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Sound quality prediction of electronic expansion valve based on subjective and objective evaluation

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ABSTRACT
The sound quality of electronic expansion valve(EEV) influences both consumers' psychological feelings and the market competitiveness. The conventional subjective assessment of evaluating the sound quality of EEV is implemented by experienced experts. However, the conventional methods have the following three deficiencies:(1) there are no uniform standard on the procedures of the assessment. (2) the perception of the experts does not comprehensively represent the perception of ordinary people. (3) conventional methods are tedious and time consuming. To reduce the time consumption, grouped paired comparison method was employed to carry out subjective evaluation. Six existing psychoacoustic metrics are utilized based on the recorded sound of EEV and the correlations between subjective evaluation results and psychoacoustic metrics are analyzed. An artificial neural network model which has been trained to best performance is proposed to predict the EEV sound quality. The result shows that the neural network model can predict the sound quality of EEV accurately and efficiently. This study lays the foundation for sound quality improvement of EEV.

Keywords: Electronic expansion valve, Sound quality, Psychoacoustics
I-INCE Classification of Subject Number: 79

1. INTRODUCTION

A variable refrigerant flow multi-spilt air conditioning (VRF) system consists of one outdoor and multiple indoor units[1]. The VRF system is widely used to create an acceptable indoor air quality (IAQ)[2]. The customer acceptance of the VRF system is not only determined by the performance of creating an acceptable indoor air quality but also depends on consumers' psychological feelings of the indoor noise[3]. The electronic expansion valves (EEVs) are employed to adjust refrigerant flow rate in order to keep the zone air temperature constant at the set-point[4, 5]. However, the prominent drawback of EEV is the noise producing, which is the main cause of annoyance to machine operators and customers in the VRF system[6].

With the use of more high pressure systems in the VRF system, noise generated

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by valves becomes an increasingly important consideration in system design. The main noise of EEV are mechanical noise and aerodynamic noise. Mechanical noise is introduced by part vibration, jitter, or impact and Aerodynamic noise is mainly caused by intensive fluid deceleration, expansion, or impingement[7].

Most of exceting studies focus on the vibro-acoustic property of valves. Valve and piping noise was analyzed and the noise produced by valve cavitation was explained[8]. Structure modifications is one approach to reduce the noise. A low noise valve includes a perforated cage and a perforated closed end tube was invented to maximize the dissipation of that noise[9]. Valve noise was reduced at a lower power consumption leve in a system which armature levitation is strategically used[10]. A control valve with low noise including a slotted cylindrical skirt and a tapered metal ring is disclosed[11]. Some researcher investigated the valve noise excitation sources by simulation. A valve with water injection modified the turbulence structure and resulted in noise reduction, the noise under the gas flow rate of 0.11kg/s and 0.15kg/s were respectively reduced by 4dB and 11dB[12]. An optimization of the opening process of valve was designed and the impulse exhaust noise emitted from valve was reduced by up to 10dB[13]. Based on computational fluid dynamics (CFD), flow-induced noise in high pressure reducing valve was studied to provide the higher inlet pressure will cause the larger sound pressure level (SPL)[14].

It is observed that all above mentioned researches aim for SPLs reduction of EEV. However, human’s auditory perception of sound quality is not only represented by SPLs[15]. The customers become more and more sensitive to noise, the better sound quality of products is more demanding than ever before In order to reflecting human’s preception comprehensively, more detatlied evaluation need to be done.

Objective psychoacoustic parameters and subjective jury test are generaly used to evaluate sound quality in engineering application, especially in the evaluation of vehicle interior noise. The objective evaluation refers to analytical methods to determine the quantification of sound quality. Loundness, sharpness, roughness and fluctuation strength are often used as psychoacoustic metrics to quantify sound quality[16]. A roughness model based on human auditory perception was developed for the sound quality evaluation of vehicle noise[17]. A sound quality index was proposed to ensure the objective assessment of the sound quality of automatic washing machines[18]. Psychoacoustic metrics were used to investigate the relationship between consumer satisfaction and electric vehicle signature sound[19]. a model of psychoacoustic sportiness excluding loudness for vehicle interior sound was developed to target the “sporty” image of vehicles[20]. Loundness, sharpness, roughness and fluctuation were used as the output of the back propagation neural network to establish a sound quality prediction model of the vehicle noise[21]. Loundness and sharpness were proved effective in sound quality evaluation of air-conditioner noise based on factors of the autocorrelation function[6].

