

Application of Psychoacoustics and Sound Quality Assessment in Noise Control in Rooms

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ABSTRACT

Room acoustics uses mostly physical values. However, room acoustics should also describe the conditions leading to good hearing in a room. Because hearing characteristics are described by psychoacoustical data and values, it seems reasonable to introduce these values into the description of room acoustics. This often means that temporal and spectral effects should be described using total loudness as a function of time, or the three-dimensional distribution of specific loudness versus critical-band rate pattern as a function of time. In addition to that, other psychoacoustics values such as fluctuation strength, partial masking or sharpness, roughness, RASTI value, can be used to describe the influence of room acoustics on the characteristics of sound at the place of a listener. A few examples will illustrate these effects. Among which the sound generated by the exhaustor in a kitchen is one of the noise sources to make people annoying. The assessment of the sound quality of a specified exhaustor is assessed by using the head/ torso simulator and the software dB-sonic to identify the cause of annoyance. It has shown that the sharpness and the loudness are the two predominant factors to cause annoyance. To improve the sound quality in a kitchen, the proposed countermeasures have attained the improvements as that the noise level is reduced 12.9 dB, the loudness reduced 13.1 sone, the vibration levels of the exhaustor casing shell are reduced in a range of 1~5 dB, and the annoyance index of the sound quality is reduced from 13.2 to 8.2.

1. INTRODUCTION

The noisiness of an occupied indoor space and/or a reverberant environment are the major factors affecting speech intelligibility. One of the most serious consequences of noise is that it prevents us from understanding what other people say when they talk to us directly (i.e., face-to-face) or over a telephone or public address system.

Noise levels generated in apartments vary widely from room to room. Kitchen are usually noisy than bed rooms; living rooms may be quiet, or they may be the source of speech or sound from radios or TV set. Placing a sensitive area such as a bedroom next to a noisy machine room requires high noise reduction to achieve a quiet environment in the bedroom. Thus, a carefully chosen layout reduces the required noise reductions between spaces and therefore the sound insulation needed for the components of the building. This variation in activity and noise levels between rooms is taken into account in the recommendations given in Table 1 by Warnock and Quirt [1].

Among the indoor noise sources, the noise control of the heating, ventilating, and air-condition (HVAC) system in buildings needs to pay high attention to. One important

Table 1. Minimum requirements for airborne sound insulation of walls and floors and impact insulation of floors separating dwellings, expressed in terms of impact insulation class (IIC) [1] separating dwellings, expressed in terms of sound transmission class (STC)

Separated spaces for STC Source space (upper) (above receiving space) for IIC	I.Bedrooms		II.Living, dining, family rooms		III.Kitchen, bathroom, ancillary spaces	
	STC	IIC	STC	IIC	STC	IIC
I— Bedrooms	55	55		55		50
II— Living, dining, family rooms	55	55	50	55		50
III— Kitchen, bathroom, hallway, foyer, storage, utility space	55	55	50	55	50	50

*If two or more of the categories are combined in one unpartitioned space, the higher requirement shall govern.

consideration is that of allocating sufficient space in a building to utilize energy-efficient fan equipment and to size ductwork, controls, and terminal devices appropriately in order to minimize noise generation of these elements in the air distribution system.

Single-number rating systems in common use for expressing noise control objectives in HVAC system design include A-weighted sound level, NC curves, and RC curves. The use of these rating system for HVAC noise is valid for only continuous steady-state noise that exhibits no obvious fluctuations in sound level with time. Failure to recognize this limitation usually leads to serious errors in rating the noise produced by a system. Such fluctuating noise levels may occur as a result of the unstable operation of a fan or as a result of “beats” between two or more fans, or other rotating equipment in the system, which operate at nearly the same speed. For the purpose of revising the rating system, the NCB curves (Balance Noise Criterion curves) [2] and RC curves (Room Criterion rating curves of a noise spectrum) [3] have been developed.

