Sound quality improvement of residential exhauster

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Abstract: In everyday life, the noise generated by exhauster in kitchens can be very annoying and therefore could affect life quality. In this article, the noise level spectrum and sound quality parameters for a specific exhauster are measured and analyzed by the sound level meter, the head/torso simulator and the software dB-sonic respectively. The results show that, at the position of human ears, the SPL is 68.1 dB(A), the roughness is 33.5 asper, the loudness is 27.8 sone, the fluctuation intensity is 6.8 vacil, the sharpness is 1.64 acum and the annoyance index based on the Wang's model of sound quality (SQ) assessment is 13.19, of which the sharpness and the loudness affects the SQ of the exhauster to the largest extent. By measuring vibrations on the exhauster casing and the motor seat, and comparing the vibrational spectra with that of the radiated vibroacoustic noise spectrum, it has been identified that the major peak components of the noise occur at the frequencies of 500Hz and 100Hz. The 500Hz sound component comes from the flow vortex at the intake, while the 100Hz sound component is induced by the casing vibrations. In order to improve the SQ of the exhauster, five countermeasures are adopted in this study to reduce both the sharpness and the loudness, namely: the installation of a muffler at the intake end; the installation of some absorption glasswool on the inside surface of the casing and the coverage of the glasswool with a thin PU film; the adhesion of damping tape on the casing surface and ventilation pipewall; and the combination of the above four measures. As a result, the noise level is reduced to 55.2 dB(A), the vibrations is reduced by1~5 dB, the loudness reduces to 14.7 sone, the sharpness reduces to 1.35 acum and the annoyance index reduces to 8.16.
Key words: Sound quality; psychoacoustic annoyance index; loudness; sharpness; roughness; fluctuation

0 INTRODUCTION

Noise, generated by an exhauster in kitchens, needs to be limited, In the 1960's, there were many methods used to measure noise. As a result, the International Standardization Organization (ISO) was pushed to standardize a method which was not only practical but would also produce correct and adequate values. Standardization is a time-consuming process, and finally decided to solve the problem in two stages. Stage one produced a simple method which could easily be implemented using relatively cheap equipments i.e. the measurement of A-weighted sound pressure level (SPL). However, this initial method, might produce inaccurate or even misleading results in noise control, which the ISO was aware of. Therefore, the ISO produced a second standard which was not as simple as the former but could produce much more appropriate values based on the human sensation of loudness. The two corresponding methods were described as loudness calculation procedures in ISO 532 and were published a few years after the dB(A)-proposal[1].

Apart from loudness, other indices such as sharpness, roughness and fluctuation, are needed to reflect the hearing sensation related to the sound stimuli. The combination of these indices can constitute a synthetic index to assess the psychoacoustic annoyance (PA)[1]. The quieter the environment, the more acoustically comfortable the customer senses. Sound quality measurement has become more and more important. However, the standard measurement microphones are not designed for simulating human sensation. It's insufficient to pursue the one-dimensional goal of reducing the sound pressure level of a manufactured product. Sound quality, the noise output of a product (or the stimulus) and the auditory events, has become a phenomenon with multi-dimensional aspects of the sound, such as psychoacoustics aspects, physics aspects, cognitive design aspects.

Psychoacoustics aspects of noise are important in the sound quality evaluations. The sound quality evaluation procedure includes using human subjects together with the design of different methods to rank or scale the sound events[2,3]. After which, the binaural

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recording of the product noise with an artificial head and play back to subjects were used to do the sound quality investigation[4]. Various standard artificial head measurement systems were developed for the diagnosis and analysis of sound and were available for different application, such as vehicles[5,6], home appliances[7,8], and IT industries. This paper is aimed at the sound quality improvement of an existing residential exhauster.