Subjective evaluation refers to perceptual investigation of the sound and many methods for subjective evaluation can be employed. Semantic differential method was utilized to evaluate the noise emitted from axial piston pumps[22]. Through paired comparison method, the sound quality of different aircraft sounds was evaluated[23]. Rating scale method was uesd, where the noise signals were listened and given a score based on the difference with the anchor signal by the jury[24]. The sound quality prediction models based on three different algorithms, the lasso, elastic-net and stepwise, were compared with the jury test[25].

However, there are very few studies about sound quality evaluation of EEVs. The main purpose of this study is to create an evaluation and prediction model about the sound quality of EEVs based on the correlation of the subjective and objective evaluation assessment. The rest of this paper is organized as follows: Section 2 describes the noise test procedures of EEVs. Section3 presents the grouped paired comparison method and subjective evaluation and Spearman rank correlations and factor analyses were exercised to evaluate the reliability of each jury member. In Section4, the psychoacoustics metrics were introduced and calculated to extract noise features manually. In Section6, an acoustic prediction model based on the neural network to predict the sound quality of EEVs is developed. Section 6 presents the conclusion.

2. Noise Measurement

2.1 Descriptions of Test EEVs

The test EEVs are located in each indoor unit of the flow multi-spilt air conditioning system, and Table 1 shows the main parameters of test EEVs.

Table 1 *The main parameters of test EEVs*

No.	Descriptions	Specifications
1	Valve leakage	<80ml/min
2	Valve open pulse	32±15
3	Maximum operation voltage	12V under idle pressure 6V under 3.5MPa
4	Reverse operation differential pressure	>2.5MPa
5	Outline dimension	65mm×35mm×85mm

Six models of direct-driven EEVs of different product class made by differet manufacturers were selected. The sound signal of EEVs were recorded under three operation models (opening, stable-running, shutdown) of air condition.

2.2 The recording procedure of sounds

The dimension room of the anechoic chamber was 6m×5m×4m. The anechoic chamber maintained a uniform temperature at 27℃ and the humidity was around 50%. The arrangement of each experimental equipment is shown in Fig.1. Digital artificial head measurement system (HMS) was employed to perform aurally-accurate binaural recordings of EEVs . The distance between the measuring point of the HMS and the geometrical center of the test EEVs was nearly 0.5m×0.5m and the digital artificial head face the EEV directly. Fig.2 shows EEV was installed externally in the indoor units of multi-spilt air conditioning so that there is no barrier between HMS and EEV. To eliminate other noise, the blower of indoor unit was not working and the outdoor unit was located outside. Only one indoor unit was operating when running the tests. The HMS was calibrated before the tests and collected the sound pressure signal.

The opening sound was recorded with a time length of 100s when the indoor unit started up. After further operating for around 30minutes to stabilize the flow condition, the stable-running sound of EEV, with a time length of 100s, was recorded, and the sound signal of shutdown was recorded from the shutdown button was pressed to the indoor unit completely stopped.