Also, the fan noise, generated by an exhaustor in kitchen, needs to be limited. Besides 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) [4]. As environment becomes more and more quiet, the customer’s sensitiveness for the acoustical comfort increases.

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 ways to rank or scale the sound events [5][6]. Then, binaural recording of the product noise with an artificial head and play back to subjects were used to do the sound quality investigation[7]. Various standard artificial head measurement systems were developed for the diagnosis and analysis of sound and have been available for different application, such as vehicles [8][9], home appliances [10][11], and IT industries. This paper is devoted to the sound quality improvement of an existing residential exhaustor.

2. RATING SYSTEMS FOR HVAC NOISE

Because noise induced annoyance is not directly proportional to loudness, therefore the A-weighted sound level can be very unreliable in assessing HVAC noise inside buildings. Since in the use of A-weight sound level, none of the factors other than loudness that affect the listener’s reaction to the noise are revealed. For example, although the three typical noises shown in Fig.1 have significantly different spectrum shapes, each has an A-weighted sound level of 40 dB(A). Even though these noise might be considered equally loud, if judged purely on the basis of relative loudness, the rank ordering could be significantly different if the judgment were to be based on relative annoyance.

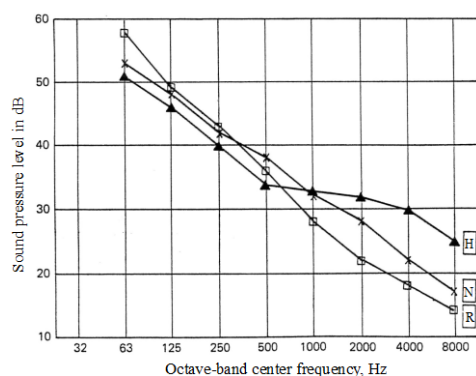


Figure 1. Three typical HVAC spectra, each having the same A-weighted sound level: 40 dB(A).

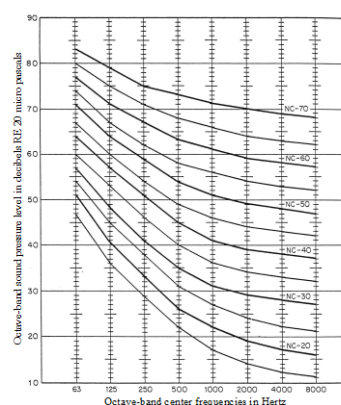


Figure 2. NC curves

The spectrum labeled H probably would be judged too hissy because of its excessive high-frequency imbalance; the spectrum labeled R would be judged too rumby because of its steeply rising low-frequency characteristic. On the other hand the spectrum labeled N has a more balanced loudness distribution vs. frequency that makes it “neutral” sounding and not likely to be objectionable as background noise, if presented at a level which is appropriate to the environment.

2.1 NC Curves

In evaluating noise problems, NC curves as shown in Fig.2 are used as a reference point from which noise reduction requirements can be determined. This rating system is based on the premise that two factors have the greatest influence on how people respond to HVAC background noise in their own environment: the loudness of this background noise and its spectrum shape and level in the speech frequency region. This rating system assumes that the potential for complaints to occur is minimized in a speech communication environment acceptable to the occupant, if the numerical loudness level of the noise does not exceed the numerical speech interference level by more than 22.

The choice of which NC curves to use as a design criterion for background noise control depends on the type of space use being considered. In an office environment, the desired speech communication (or speech masking) potential is a primary consideration. In contrast, in a concert hall environment the quality of speech communication is not a governing factor; instead, the objective is to avoid masking the faint; pianissimo passages that occur in most musical scores. The octave-band values for specified NC curves are sometimes considered as levels not to be exceeded, irrespective of the shape of the actual background spectrum. It has even become common practice to assign an NC rating to a noise, in accordance with the highest NC curve tangent to the spectrum.