Five countermeasures are adopted to reduce both the sharpness and the loudness. The individual installation of muffler at the intake end, glasswool on the inside surface of the exhauster casing, packed glasswool with PU film, damping tape on the casing surface and the ventilation pipe wall respectively, and the combination of the above four individual measures etc. are studied and compared the effectiveness of the sound quality improvement of each measure has been evaluated and compared.

1 PSYCHOACOUSTICS PARAMETERS CALCULATION FOR ANNOYANCE EVALUATION

To develop the subjective assessment of the psychoacoustics annoyance (PA) of the hearing sensation from an exhauster, the quantitative description of annoyance ratings can be obtained in psychoacoustic experiments. The related psychoacoustic parameters including in the evaluation model of PA are loudness, sharpness, fluctuation strength and roughness. Therefore, both subjective evaluation test and objective quantificational description of the exhauster noise are taken into consideration.

1.1 Evaluation model of psychoacoustic annoyance

Psychoacoustic annoyance depends on the loudness, the timbre, and the temporal structure of sounds. Zwicker's model for unbiased annoyance (UBA) was expressed as:

$$UBA = d \cdot N_{10}^{13}\{1+0.25(S-1)\log(N_{10}+10)+ [0.3F(1+N_{10})/(0.3+N_{10})]\} \quad (1)$$

where N_{10} is the percentile loudness for upper 10% temporal loudness, S is the sharpness, F the fluctuation, d the influence factor; where $d \approx 15\,\text{dB}$ or 2 sone, during daytime; and $d = 1+(0.25N_{10})^{0.5}$, at night[9].

On the other hand, Amman and Greeberg[10] and Wang[11] established the relationships between annoyance index for the sound quality (SQ) of automobile noise and the loudness (L), sharpness (S), roughness (R) and fluctuation (F) with the following equation:

$$SQ = aL + bS + cR + dF \quad (2)$$

where a, b, c and d are the regression coefficients determine by the psychoacoustic experiments. The results indicates that, as a consequence of the regression, the parameters of loudness (L) and sharpness (S) are more sensitive than roughness (R) and fluctuation (F), especially under steadily and continuously operating machines.

Thus, Eq.(2) becomes[11]:

$$SQ = 0.186L + 10.375S - 8.995 \quad (3)$$

Note that Eq.(3) is used in this paper.

1.2 Loudness

Loudness is the sensation value of the human perception of sound volume where the distribution of critical bands and masking properties in hearing need to be taken into consideration. There are many computing methods for time varying loudness, such as Stevens method (ISO532A), Zwicker method (ISO532B), and the Aures version of Zwicker method, ISO532B extension. The unit of loudness is sone. A sine tone of frequency 1 kHz of level 40 dB is defined to have loudness 1 sone.

In the Zwicker method , the loudness (N) is expressed as the integral of specific loudness (N') over a critical-band rate:

$$N = \int_0^{24Bark} N' \mathrm{d}z \quad (4)$$

where z is the frequency band scale in Bark number, and

$$N' = 0.08\left(\frac{Q_{TQ}}{E_D}\right)^{0.23}\left[\left(0.5+0.5\frac{E}{E_{TQ}}\right)^{0.23}-1\right]\text{Sone}_G/\text{Bark} \quad (5)$$

Where Q_{TQ} is the excitation of threshold in quiet and E_D is the excitation corresponding to the reference intensity $I_0 = 10^{-12}\ \text{W/m}^2$. The index G is added at the bottom of the unit "sone" as a hint for the user that the loudness given in this value is produced using the critical-bands levels.

1.3 Sharpness

Sharpness is the ratio of high frequency level to overall level. It is calculated as the integration of a specific loudness which exhibits the distribution of loudness across the critical bands multiplied by a weighting function, and then divided by total loudness (hence, sharpness is level-independent). When normalized to a reference sound, a narrow band of noise centered at 1 kHz at the level of 60dB with a bandwidth of 160 Hz, has an agreed value of 1 acum.