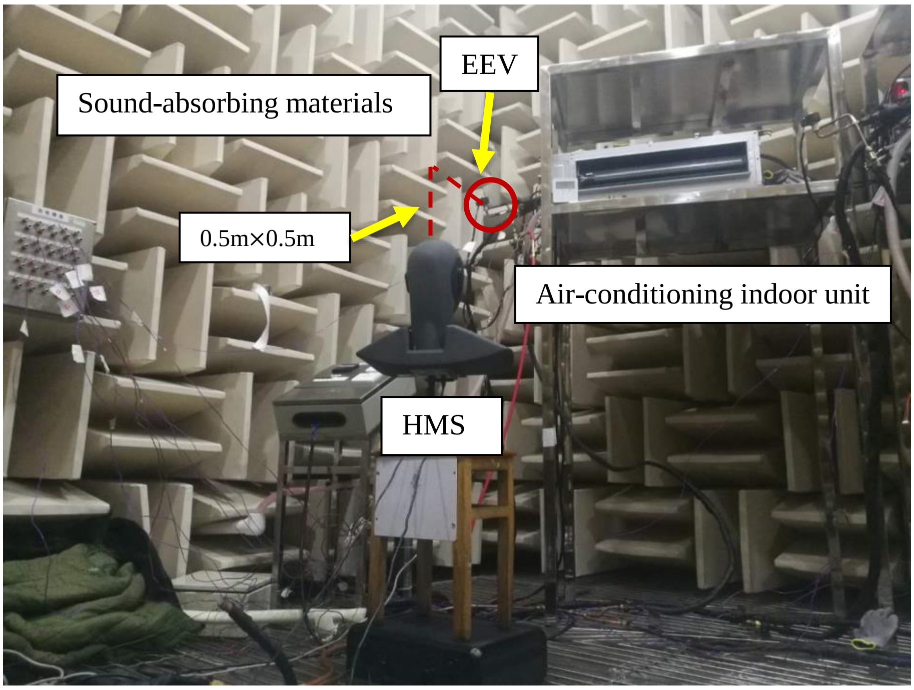


Fig.1 *Arrangement of experimental equipment*

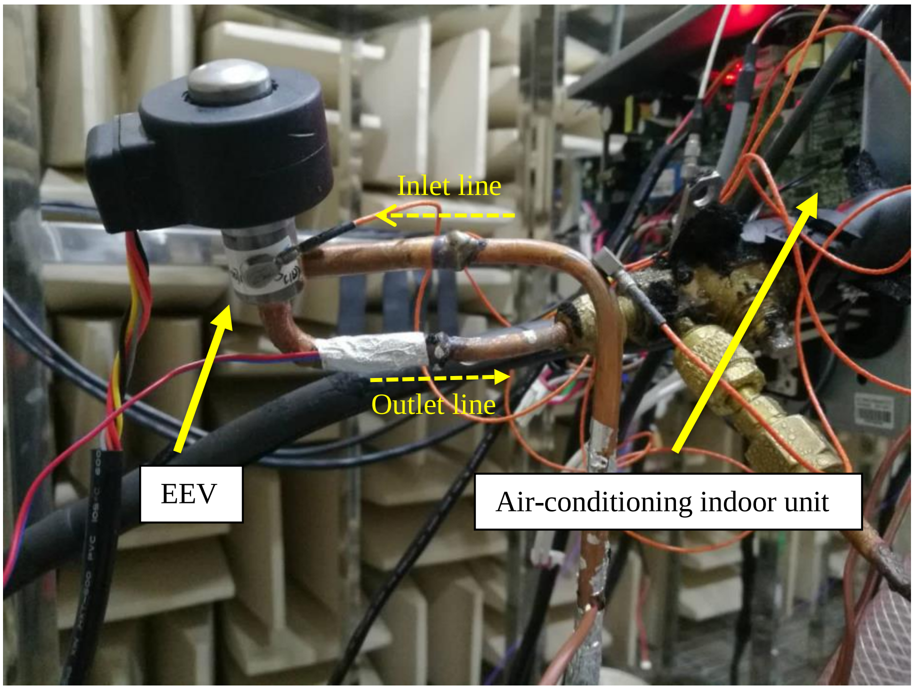


Fig.2 *Installation of EEV*

3. Subjective Evaluation of Sound Quality

3.1 Grouped paired comparison method

Human's perception of noise can be reflected by subjective evaluation. However, time consumption grows exponentially with the number of samples is the prominent drawback of traditional paired comparison method. Grouped paired comparison (GPC)method can greatly decrease time requirement and difficulties of traditional paired comparison method[26]. The whole samples are divided into n groups and each group contains link samples(LSs):R1 and R2, as shown in Fig.3.