The NC rating of a noise by this tangent-contour convention yields essentially a quasi-loudness-based number that provides no useful information about the spectral characteristics that might adversely affect how the noise sounds to the ear. The disadvantage of using this procedure for noise rating is illustrated in Fig.3. The three typical HVAC spectra shown are distinctly different noises but have essentially the same NC tangent-contour rating of NC 33. In which, the first spectrum, labeled H, generally would be subjectively rated by a listener as hissy; the rating of NC33 is assigned because the highest numbered tangent contour is the NC 33 curve at 2000Hz (the common convention permits extrapolation between curves in whole-number increments). The second spectrum, labeled R, would most likely be rated by a listener as rumby; the rating of NC 33 is assigned because the highest numbered tangent contour is the NC 33 curve at 250Hz. The third spectrum, labeled N, will be typically classified as neutral by the listener; the NC 33 rating is assigned because the NC 33 curve is tangent to the noise spectrum at 500 Hz.

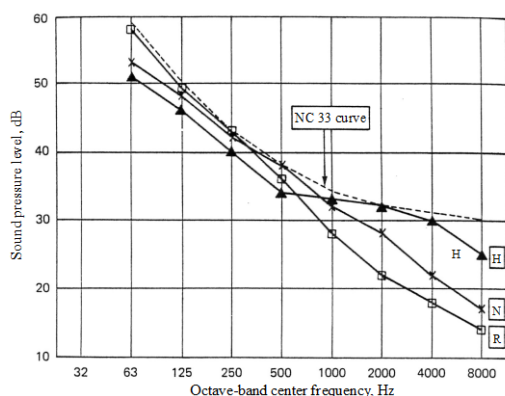


Figure 3. Three typical HVAC spectra, each with the same NC rating.[3]

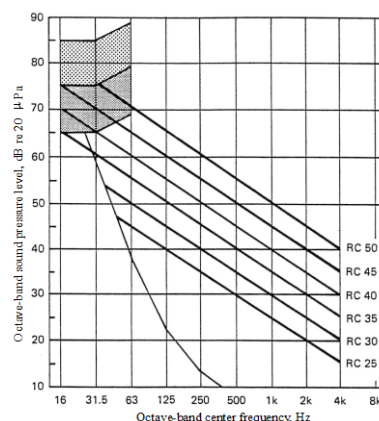


Figure 4. RC curves.

2.2 RC Curves

RC curves [3] may be used to specify the maximum level in a room supplied by an HVAC system, as the preferred alternative to either NC curves or A-weighted sound level. This is because this rating system (1) takes into account the influence of both spectrum shape and level on the subjective assessment process, (2) includes data in the octave bands centered at 31.5 and 16 Hz, and (3) takes into account the ability of low-frequency acoustic energy to induce perceptible vibration in lightweight building construction.

The family of RC curves illustrated in Fig. 4 is based on the analysis of a large database collected during an ASHRAE-sponsored research study of “acceptable” background noise in a wide range of typical office environments [12]. The -5dB/octave slope of the RC curves corresponds to the average spectrum slope of the measured data obtained in a large number of air-conditioned office environments rated as acceptable to the occupants. The slope of the RC curves does not change with level over the range shown, and the numerical designation of each curve corresponds to the level in the 1000-Hz octave band. Over the range of recommended application, RC 25 to RC50, the contours correspond to neutral-sounding spectra which are approximately balanced with respect to relative loudness in the low-frequency and high –frequency regions of the spectrum.

The low-frequency levels of the curves are influenced by hearing threshold at one extreme and at the other by a concern for avoiding perceptible acoustically induced forced vibration in lightweight building construction; the two crosshatched areas illustrated in the low-frequency region are indicative of the range of sound pressure levels where the possibility of noise-induced forced vibration should be considered. In the upper crosshatched region, there is a high probability that noise-induced vibration may be clearly perceptible; in the lower crosshatched region, the effects of noise-induced vibration may be only moderately perceptible but capable of causing acoustical ceilings and lighting fixtures to creak and rattle.

The RC rating of a noise requires the use of two descriptors: the first term is a number [it corresponds, approximately, to the speech interference level (SIL) of the spectrum]; the second term is one of four letters that identifies the “quality” of the second as it might be subjectively described by an observer.

