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Research on nonlinear evaluation model of cooling fan sound quality

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Abstract

The cooling fans are usually used for cooling machines to keep them running well. However, they also cause noise and do harm to users' hearing system, nervous system, even cardiac and cerebral functions. Aiming at providing evaluation criterion to noise deduction by predicting the human's feeling about noise, this paper established a nonlinear evaluation model of cooling fans' sound quality. 13 sound samples of cooling fans were collected with HEAD Recorder and HMS IV. After editing, 33 samples were saved with the duration of 5s. In the subjective evaluation experiment, 30 subjects were recruited to mark each sound sample. For objective evaluation, the 33 samples were imported into ArtemiS to analysis psychoacoustic parameters, Sound Pressure Level (SPL) and A-weighed Sound Level. A Correlation Analysis was done first to screen parameters roughly and tonality was removed with low correlation coefficient of -0.493. Then research did Linear-regression Analysis and screened parameters strictly. According to the Run Test results of Standardized and Studentized Residual, the Asymptotic Significances (2-tailed) were both less than 0.05 which indicates that residuals were not mutually exclusive and this model was not functional. The model was repeatedly modified until the Asymptotic Significances (2-tailed) became greater than 0.05. A nonlinear evaluation model was established finally with independent variables of loudness, sharpness, SPL and A-weighed sound level.

Keywords: cooling fan sound quality, subjective evaluation, psychoacoustic parameters, Regression Analysis

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1 Introduction

Noise of cooling fans in machine room causes lots of complains from both staffs and neighbours. The noise seems not a big deal as the cooling fans are good for machines. However, if the noise inside the machine room stays in 75 dB (A), there will be health issues inside human body in the environment [1], such as stomach disorder, temporary deafness, etc.

Noise Reduction has been done to these machine rooms. The A-weighted sound level of noise became qualified, but people living or working around cooling fans were still not satisfied. It is because human feeling about noise does not only depend on A-weighted sound level [2], there must be other factors influencing subjective feeling of people. Thus, subjective evaluation of cooling fan noise is necessary in Noise Reduction.

It is obvious that subjective and objective evaluations are nonlinear correlation [3]. So a nonlinear evaluation model is to be established in the research to predict subjective feeling. In this paper, Regression Analysis is used in nonlinear analysis. Usually the linear Regression Analysis is used in research first. If there are errors about the model, other methods will be selected, such as, Path Analysis, Neural Network, Fuzzy Evaluation, etc. But in the paper, the linear regression model will be modified and turned into a nonlinear model to evaluate sound quality correctly.

In this research, sound samples are collected in some signal transmission station in Heilongjiang, China. The commonly used cooling fans in station are as shown in Figure 1. These samples are edited in HEAD Monitor and analysed objective parameters in ArtemiS. Regression analysis is carried on after subjective evaluation is finished. Linear Regression Analysis is done first and modified after finding errors about the model. The evaluation model is completed until Asymptotic Significances of Residual is qualified.

Figure 1: The most commonly used cooling fans in the station

2 Objective evaluation of cooling fan sound samples

2.1 Cooling fan sound collecting and editing

The signal transmission station including TV and radio signals. And both transmission sections own large areas and are suitable to collect sound samples. Normally, a 10kW TV signal transmission machine has two cooling fans around to keep the temperature proper. And a 3kW radio signal transmission machine possesses 5 fans to cool it.

During the collection, only one cooling fan is working to avoid other sound sources. 6 collecting spots are set in the TV signal section, including 4 spots around the cooling fan and two ones on the furthest and closest working spot to cooling fan. 4 collecting spots in radio signal section surround its cooling fan and working spots. Also, there are also 3 collecting spots in the office, including 2 spots on the seat of workers and 1 spot on the centre of office room.

Collection is carried on with HMS IV of HEAD Acoustics to guarantee sound samples in accordance with the sound that human heard. As shown in Figure 2, HMS IV is designed in form of human head and following the Binaural Effect of human hearing [4], so the collected sound samples will be appropriate for both objective evaluation and the following subjective experiment.