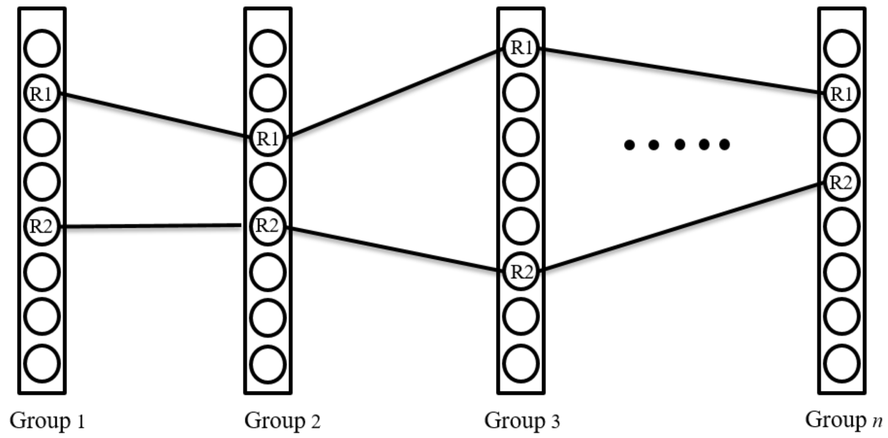


Fig.3 *Grouped paired comparison method (R1,R2 are link samples)*

Because of the diverse composition of each group, for example, in Fig.3, R1 and R2 may have different results among different groups, meanwhile, the difference of results between R1 and R2 in each group may probably be different as well. From subjective results of each group, final results of all samples can be reconstructed as Eq.1.

$$S_{ij} = \frac{\alpha}{(R_{1j} - R_{2j})}(V_{ij} - R_{1j}) + \beta \qquad \text{Eq.1}$$

Where S_{ij} is the final result of i-th sample of j-th group, R_{1j} and R_{2j} respectively are the raw results of R1 and R2 in j-th group, α is proportionality coefficient, β is translation adjustment.

α and β are varied among each pair of groups and these two variables can ensure the final results of all samples in the appropriate scale range. There are three criterion need to be considered when selecting LSs: (1)the characteristics of LSs' sound quality should be neutral. (2) the sound quality of each LS can be distinguished distinctly. (3) the sound qualtiy of each group should be similar.

3.2 Procedure of subjective evaluation

58 sound signals of EEV were utilized as samples to implement the subjective evaluation, the time length of each sample was 5s. Two RLSs were selected manually and the rest of 56 samples were divided into 7 groups. Therefore, each groups consisted of 10 kinds of sound samples and all samples were arranged randomly.

The jury consisted of 30 members (24 males and 6 females). The average age of jury was 25. Most of members are untrained in the field of acoustics. Subjective evaluation was carried out in semi-anechoic room, the background noise was around 21dB(A), the temperature was around 22℃ and the humidity was around 50, the other indexes all met the requirements of the indoor air quality standard. A headphone, a laptop, and HEAD ArtemiS 10 were employ to replay the recorded sounds. The arrangement of jury evaluation equipment is shown in Fig.4. Before the jury test, the jury members were asked to sit calmly on a chair. Grouped paired comparison method and descriptions of the sounds were explained. Each jury member performed the evaluation individually and multiple times replay was allowable. The jury could take the evaluation result down in a fillable PDF form, as shown in Table5. In Tabel5, the row samples were compared with column samples.

Each member of jury had to give a score of -1,0 and 1 for each comparison, -1 means the sound quality of row sample is worse than the column samples, 1 means the sound quality of row sample is superior to the sound quality of the column sample and 0 means they have the same sound quality. Semi-matrix form was used in order to reduce the time consumption.