The following criteria are used to assign the appropriate letter descriptor of sound quality:

- Neutral spectrum(N): The level in the octave band at 500Hz and below must not exceed the octave-band levels of the reference spectrum by more than 5 dB at any point in the range; the levels in the octave bands centered at 1000Hz and above must not exceed the octave-band level of the reference spectrum by more than 3 dB at point in the range.
- Rumbly spectrum (R): The level in the octave bands at 500 Hz and below exceeds the octave-band levels of the reference spectrum by more than 5 dB at one or more points in the range.
- Hissy spectrum (H): The level in the octave bands centered at 1000Hz and above exceeds

the octave-band level of the reference spectrum by more than 3 dB at one or more points in the range.

- Tonal spectrum (T): If there is a tonal component in a noise, there is usually an abrupt change in sign of the spectrum slope that introduces a peak in a particular octave band, relative to the levels in the two adjacent bands. If the projection of this peak is more than 3 dB above a line constructed between the levels of the two adjacent bands, the tone may be audible to the ear. Although a one-third-octave-band analysis provides a more positive determination of the presence of a tonal component, a simple listening test may be sufficient to validate the audibility of the tone.
- Acoustically induced perceptible vibration (RV): The crosshatched region of the RC curves of Fig.4 illustrates the frequency and amplitude range of octave-band sound pressure levels that may introduce perceptible vibration in the walls and ceilings of lightweight building construction. The acoustically induced vibration may also cause “secondary” noise radiation such as rattles in cabinet doors, pictures, ceiling fixtures, and other room furnishings in contact with the walls.

The graph format for RC rating is shown in Fig.5. And the RC rating examples of neutral, rumbly, hissy and tonal of HVAC spectrum are shown in Fig.6-Fig.9 respectively. The example of a RC rating of HVAC spectrum capable of perceptible acoustically induced vibration is shown in Fig.10.

Table 2 lists recommended HVAC background noise criteria for a variety of space uses. The criteria are expressed in terms of the two most commonly used procedures for noise rating. The “Preferred” column is based on the use of the RC curve noise-rating procedure. This criterion is recommended whenever the quality of space use dictates the need for a neutral, unobtrusive background sound. The “Alternative” column is based on the use of the NC curve noise-rating procedure.

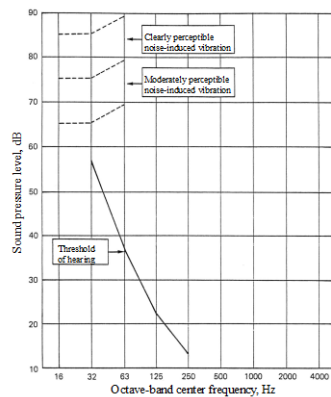


Figure 5. Graph format for RC rating

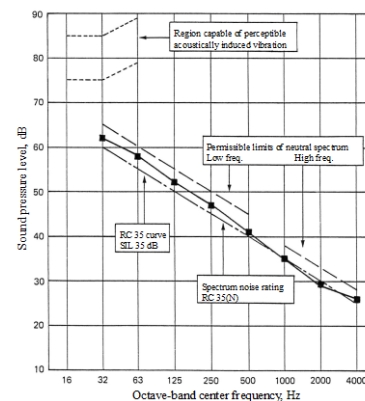


Figure 6. RC rating of neutral HVAC spectrum.