According to *DIN*(455692 draft standard, measurement technique for the simulation of the auditory sensation of sharpness), sharpness calculation method was developed by *Aures* and *von Bismarck*. However the zwicker's method is used here.

$$S=0.11\left(\int_0^{24\text{Bark}} N'\cdot g(z)\cdot z\cdot \mathrm{d}z \Big/ \int_0^{24\text{Bark}} N'\cdot \mathrm{d}z\right)(\text{acum}) \quad (6)$$

In the equation above, S represents the sharpness to be calculated. The denominator gives the total loudness (N). The numerator looks like the first moment of a specific loudness over the critical-band rate, but with an additional factor, $g(z)$, which depends on the critical-band-rate. This factor is expressed as a function of critical-band rate as follows:

$$g(z)=\begin{cases}1, & (z\le 16\text{Bark})\\ 0.066e^{0.171Z}, & (z>16\text{Bark})\end{cases} \quad (7)$$

It can be interpreted from Equation (7), that, only when the critical-band rates are greater than 16 Bark the factor can increase from unity to a value of four at the end of the critical-band rate near 24 Bark. This explains why the sharpness of narrow band noises increases unexpectedly fast at high centre frequencies.

1.4 Fluctuation

Modulated sounds can elicit two different kinds of hearing sensations: the hearing sensation of fluctuation strength produced at low modulation frequencies up to a modulation frequency of about 20 Hz and the hearing of roughness occurring at higher modulation frequencies. From modulation frequencies of around 20Hz on, there is a transition between the hearing sensation of fluctuation strength and that of roughness. A model of fluctuation strength based on the temporal variation of the masking pattern can be expressed as follow[1]:

$$F=\Delta L/(f_{\text{mod}}/4+4/F_{\text{mod}}) \quad (8)$$

The above equation shows how the fluctuation strength (F) is affected by changes in masking depth (ΔL) of the temporal masking pattern and the nodulation frequency (f_{mod}) respectively.

1.5 Roughness

Three parameters are used in order to describe roughness quantitatively. In the case of amplitude modulation (AM), the important parameters are the degree of modulation and the modulation frequency. While in the case of frequency modulation, it is the frequency modulation index and modulation frequency that matters the most. Using the boundary condition that a 1-kHz tone at 60 dB and 100%, 70 Hz AM, produces the roughness of 1 Asper, the roughness (R) of any sound can be calculated using the following equation:

$$R=0.3 f_{\text{mod}}\int_0^{24\text{Bark}} \Delta L_E(z)\mathrm{d}z \quad (9)$$

where f_{mod} is the modulation frequency, and ΔL_E is the masking depth in critical-band.

1.6 Critical bands

The critical bands are auditory band passing filters whose band number scale ("psychoacoustic" or "Bark" scale) is a frequency scale of the numbered critical bands 1 through to 24, named Bark (named after von Barkhausen), and displayed with equal widths. The width of a given critical band is approximately:

100 Hz, at center frequencies below 500 Hz,

$0.2xf_c$, at center frequencies above 500 Hz.

These bands are derived from the frequency-to-place transform on the basilar membrane. Many psychoacoustic parameters involve the critical band (loudness, roughness, masking, etc.).

2 PSYCHOACOUSTIC PARAMETER MEASUREMENT AND ANALYSIS

2.1 Experiment set ups

In order to improve the sound quality of a residential exhauster as shown in Fig.1, the parameters relating to the sound quality calculations were measured by an artificial head and torso simulator (Fig.2). Meanwhile, noise were measured at 3 different locations (Fig.3) in front of the exhauster and vibrations were measured at 38 different locations on the exhauster (Fig.4). In where the sound level meters and the artificial head are put in front of the exhauster by a distance 10 cm and a height 150 cm above the floor. Based on the data collected, one can identify the positions of airborne and structure-borne noise sources and the binaural masking effect. During the measurements, the room temperature is ranged form 28℃ to 30℃.