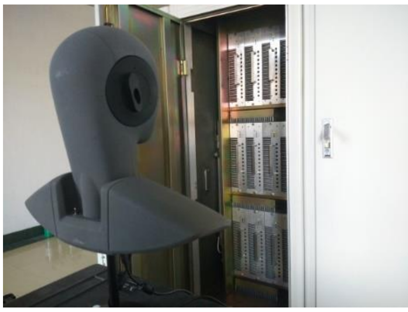

Figure 2: Collecting scene of HMS IV

In the end, 18 samples with duration of 180s are collected. And 13 samples are saved after removing sound samples with useless sound, such as, door opening, door closing, workers' talking, etc. As shown in Figure 3, the editing selects sample with duration of 5s among the stable wave. And finally, 33 samples with 5s are saved for the following evaluation process.

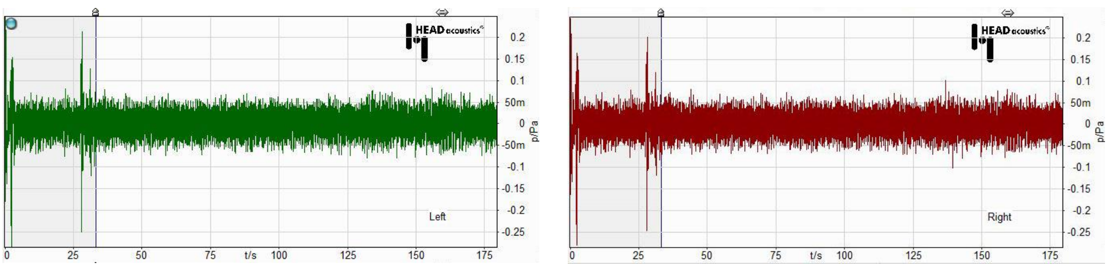

Figure 3: Editing of sound samples

2.2 Analysing objective parameters of sound samples

In objective evaluation, the psychoacoustic parameters, sound pressure level and A-weighted sound level are included for analysis. And for the psychoacoustic parameters [5], sharpness, loudness, fluctuation strength, roughness, tonality, articulation index and speech intelligibility are considered for objective evaluation in research.

Sharpness represents the perception of human on harsh sound. In the paper, 3 algorithm models are included [6]. And one of them will be chosen as the best algorithm to carry on the next Regression Analysis. Loudness means human feelings on sound intensity. Fluctuation strength and roughness are actually with same property. When the modulation frequency is between 0~20 Hz, fluctuation strength plays a role in sound. However, if the modulation frequency goes up from 20 Hz, the roughness will appear [7]. Tonality indicates the rate of pure tone in the whole sound sample. Articulation index and speech intelligibility both represent the percentage of understandable speech in noisy environment [8].

Taking one of the samples as an example, Figure 4 shows the loudness, fluctuation strength, roughness and tonality. And its objective evaluation result is as shown in Table 1.