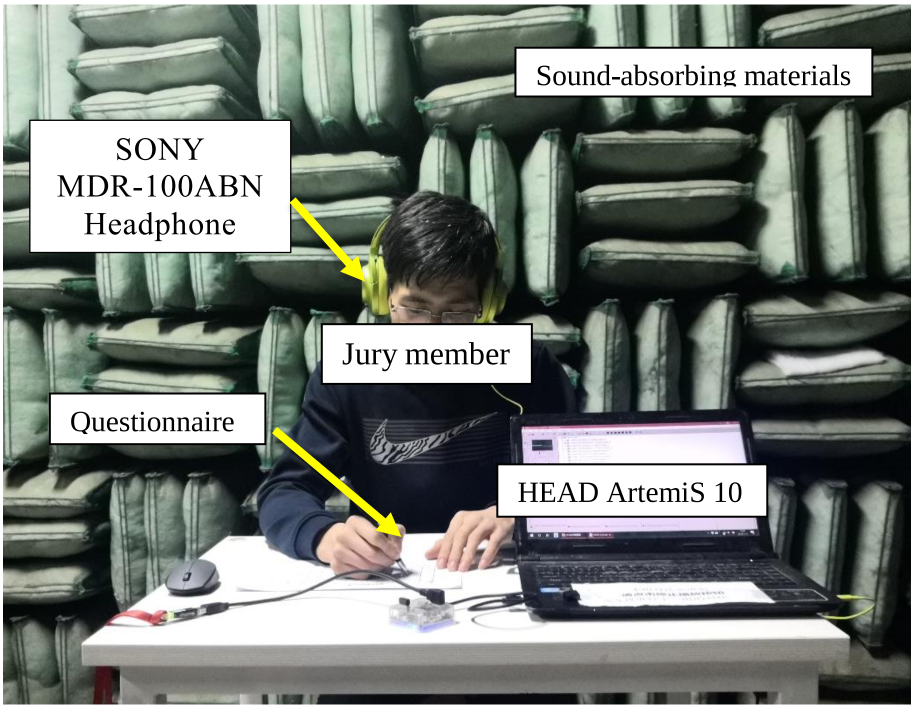


Fig.4 *Arrangement of jury evaluation equipment*

Table 2. *The form of grouped paired comparison method*

Grouped Paired Comperison Method										
Name:			**Age:**			**Gender：**		**Group：**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

3.3 Statistics of subjective evaluation results

Spearman correlation test provides a method to establish the strength of the relationship between variables, i.e. the correlation[27]. Spearman rank correlation analysis were determined selected to analyze the subjective evaluation results. The significant correlation coefficients between every member of jury were calculated by SPSS and then took the average value. The final correlation coefficients of jury members are shown in Table3.

Table 3 *correlation coefficient of each jury member*

Member	1	2	3	4	5	6	7	8	9	10
Correlation Coefficient	0.803	0.682	0.624	0.765	0.815	0.803	0.779	0.680	0.729	0.790
Member	11	12	13	14	15	16	17	18	19	20
Correlation Coefficient	0.759	0.722	0.810	0.754	0.810	0.764	0.819	0.780	0.811	0.765
Member	21	22	23	24	25	26	27	28	29	30
Correlation Coefficient	0.743	0.842	0.856	0.856	0.813	0.751	0.775	0.767	0.811	0.755

According to Table3, the evaluation results of 6 members whose correlation coefficient is less than 0.75 were eliminated and the rest 24 respondents' evaluation results were reliable with a significant correlation and were selected as the final jury for all analyses. The overall mean values of subjective evaluation of 24 reliable jury member were calculated and reconstructed results were normalized. The final score of all 58 samples are shown in Table4.

Table 4 *Subjective evaluation results of all sound samples*

Sound Sample	1	2	3	4	5	6	7	8	9	10
Score	2.712	1.091	7.152	1.501	3.766	4.365	4.367	3.238	1.778	7.068
Sound Sample	11	12	13	14	15	16	17	18	19	20
Score	5.898	5.061	2.894	2.772	7.448	2.226	5.463	7.610	7.880	4.871
Sound Sample	21	22	23	24	25	26	27	28	29	30
Score	1.708	1.940	5.668	6.180	1.551	7.395	5.664	2.509	6.372	6.547
Sound Sample	31	32	33	34	35	36	37	38	39	40
Score	8.244	3.013	3.832	5.691	2.073	5.564	7.502	2.073	2.270	7.266
Sound Sample	41	42	43	44	45	46	47	48	49	50
Score	6.320	4.389	7.864	2.801	2.174	2.329	5.229	1.936	5.410	7.485
Sound Sample	51	52	53	54	55	56	57	58	59	60
Score	2.639	5.945	1.534	4.228	4.233	6.144	7.894	7.338		

The subjective evaluation results reflect the degree of preference of the jury member to the samples. The high score means a better sound quality of sample. On this basis, the relationship between subjective evaluation and objective evaluation can be discussed.

4. Objective evaluation of sound quality

4.1 Psychoacoustics metrics

Sound quality can be quantified through objective evaluation approach. Compared to subjective evaluation, objective evaluation is efficient, reliable and has no constraints of sample size. Analytical methods such as analytical model, objective sound metrics and computer software are frequently used in objective evaluation. Many applicable psychoacoustic metrics to various spheres have been developed The common used psychoacoustic metrics are show in Table5.