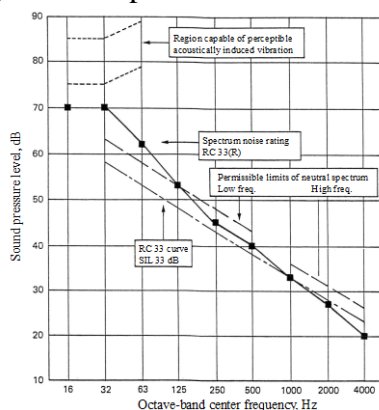


Figure 7. RC rating of rumbly HVAC spectrum

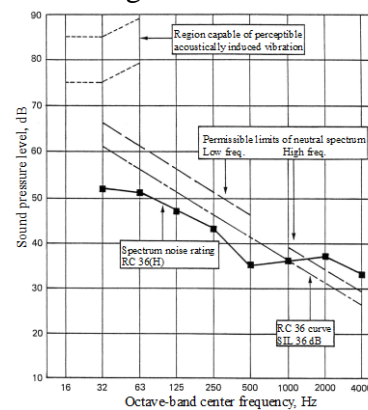


Figure 8. RC rating of hissy HVAC spectrum

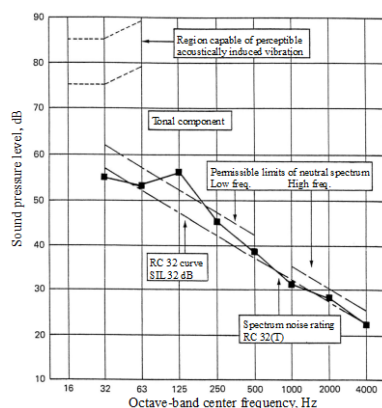


Figure 9. RC rating of tonal HVAC spectrum

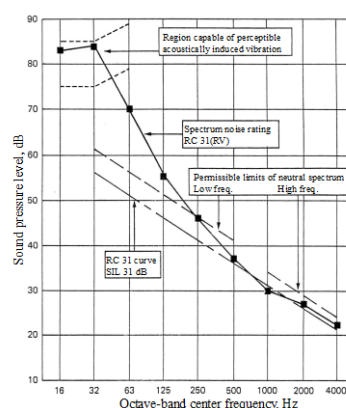


Figure 10. RC rating of HVAC spectrum capable of perceptible acoustically induced vibration

Table 2. Acceptability criteria for steady background noise in unoccupied rooms

Type of room	Recommended criterion		Approximate A-weighted sound level, dB
	Preferred	Alternative	
Recording studios	RC 10-20(N)	NC 10-20(N)	18-28
Concert and recital halls	RC 15-20(N)	NC 15-20(N)	23-28
TV studios, music rooms	RC 20-25(N)	NC 20-25(N)	28-33
Legitimate theaters	RC 20-25(N)	NC 20-25(N)	28-33
Private residences	RC 25-30(N)	NC 25-30(N)	33-38
Conference rooms	RC 25-30(N)	NC 25-30(N)	33-38
Lecture rooms, classrooms	RC 25-30(N)	NC 25-30(N)	33-38
Executive offices	RC 25-30(N)	NC 25-30(N)	33-38
Private offices	RC 30-35(N)	NC 30-35(N)	38-43
Churches	RC 30-35(N)	NC 30-35(N)	38-43
Cinemas	RC 30-35(N)	NC 30-35(N)	38-43
Apartments, hotel bedroom	RC 30-35(N)	NC 30-35(N)	38-43
Courtrooms	RC 35-40(N)	NC 35-40(N)	43-48
Open-plan offices and schools	RC 35-40(N)	NC 35-40(N)	43-48
Libraries	RC 35-40(N)	NC 35-40(N)	43-48
Lobbies, public areas	RC 35-40(N)	NC 35-40(N)	43-48
Restaurants	RC 40-45(N)	NC 40-45(N)	48-53
Public offices (large)	RC 40-45(N)	NC 40-45(N)	48-53

*A-weighted sound level are not recommended for use in the design of HVAC systems.

3. PSYCHOACOUSTICS PARAMETERS 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 considered in the evaluation model of PA are loudness, sharpness, fluctuation strength and roughness.