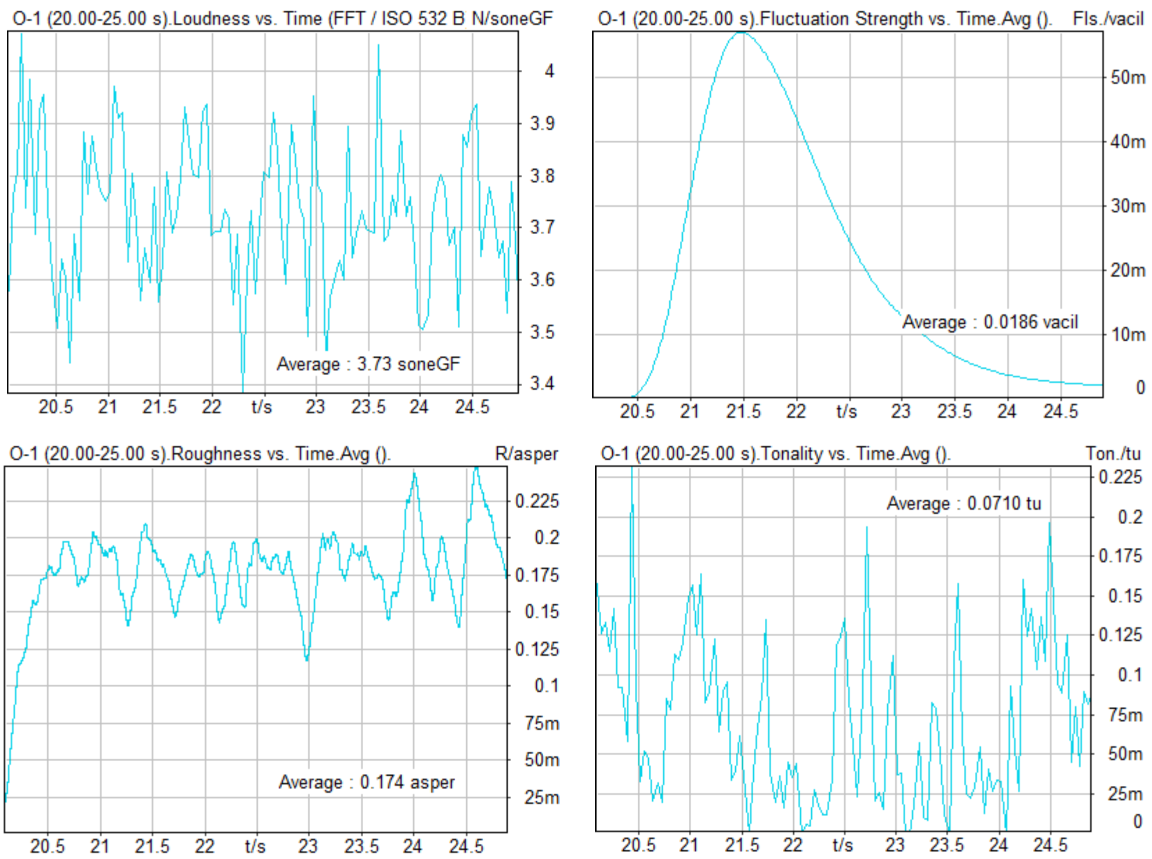

Figure 4: Wave form of objective parameters

Table 1: Objective evaluation result of one sample

Loudness	**Sharpness(Von)**	**Sharpness(DIN)**	**Sharpness(Aures)**	**Roughness**	**Tonality**
3.73 sone	0.911 acum	0.952 acum	1.17 acum	0.174 asper	0.071 tu
Fluctuation Strength	**Articulation Index**	**Speech Intelligibility**	**Sound Pressure Level**	**A-weighted Sound Level**	
0.0186 vacil	100%	98.9%	59.2 dB	42.4 dB(A)	

3 Subjective evaluation on sound of cooling fans

3.1 Paired comparison

In paired comparison method, all the samples are paired. When grading, the subjects are asked to record the rate of choosing one of samples in a pair. And the experimenter needs to calculate mark of each sample based on the rates [9]. If there is a pair containing sample i and j, the rate of choosing sample i is P_{ij} while the one of sample j is P_{ji}, the mark of sample i is defined as

$$M_i = \frac{1}{t}\sum_{i\neq j} ln\left(\frac{P_{ij}}{P_{ji}}\right) \tag{1}$$

3.2 Experiment of subjective evaluation based on Paired Comparison

The subjective evaluation experiment is conducted with method of paired comparison. 33 samples are named with number and divided into 528 pairs. It will take about 90min to play all samples, so there will be a break every half an hour to keep the subjects concentrated. 30 subjects are recruited in total with half of them are women and the rest are men. All subjects own normal hearing. Samples in each pair is named with A and B, they are asked to mark on the irritability degree with the standard shown in Table 2.

Table 2: Standard of subjective evaluation based on Paired Comparison

Conditions	**Mark**	**Conditions**	**Mark**
B is far noisier than A	0	B is similar to A, but A is noisier	0.6
A sounds better than B	0.2	B sounds better than A	0.8
A is similar to B, but B is noisier	0.4	A is far noiser than B	1

After calculating data of subjective evaluation according to equation (1), the marks of each sample is shown as Table 3.