Fig.1 Exhauster configuration

Fig. 2 Artificial head and torso simulator

2.2 Initial measurement

The noise and vibration acceleration levels at different measurement locations are shown in Fig.5 and Fig.6 respectively. The highest SPL is 68.1 dB(A) and the maximum vibration level is 130 dB.

Fig.3 Locations for noise measurement by sound level meters

The psychoacoustic parameters were measured and analyzed by the software package dB-Sonic. The results of time- domain (60 s) and frequency- domain specific loudness are shown Fig.7 and Fig.8. The time-domain and percentile sharpness are shown in Fig.9 and Fig.10. The time-domain and frequency-domain specific roughness are shown in Fig.11 and Fig.12. The corresponding specific fluctuation intensities are shown in Fig.13 and Fig.14. All these results are summarized in Table 1. Note that the critical band of maximum binaural specific loudness occured in the range of 16.9~18.3 Bark. The sharpness was very stationary varying in the range of 0.7-1.7 acum, with the mean sharpness being 1.6 acum. The specific roughness ranged from 0-0.15 asper. The annoyance index of sound quality based on Equation (3) was 13.19. Furthermore, among the four parameters related to the psychoacoustic annoyance calculation, loudness and sharpness were more sensitive. Due to the steady and continuous operation of the exhauster, the values of sharpness and fluctuation were relatively low, and the

