which complained most times by evaluators. Therefore, from the perspective of customer satisfaction, it is important for enterprise to control and improve dissatisfied conditions, otherwise it will cause the dissatisfaction and even complaint from customers, which directly affect the products sales and market share in the future.

5 Noise test and data analysis

It is necessary to carry out the experiment on test vehicle not only in order to verify the accuracy of subjective evaluation results which is calculated based on the Rough Set theory, but also seek out the complaint conditions. Figure 2. presents the install location of microphone in driver's right ear.

FIGURE 2 The install location of microphone in driver's right ear

By the analysis of subjective evaluation results, it can be found that the complaint condition is focus on the progress of acceleration. Considering the cost and time inputs, this experiment only chooses 3G WOT and 4G WOT for testing from 900rpm to 3000rpm and the testing result is as shown in FIGURE 3. and FIGURE 4..

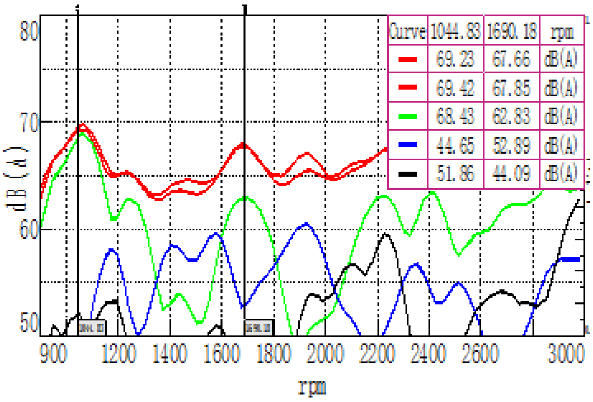

FIGURE 3 SPL of driver's right ear in 3G WOT condition

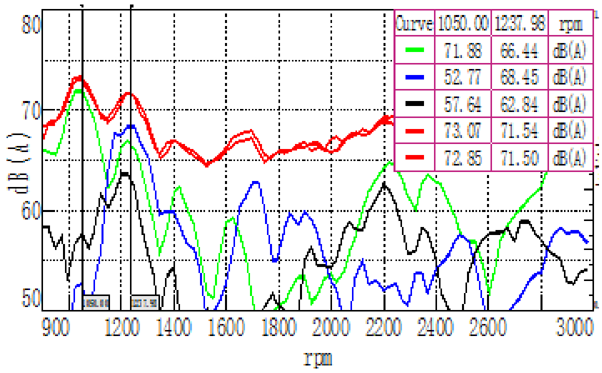

FIGURE 4 SPL of driver's right ear in 4G WOT condition

The total sound pressure level (SPL) indicated by red curves, with engine order curves, is presented in Fig. 3 and Fig.4. As described in two figures, the green, blue, and black curves show the engine second-order noise, fourth-order engine noise and sixth-order engine noise, respectively. There is a same phenomenon in Fig. 3 and Fig. 4 that the SPL of interior noise respectively appears peak at 1100rpm, 1650rpm and 2250rpm. Moreover, it is clear that the peak of interior noise mainly is caused by engine second-order noise. After a detailed diagnostic finding, the fact contributed to the interior noise in the process of acceleration is that the torsional vibration of transmission is too large. The amplified vibration generated by coupling the torsional vibration of transmission with transmission axle and sway bar of rear suspension is transmitted to the body, which easily produces a larger roar.

As demonstrated in those sections, it is clear that the complaint condition is mainly focus on certain rotate speed in the process of acceleration. Besides, on the whole, a conclusion can be made that there are good consistency between subjective evaluation and objective testing result, which not only verify the accuracy of subjective evaluation based on the Rough Set theory, but also shorten the time of improvement on design.

6 Conclusion

The rough number and average rough boundary of Rough Set theory were introduced and the importance of customer requirements was investigated from the perspective of customer satisfaction. Subsequently, the test on process of acceleration was carried out to verify the accuracy of subjective evaluation result. Based on the analysis of subjective evaluation and test, the obtained results were shown as follows:

(1) The fuzzy and subjective information of customer requirement is converted to objective values by taking advantage of the rough number and average rough boundary.

(2) Based on the market competitiveness and product hot issues, the amending factor of Kano model is introduced to amend the basic importance of customer requirements,

which is used to correct the final importance of customer requirements.

(3) The Rough Set theory trend to calculate a accurate result, which can instruct the enterprise to put less attention on unnecessary improvement, such as the customer uninterested in or not to bring profits. Furthermore, it is useful to shorten the development cycle and improve the market competitiveness of product and enterprise.

(4) There are good consistency between subjective evaluation and objective testing result. Nevertheless, because preferences of different evaluators vary slightly in interior noise, it still exits deviation for the prediction of subjective evaluation. Sometimes, the accuracy results even can't be obtained.

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