Table 3: Standard of subjective evaluation based on Paired Comparison

No.	Mark	No.	Mark	No.	Mark	No.	Mark	No.	Mark	No.	Mark
M1	-1.126	M7	-0.164	M13	-0.549	M19	-0.106	M25	0.087	M31	0.794
M2	-1.090	M8	-0.162	M14	-0.521	M20	-0.082	M26	0.090	M32	0.792
M3	-1.147	M9	-0.251	M15	-0.542	M21	-0.113	M27	0.055	M33	0.823
M4	-0.719	M10	-0.207	M16	0.205	M22	0.412	M28	1.317		
M5	-0.648	M11	-0.225	M17	0.245	M23	0.440	M29	1.350		
M6	-0.712	M12	-0.305	M18	0.264	M24	0.423	M30	1.253		

4 Establishment of nonlinear regression evaluation model for cooling fan sound

4.1 Objective parameters screening

4.1.1 Selecting algorithms for sharpness

3 algorithms of sharpness are introduced in this paper, including Von Bismarck, DIN and Aures. Yet, only one algorithm closest to subjective feeling can be saved for establishing model. So Correlation Analysis between 3 algorithm and objective parameters is done in SPSS for selection. Correlation Coefficient of algorithm is shown in Table 4.

Table 4: Correlation Coefficients of sharpness algorithm

	Von Bismarck	DIN.	Aures
Correlation Coefficient	0.725**	0.723**	0.914**
Sig. (2-tailed)	0.000	0.000	0.000

It is obvious that Aures algorithm owns the highest coefficient. Thus, in the following analysis, Aures will be selected for sharpness.

4.1.2 Correlation Analysis between objective and subjective evaluation

In the model establishment, the parameters need to be close to subjective feeling, but not all parameters can describe human feeling. So another Correlation Analysis should be done to remove the useless objective parameters. Result of Correlation Analysis is shown as Table 5.

Table 5: Result of Correlation Analysis on objective parameters

Objective parameter	Correlation Coefficient	Objective parameter	Correlation Coefficient
Sharpness	0.914**	Fluctuation strength	0.902**
Tonality	-0.493*	Roughness	0.899**
Speech intelligibility	-0.674**	Sound pressure level	0.847**
Loudness	0.956**	A-weighted sound level	0.857**
Articulation index	-0.781**		

It can be seen from Table 5, tonality only has a Correlation Coefficient of -0.493*, which means it weakly correlative with subjective evaluation. So it is not allowed to join the Regression Analysis.

4.2 Linear Regression Analysis of objective and subjective evaluation

4.2.1 Scatterplot of variables

From the scatterplot in Figure 5, it can be seen that sharpness, loudness, fluctuation strength, roughness, sound pressure level and A-weighted sound level have obvious linear correlation with subjective marks. They will be involved in model establishment.

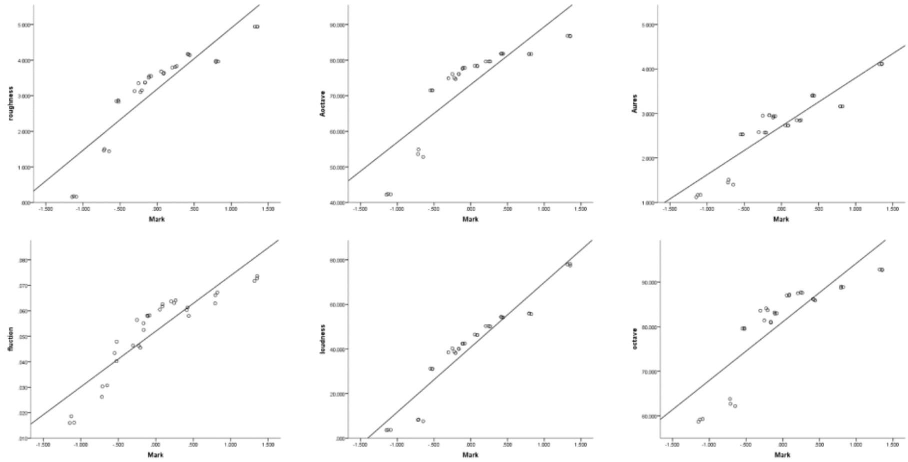

Figure 5: Scatterplot of variebles

4.2.2 Regression Analysis of sound quality evaluation

Using Stepwise method to carry on Regression Analysis and introducing selected parameters along with subjective marks, the result of analysis is shown as Table 6. Roughness and fluctuation strength are removed in process of model establishment.