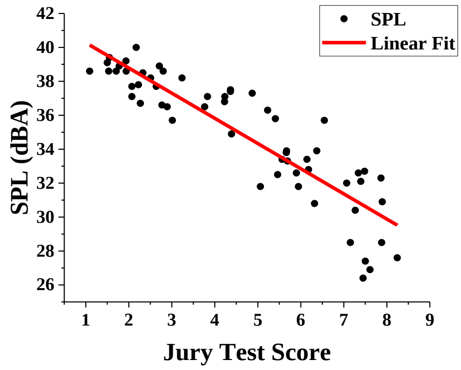
Table 5 *Defined psychoacoustic metrics*

Metric	Unit	Standard or Reference Model
A-weighed SPL	dBA	ISO 226:2003 2003b
Loudness	sone	ISO532B
Sharpness	acum	DIN 45692:2009-08 2009
Roughness	asper	Aures method[28]
Fluctuation Strength	vacil	Aures method[28]
Speech Intelligibility Index	%	ANSIS3.5-1997

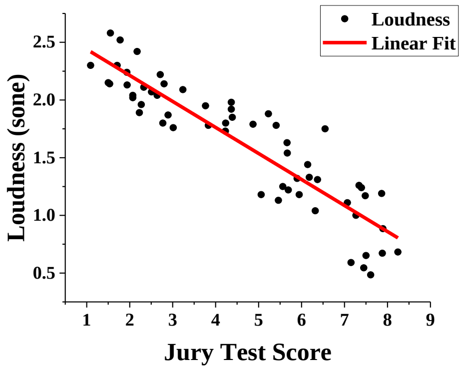
A-weighting SPL is generally used to account for the different sensitivity of the human ear in the frequency range. Loudness is considered as the metric more closely related to the perception of the sound level. Sharpness reflects the harshness of the sound[29]. Roughness and fluctuation strength(FS) are respectively related to the perception of amplitude and frequency modulation for a modulation frequency higher or lower than 20 Hz. The Speech Intelligibility Index (SII) of a noise indicates the extent to which that noise reduces intelligibility of speech. Intelligibility depends on level and the frequency of background noise and on the speech spectrum itself.

4.2 Comparison of objective semantics and subjective metrics

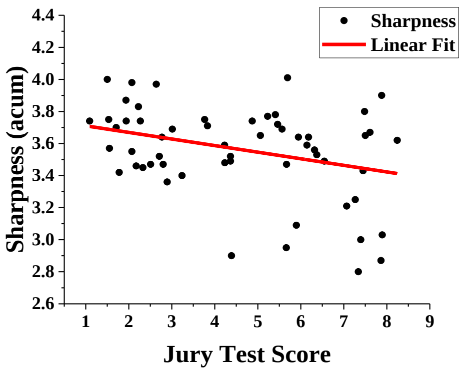
Six psychoacoustic metrics were selected and calculated. Scatterplots of subjective evaluation results and psychoacoustic metrics are shown in Fig.5. The scatter is the actual result of psychoacoustic metrics and jury test, and the curve is their linear fitting curve. The Scatterplots indicate that the jury members' perception of EEV sounds shows a good correlation with SPL, loudness, roughness, fluctuation strength and SII.