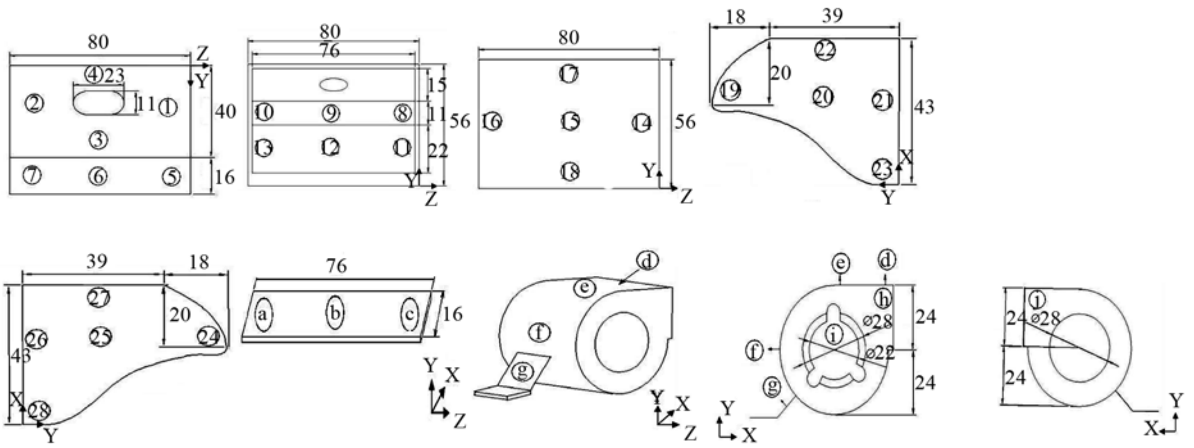


Fig.4 Locations for vibration measurements

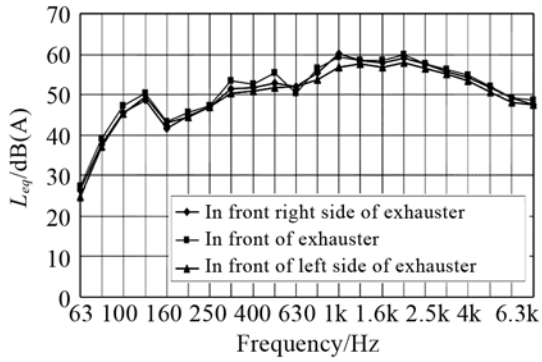


Fig.5 SPL at 3 measurement points in front of the exhauster

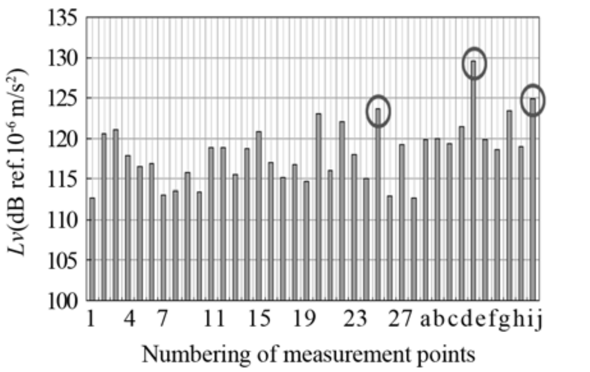


Fig.6 Vibration levels at 38 locations on different parts of the exhauster

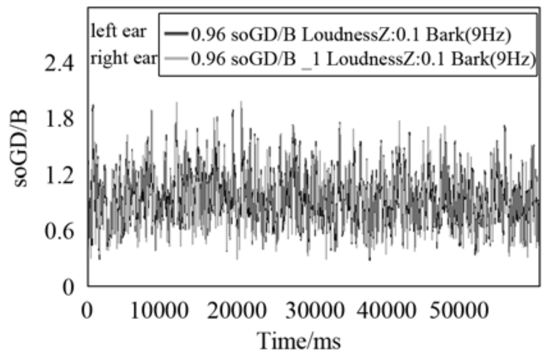


Fig.7 Time-domain specific loudness of the exhauster noise

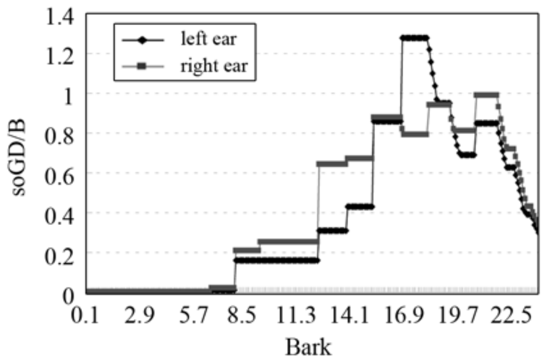


Fig.8 Specific loudness spectrum of the exhauster noise

roughness was quite stationary and less sensitive. Therefore, the countermeasure of the noise abatement remained the only approach of loudness reduction.