Table 6: Result of linear Regression Analysis

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	3.666	0.700		5.236	0.000
Loudness	0.089	0.008	2.694	10.698	0.000
Sound pressure level	-0.107	0.019	-1.634	-5.660	0.000
Sharpness	-1.044	0.202	-1.243	-5.160	0.000
A-weighted sound level	0.057	0.015	1.101	3.901	0.001

4.2.3 Run Test on the residuals

Analysing the Standardized and Studentized residuals with Run Test, the results is shown in Table 7 and Table 8.

Table 7: Result of Run Test (Median)

	Standardized Residual	Studentized Residual
Test Value[a]	-0.19154	-0.22972
Cases < Test Value	16	16
Cases >= Test Value	17	17
Total Cases	33	33
Number of Runs	11	11
Z	-2.119	-2.119
Asymp. Sig. (2-tailed)	0.034	0.034

Table 8: Result of Run Test (Mean)

	Standardized Residual	Studentized Residual
Test Value[a]	0.0000000	-0.0041549
Cases < Test Value	21	21
Cases >= Test Value	12	12
Total Cases	33	33
Number of Runs	10	10
Z	-2.212	-2.212
Asymp. Sig. (2-tailed)	0.027	0.027

The Asymptotic Significances from the tables both are less than 0.05, which means the residuals are not mutually exclusive.

4.3 Modifying regression evaluation model of cooling fan sound quality

Observing the scatterplots again, correlations among sound pressure level, A-weighted sound level and subjective evaluation are redefined with Logarithmic relationship. And sound pressure level is renamed $\ln octave$ while A-weighted sound level is named $\ln Aoctave$. The result of Regression Analysis is as shown in Table 9.

Table 9: Result of modified Regression Analysis

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	17.231	2.501		6.889	0.000
Loudness	0.082	0.007	2.497	11.506	0.000
ln octave	-7.101	1.132	-1.473	-6.276	0.000
Sharpness	-0.868	0.168	-1.034	-5.164	0.000
ln Aoctave	3.024	0.684	0.938	4.421	0.000

Run test the Standardized and Studentized residuals, the results based on median and mean are shown as Table 10 and Table 11.

Table 10: Result of Run Test (Median)

	Standardized Residual	**Studentized Residual**
Test Value[a]	-0.08051	-0.08400
Cases < Test Value	16	16
Cases >= Test Value	17	17
Total Cases	33	33
Number of Runs	13	11
Z	-1.411	-1.411
Asymp. Sig. (2-tailed)	0.158	0.158

Table 11: Result of Run Test (Mean)

	Standardized Residual	**Studentized Residual**
Test Value[a]	0.0000000	-0.0081994
Cases < Test Value	20	19
Cases >= Test Value	13	14
Total Cases	33	33
Number of Runs	12	12
Z	-1.579	-1.674
Asymp. Sig. (2-tailed)	0.114	0.094

From the above tables, Asymptotic Significances exceed 0.05 after modifying. The residuals are mutually exclusive. Also, R^2 of model improves, even though the difference is small, it still indicates more dependent variables can be explained. In short, after modifying, the evaluation model is more stable and accurate. The modified regression model is as follow:

$$M = 17.231 + 0.082x_N - 7.101x_{LP} - 0.868x_s + 3.024x_{LA} \qquad (2)$$

In equation, M means marks of subjective evaluation, x_N is loudness of sound samples, x_{LP} is the logarithm value of sound pressure level, x_S is sharpness of sound samples and x_{LA} is the logarithm value of A-weighted sound level.

5 Conclusions

In conclusion, the evaluation model based on Regression Analysis is established as above. With this nonlinear model and input of loudness, sharpness, etc., the mark of certain sample is possible to be predicted.

Only variables of loudness, sound pressure level, sharpness and A-weighted sound level are saved in the process of Regression Analysis, which means these four psychoacoustic parameters are related to subjective evaluation.

Besides, before carrying on Regression Analysis, scatterplots of various parameters should be observed to predict the relationship roughly between variables. In this way, workload can be cut down and save more time in model establishing.

After establishing evaluation model, Run Test is utilized to examine whether the model is valid or not. If the Asymptotic Significance is less than 0.05, then residuals are not mutually exclusive and model needs to be modified. On the contrary, if Asymptotic Significance is more than 0.05, the model is qualified.

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