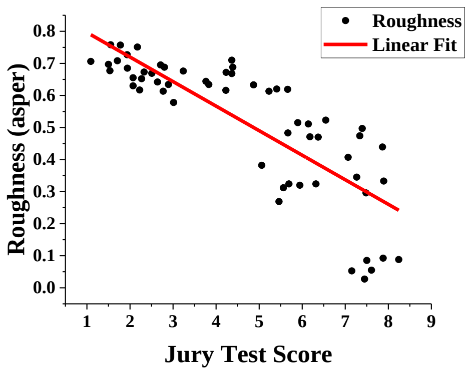
(a) Scatterplots of SPL and test score



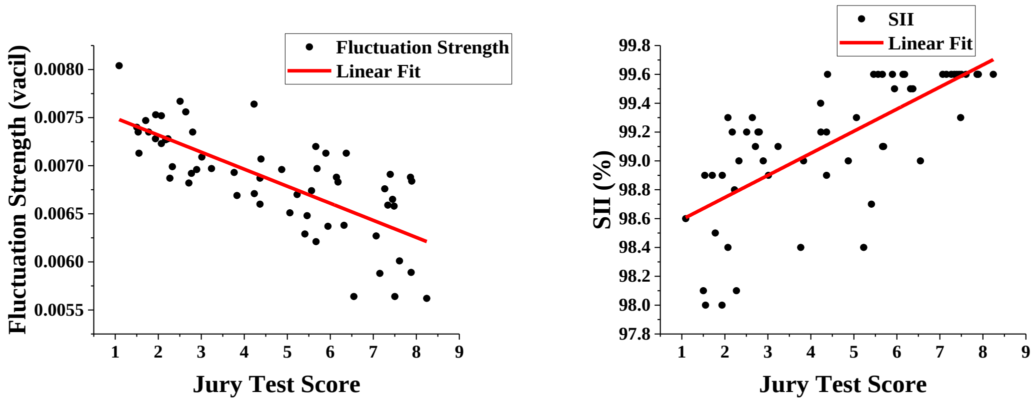
(b) Scatterplots of loudness and test score



(c) Scatterplots of sharpness and test score



(d) Scatterplots of roughness and test score



(e) Scatterplots of fluctuation strength and test score (f) Scatterplots of SII and test score

Fig.5 *Scatterplots of subjective evaluation results and psychoacoustic metrics*

The Pearson correlation parameters between jury test score and psychoacoustics metrics were calculated and the results are shown in Table5. It can be seen that SPL, loudness, roughness and fluctuation strength have strong negative correlation with subjective perception. SII has strong positive correlation with subjective perception and the correlations between sharpness and subjective evaluation are weak.

Table 5 *The Pearson correlation parameters.*

	SPL	Loudness	Roughness	Sharpness	FS	SII
Jury Test Score	-0.893	-0.908	-0.816	-0.301	-0.734	0.718

5. Sound quality prediction model of EEV

5.1 Artificial neural network

In recent years, artificial neural network(ANN) has been widely used to study the sound properties, especially for the evaluation and prediction of sound quality[21, 22, 24]. In this paper, a three layers ANN, as shown in Fig.6, was established to evaluate the relationship between the psychoacoustic metrics and the jury test results.

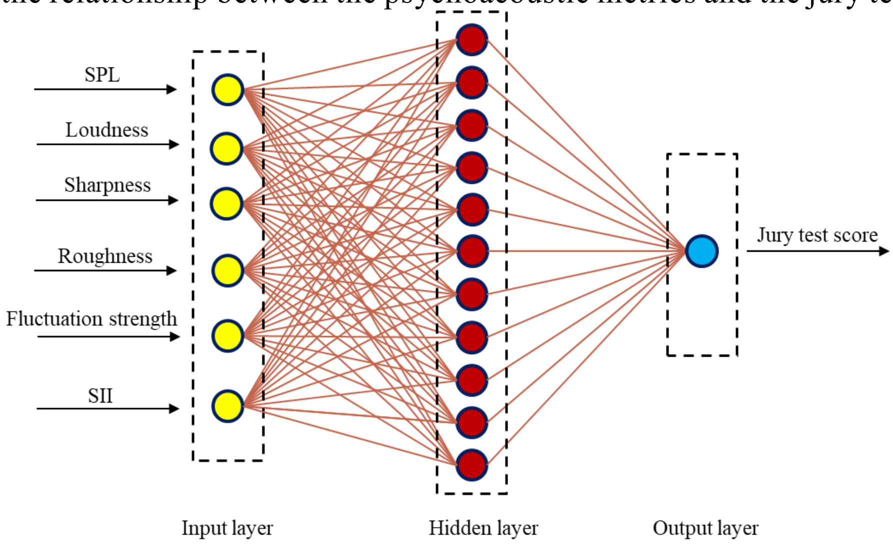


Fig.6 *The architecture of ANN*

The whole sound samples were divided into training samples (75%), validation samples (15%) and testing samples (15%). Six psychoacoustic metrics were presented to input layer of the neural network as input data, the output layer including only one neuron is the jury test results of the EEV sound. Levenberg–Marquardt algorithm (trainlm), the fastest training algorithms for networks of moderate size, was selected as the train algorithm The number of neurons of hidden layer can be calculated by the empirical formula shown as Eq.2.