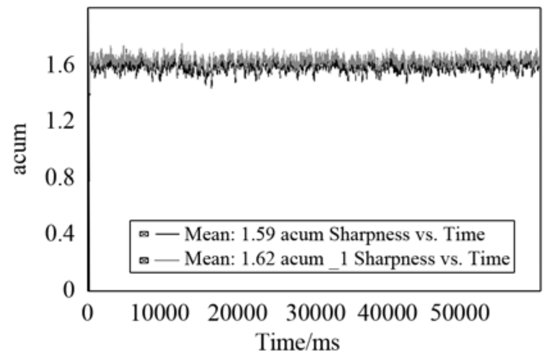


Fig.9 Time-domain specific sharpness of the exhauster noise

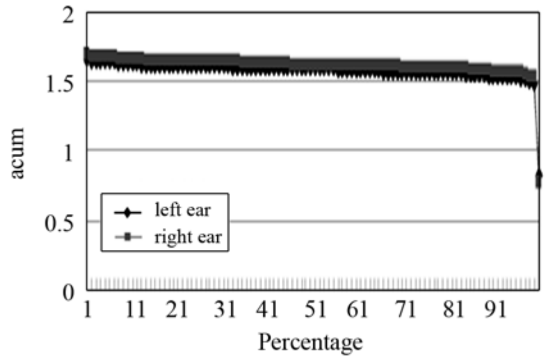


Fig.10 Percentile sharpness of the exhauster noise

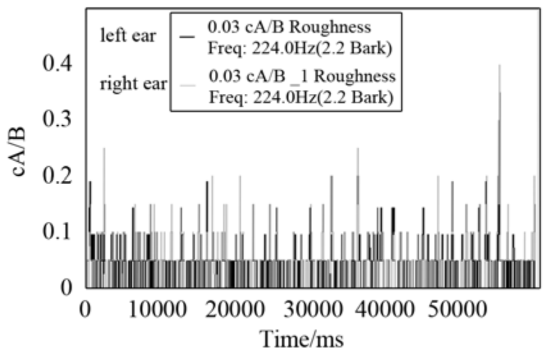


Fig.11 Time-domain specific roughness of the exhauster noise

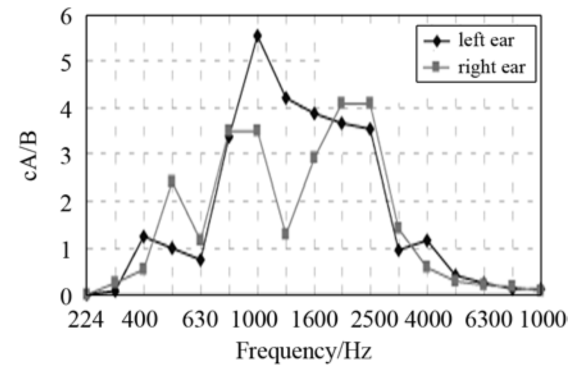


Fig.12 Specific roughness spectrum of the exhauster noise

2.3 Countermeasures for sound quality improvement

For a preliminary feasibility study, five measures were taken into consideration for the purpose of noise

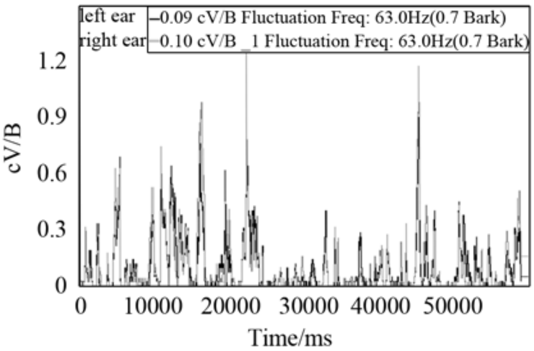


Fig.13 Time-domain specific fluctuation intensity of the exhauster noise

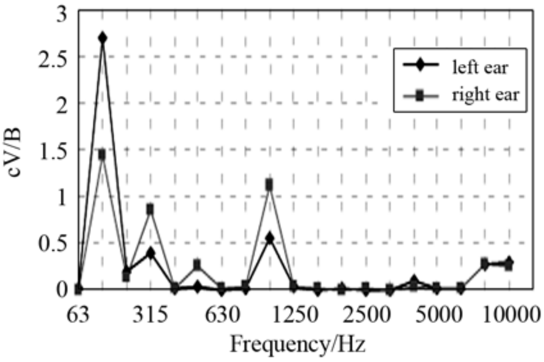


Fig.14 Specific fluctuation intensity spectrum of the exhauster noise

Table 1 Psychoacoustic parameter results by measurement

Psyachoustic Paramenter		Unit	Left Ear	Right Ear	Binaural Average	Standard deviation
Loudness	Nmax	sone	31.2	28.9	30	1.2
	Nmean	sone	27.8	26.0	26.9	0.9
	Nperc	sone	28.8	26.9	27.8	1
Sharpness	Smax	acum	1.71	1.74	1.73	0.01
	Smean	acum	1.59	1.62	1.61	0.01
	Sperc	acum	1.63	1.66	1.64	0.01
Fluctuation Intensity	Fmax	cVacil	9.5	8.3	8.9	0.6
	Fmean	cVacil	5.9	5.1	5.5	0.4
	Fperc	cVacil	7.2	6.3	6.8	0.4
Roughness	Rmax	cAsper	35.7	43	39.3	3.7
	Rmean	cAsper	28.4	32	30.2	1.8
	Rperc	cAsper	31.4	35.7	33.5	2.2