3.1 Evaluation model of psychoacoustic annoyance

Basically, psychoacoustic annoyance depends on the loudness, the tone color, and the temporal structure of sounds. Amman and Greeberg [14] and Wang [15] have established the relation between annoyance index for the sound quality (SQ) of automobile noise and the loudness (L), sharpness (S), roughness (R) and fluctuation (F) as given by:

$$SQ = aL + bS + cR + dF \quad (1)$$

where a , b , c and d are the regression coefficients determine by the psychoacoustic experiments. It is found that, as a consequence of the regression, the parameters of loudness (L) and sharpness (S) are rather sensitive than roughness (R) and fluctuation (F), especially for the case of machine under continuously steady operation.

Thus, Eq.(2) becomes:

$$SQ = 0.186L + 10.375S - 8.995 \quad (2)$$

Eq.(3) is used in the study.

3.2 Psychoacoustic parameters

Loudness is the sensation value of the human perception of sound volume and it needs to consider the distribution of critical bands and masking properties in the hearing. As the Zwicker method, the loudness (N) is expressed as the integral of specific loudness (N') over critical-band rate:

$$N = \int_0^{24 \text{ Bark}} N' dz \quad (3)$$

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

$$N' = 0.08 \left(\frac{Q_{TQ}}{E_D} \right)^{0.23} \left[\left(0.5 + 0.5 \frac{E}{E_{TQ}} \right)^{0.23} - 1 \right] \text{ Sone}_G / \text{Bark} \quad (4)$$

In which, Q_{TQ} is the excitation at threshold in quiet and E_D is the excitation that corresponding to the reference intensity $I_0 = 10^{-12} \text{ W/m}^2$.

Sharpness is the ratio of high frequency level to overall level. It is calculated as the integration of specific loudness which exhibits the distribution of loudness across the critical bands multiplied by a weighting function, divided by total loudness (hence, sharpness is level-independent). Here the zwicker's method is used for the sharpness S calculation:

$$S = 0.11 \left(\int_0^{24 \text{ Bark}} N' \cdot g(z) \cdot z \cdot dz / \int_0^{24 \text{ Bark}} N' \cdot dz \right) \text{ (Acum)} \quad (5)$$

where the denominator gives the total loudness (N). The upper integral is like the first moment of specific loudness over critical-band rate, but uses an additional factor, $g(z)$, that is critical-band-rate dependent. This factor is expressed as :

$$g(z) = \begin{cases} 1, (z \leq 16 \text{ Bark}) \\ 0.066e^{0.171z}, (z > 16 \text{ Bark}) \end{cases} \quad (6)$$

Where only for critical-band rates larger than 16 Bark does the factor increase from unity to a value of four at the end of the critical-band rate near 24 Bark. This takes into account that sharpness of narrow band noises increases unexpectedly strongly at high centre frequency.

Owing to modulated sounds can elicit two different kinds of hearing sensations: at low modulation frequencies up to a modulation frequency about 20Hz, the hearing sensation of fluctuation strength is produced. At higher modulation frequencies, the hearing of roughness occurs. From modulation frequencies around 20Hz, 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 [4]:

$$F = \Delta L / (f_{\text{mod}} / 4 + 4 / F_{\text{mod}}) \quad (7)$$

which shows the relationship between fluctuation strength (F) and the masking depth (ΔL) of the temporal masking pattern, as well as the modulation frequency (f_{mod}).

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

$$R = 0.3 f_{\text{mod}} \int_0^{24 \text{ Bark}} \Delta L_E(z) dz \quad (8)$$

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

3.3 Critical bands

The critical bands are auditory band pass filters and its band number scale

(“psychoacoustic” or “Bark” scale) is a frequency scale of the numbered critical bands 1 through 24, named Bark (named after von Barkhausen), and 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 derive from the frequency-to-place transform on the basilar membrane.

4. PSYCHOACOUSTIC PARAMETER MEASUREMENT AND SOUND QUALITY IMPROVEMENT [11]

4.1 Measurement arrangement

To improve the sound quality of a residential exhauster as shown in Fig.11, the parameters related to the sound quality are measured by an artificial head and torso simulator (Fig.12). Meanwhile, noise at 3 locations in front of the exhauster and vibrations at 38 locations were measured. From the measurement data, one can identify the positions of airborne and structure-borne noise sources and the binaural masking effect.