$$N_{hidden} = \sqrt{N_{input} + N_{output}} + c \qquad \text{Eq.2}$$

where N_{hidden} represents the number of neurons of hidden layer, N_{input} represents the number of neurons of input layer and N_{output} represents the number of neurons of output layer, c is constant and can be selected from 1-10 nomoraly.

5.2 The results of ANN model

In most cases, N_{hidden} has a strong influence on the accuracy and training time of ANN model. Various neurons in the range from 4-14 according to Eq.2 were investigated in order to compare the prediction quality and Mean squared Error (MSE) , and coefficient of determinations R^2 were utilized to assess the performance of ANN models. The best 3 training results of different ANN structures are shown in Table 6.

Table 6 *Prediction results for different ANN models*

Model	N_{hidden}	Training R^2	Validation R^2	Testing R^2	All R^2	All MSE
Net11	11	0.999	0.953	0.912	0.983	0.171
Net6	6	0.997	0.966	0.928	0.978	0.209
Net13	13	0.984	0.963	0.955	0.978	0.207

In a word, the Net11, with the structure 6-11-1, shows the highest R^2 and lowest MSE of all data. Fig.7 shows the comparison of predicted results of Net11 with the jury test results. It can be seen that most of the predicted results of Net11 agree very well with the jury test results. These results imply the ANN model can be used to estimate the sound quality of EEV accurately and efficiently.

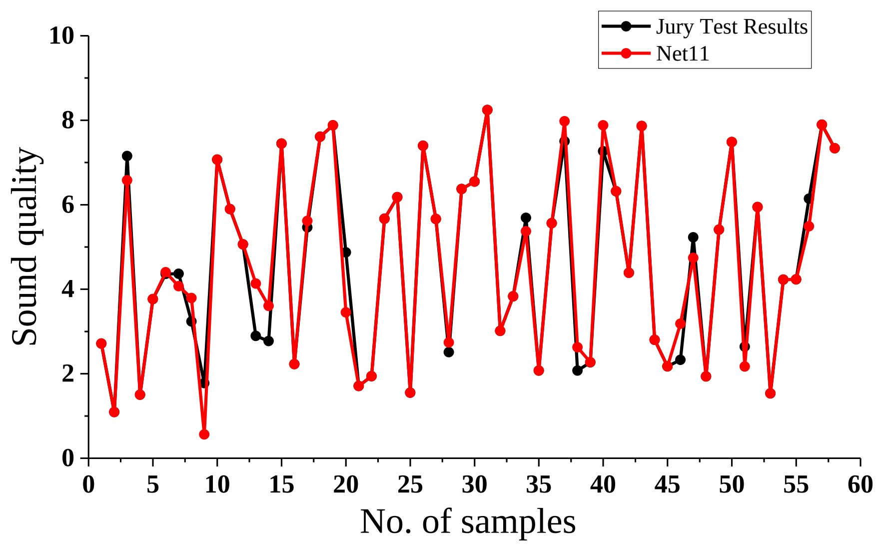


Fig.7 *Comparison of predicted and test sound quality*

6.Conclusions

Base on the subjective and objective evaluation method, an ANN model was proposed to predict and evaluate the sound quality of EEV. Group paired comparison method and six psychoacoustic metrics were utilized to establish the model. Three conclusions can be drawn in this study: (1) Group paired comparison method is an efficient subjective method and it is sufficient in term of evaluating large numbers of samples; (2) There were strong correlations between SPL, loudness and roughness and perception of EEV sound. The correlations between the fluctuation strength, SII and the perception of EEV sound were moderate. The correlation between sharpness and the perception of EEV sound was weak. (3) Sound quality model based on ANN method can predict and evaluate the sound quality of EEV accurately.

It is except that this study can lay a good foundation for the further sound quality study especially for the study of EEV sound. The sound quality measurement and evaluation of other household products can also use the developed method in this study.

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