(a) Muffler (b) Installation of muffler

Fig.15 Muffler installation at intake

abatement and vibration attenuation, namely:

(1) The installation of muffler at the intake end; (Fig.15)

(2) The installation of some absorption glasswool on the inside surface of the exhauster casing; (Fig.16)

(3) Packing the absorption glasswool with a thin PU film; (Fig.17)

(4) The adhesion of damping tape on the surfaces of exhauster casing and ventilation pipewall; (Fig.18)

(5) The combination of the above four methods. (Fig.15)

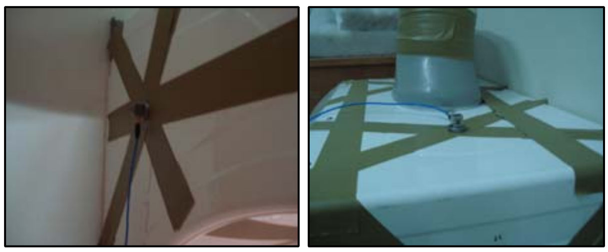
2.4 Improvement effectiveness

The results for different methods are shown in Table 2 and Table 3 respectively for comparison. The best results were attained by countermeasure 5, where the noise level was reduced from 68.1 dB(A) to 55.2

Fig.16 Absorption of glasswool on the inside of exhauster

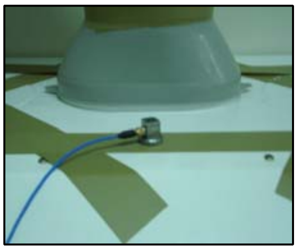
Fig.17 Absorption glasswool packed by PU film

(a)Tape at position E (b)Tape at position 20



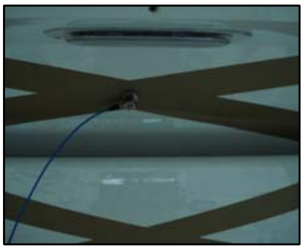
(c)Tape at position 25 (d)Tape at position 1

(e) Tape at position 2

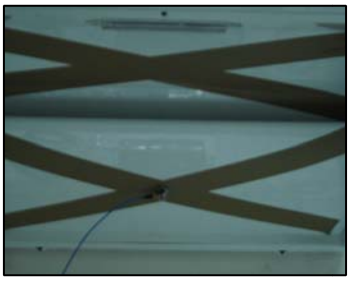


(f) Tape at position 3

(g) Tape at position 4



(h) Tape at position 9



(i) Tape at position 12

Fig.18　Damping tape adhesion

Table 2　Comparison of the sound quality improvements

Psychoacoustic Parameter		Unit	Before Improve-ement	Countermeasures				
				1	2	3	4	5
Loud-ness	Nmax	sone	30	28.3	20.3	21.8	24.1	15.7
	Nmean	sone	26.9	25.3	17.2	19.4	21.4	14.2
	Nperc	sone	27.8	26.3	18	20	22.2	14.7
Sharp-ness	Smax	acum	1.73	1.78	1.55	1.63	1.58	1.5
	Smean	acum	1.61	1.63	1.32	1.5	1.43	1.35
	Sperc	acum	1.64	1.66	1.36	1.54	1.47	1.39
Fluctua-tion Intensi-ty	Fmax	cVacil	8.9	7.1	11.4	6.3	8.2	5
	Fmean	cVacil	5.5	4.4	6.1	4.3	5.4	3.3
	Fperc	cVacil	6.8	5.4	7.6	5.1	6.8	4.1
Rough-ness	Rmax	cAsper	39.3	40.1	41	36.8	38.6	32.9
	Rmean	cAsper	30.2	30.3	26.5	28.8	29.3	25.7
	Rperc	cAsper	33.5	33.8	29.5	32.2	32.8	28.5
Annoyance index		nil	13.19	13.11	8.46	10.7	10.39	8.16
Remark: perc(per capite)								

dB(A), the loudness was reduced from 27.8 sone to 14.7 sone, the sharpness was reduced from 1.64 acum to 1.39 acum, the fluctuation intensity was reduced from 6.8 vacil to 4.1vacil, the roughness was reduced from 33.5 asper to 28.5 asper, and the annoyance in-