Figure 11. Exhauster configuration



Figure 12. Artificial head and torso simulator

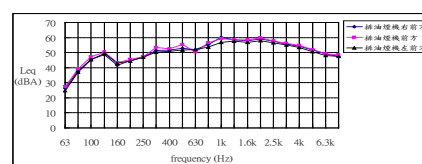


Figure 13. SPL at 3 measurement points in front of the exhauster

4.2 Measurement results before improvement

The noise and vibration levels at different measurement locations are shown in Fig.13 and Fig.14. The highest SPL is 68.1 dB(A) and the maximum vibration level is 130 dB. The psychoacoustic parameters were measured and analyzed by the software package dB-Sonic. The results of time-domain (60s) and frequency-domain specific loudness, percentile sharpness, specific roughness and specific fluctuation intensity are shown Fig.15 to Fig.22 respectively. All of these results are summarized in Table 3. In which, the critical band of maximum binaural specific loudness occurs in the range of 16.9~18.3 Bark. The sharpness is very stationary and keeps in the range of 0.7-1.7 acum, mean sharpness is 1.6 acum. The specific roughness is ranged from 0-0.15 asper. The annoyance index of sound quality base on Eq.(3) is 13.19. Among the four parameters related to the psychoacoustic annoyance calculation, the most sensitive ones are loudness and sharpness. Owing to the steady continuous operation of the exhauster, the values of sharpness and fluctuation are relatively low, and the roughness is quite stationary and less sensitive. Therefore, the countermeasure of the noise abatement remains to only the approach of loudness reduction.

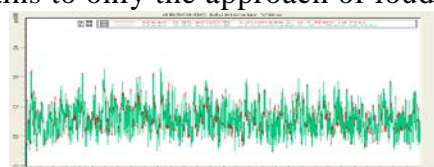


Figure 15 – Time-domain specific loudness

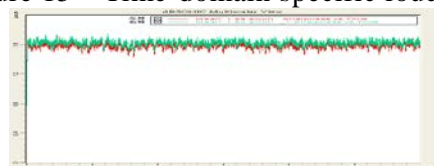


Figure 17 – Time-domain specific sharpness

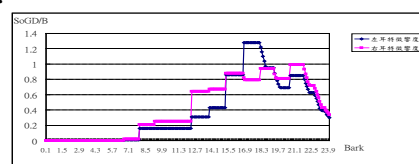


Figure 16 – Specific loudness spectrum

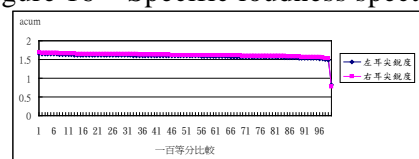


Figure 18 – Percentile sharpness



Figure 19 – Time-domain specific roughness



Figure 21 – Time-domain specific fluctuation intensity

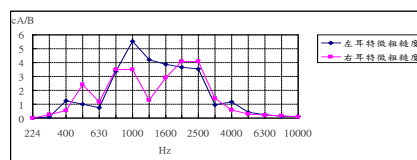


Figure 20 – Specific roughness spectrum

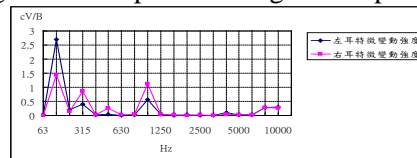


Figure 22 – Specific fluctuation intensity spectrum

Table 3. Psychoacoustic parameter results by measurement

Psychoacoustic Parameter		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

4.3 Countermeasures for sound quality improvement

Five measures are taken into consideration for the purpose of noise abatement and vibration attenuation. They are: 1.Installation of muffler at the intake end; 2.Installation of absorption glasswool on the inside surface of the exhaustor casing; 3.Pack the absorption glasswool with a thin PU film; 4.Adhesion of damping tape on the surfaces of exhaustor casing and ventilation pipewall; 5.Combination of the above four methods.