Table 3　Comparison of the vibration level improvements

Measurement location	Before im-provement	Countermeasures			
		1	2	3	5
E	119.1	115.4	118.7	119.6	nil
20	117.5	118.1	115.5	114.9	115.1
25	117.4	116.8	116.1	118.1	116.3
1	117.8	116.3	114.5	114.8	113.7
2	119.6	118.5	116.8	118.1	114.8
3	117.1	116.4	113.9	115.9	117.7
4	115.8	114.9	111.9	114.6	114.6
9	117.5	116.9	114.5	115.6	115
12	114.6	113.1	112	112.7	115.1

dex of sound quality was reduced from 13.19 to 8.16. Further, the vibration levels of the exhauster casing shell were reduced by an amount of 1~5 dB each.

3　CONCLUSIONS

This study establishes an improvement methodology of sound quality of a specific machine using the psychoacoustic parameter assessment. It is rational to use the subjective assessment of the annoyance index of the hearing sensation from the exhauster, and transfer it to an objective quantificational description of the exhauster noise improvement.

Amongst the improvement countermeasures, the installation of muffler at the intake end was effective for reducing the fluctuation intensity of the fan noise, the installation of the absorption glasswool on the inside surface of the casing was useful for reducing loudness, sharpness, roughness and annoyance index simultaneously. The PU film shield of the glasswool could reduce the loudness, the fluctuation intensity and the roughness simultaneously, while the adhesion of the damping tape on the surfaces of the casing and the ventilation pipe wall mainly reduced the sharpness.

The combination of the above measures had an integrated effect which reduced the noise pressure level from 68.1 dB(A) to 55.2 dB(A), the loudness from 27.8 sone to 14.7 sone, the sharpness from 1.64 acum to 1.39 acum, the fluctuation intensity from 6.8 vacil to 4.1 vacil, and the roughness from 33.5 asper to 28.5 asper. In addition, the annoyance index of sound quality was reduced from 13.19 to 8.16. and that the vibration levels of the exhauster casing shell were reduced by an amount of 1~5 dB universally.

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住宅抽油烟机的声音质量改进

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摘要：在居家生活中，抽油烟机之噪声甚为扰人而影响生活质量。就现有某型常用抽油烟机，利用声级计量测其噪声量与频谱，并利用人工耳及 dB sonic 软件分别量测分析其声音质量参数值，所得结果在人耳位置之声级为 68.1 dB(A)，音质粗糙度为 33.5 asper，响度为 27.8 sone，波动强度为 6.8 vacil，尖锐度为 1.64 acum，并按王氏之烦躁度模式评估出烦躁度指针为 13.19，其中以响度及尖锐度对音质评估之烦躁度指标影响最大。经机壳与机座之振动量测频谱与噪声频谱比较，鉴定出噪声主要峰值频率为 500 Hz 与 100 Hz 两个成分音，其中 500Hz 者为进气口之涡流噪声；而 100 Hz 者为机壳之振动辐射声。为降低排油烟机之响度及尖锐度以改善其运转时之声音质量，采用了几项对策。分别是：在进气口加装消声器，在机壳内侧贴吸声棉及包覆 PU 塑料膜，并黏贴阻尼材，所得效果可使噪声量降为 55.2 dB(A)，振动量减 1~5 dB，响度降为 14.7 sone，尖锐度降为 1.35 acum，烦躁度指标降为 8.16。

关键词：声音质量；烦躁度指针；响度；尖锐度；粗糙度；起伏度

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