4.4 Improvement effectiveness

Comparisons of the improvements of the sound quality index and the psychoacoustic parameters, are shown in Table 4. The maximum improvement are attained by countermeasure 5. Where the noise level is reduced from 68.1 dBA to 55.2 dBA, the loudness is reduced from 27.8 sone to 14.7 sone, the sharpness is reduced from 1.64 to 1.39, the fluctuation intensity is reduced from 6.8 to 4.1, and the roughness is reduced from 33.5 to 28.5. The annoyance index of sound quality is reduced from 13.19 to 8.16.

Table 4. Comparison of the sound quality improvements

Psychoacoustic Parameter		Unit	Before Improvement	Countermeasures				
				1	2	3	4	5
Loudness	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
Sharpness	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
Fluctuation intensity	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
roughness	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)								

5. CONCLUSIONS

Room acoustics utilized to control the noise for life quality is reviewed. Besides the loudness level, other parameters of the sound related to the psychoacoustic annoyance and speech interference should be taken into consideration. An improvement methodology of sound quality of a specific machine by using the psychoacoustic parameter assessment is established. It is a rational way that use the subjective assessment of the annoyance index of the hearing sensation from the exhauster, to transfer to an objective quantificational description of the exhauster noise improvement.

6. REFERENCES

- [1] A.C.C. Warnock and J.D.Quirt, "Noise control in Buildings", Chap.33, Handbook of Acoustical Measurements and Noise Control, Edited.by C.M. Harris, 3rd ed. McGraw-Hill, Inc., 1991.
- [2] L.L.Beranek, "Application of NCB Noise Criterion Curves", Noise Control Engineering, Vol.33, No.2, 1989, pp.45-56.
- [3] W.E. Blazier, Jr., "Revised Noise Criteria for Application in the Acoustical Design and Rating of HVAC Systems", Noise Control Engineering, Vol.16, 1981, pp.64-73.
- [4] H.Fastl and E. Zwicker, "Psychoacoustics, Facts and Models", Springer-Verlag Berlin Heidelberg, 2009, pp.327-329.
- [5] H. Fastl, "The Psychoacoustics of Sound-Quality Evaluation" Acustica, Vol.83, 1997 pp. 754-7694,.
- [6] Paul E. Green, Franlc J. Carmone and Yoram Wini "Subjective Evaluation Models and Conjoint Measurement", Behavioral Science, Vol.17, , 1972, pp.288-299.
- [7] K. Genuit, "Standardization of Binaural Measurement Technique", Journal de physique, Vol. III -2,1992, pp.405-407.
- [8] E.Parizet, E. Guyader and V. Nosulenko. "Analysis of Car Door Closing Sound Quality", Applied Acoustics, Vol.69,2008, pp.12-22.
- [9] K. Genuit, "The Sound Quality of Vehicle Interior Noise: A Challenge for the NVH-Engineers", J. Vehicle Noise and Vibration, Vol.1,2004, PP.158-168.
- [10] H. Wu, C.F. Hung, S.H. Chang, W.H. wang and C.Y. Cheng "Psychoacoustic Evaluation of Indoor Sound Qality of a Habitat Space by Head / Torso Simulator and Jury Test, Proceedings of Inter". Noise 2011, Osaka, Japan, 2011.
- [11] Y.C.Wen and W.H. Wang, "Noise and Vibration Analysis and Sound Quality Improvement of Residential Exhauster", Proceedings Inter· noise 2013, Insbruck, Austria, 2013.
- [12] ASHRAE Research Project RP-126, rep.E2063, Lewis S. Goodfriend and Associates.
- [13] M.J. Hussain, J. Golles, A. Ronacher and H. Schiffbanker, "Evaluation of an Annoyance Index for Engine Noise Recordings", SAE Technical Paper Series, 1991.
- [14] S. Amman and J. Greeberg, "Subjective Evaluation and Objective Quantification of Automobile Strut Noise", Noise Control Eng. J. 1999.
- [15] D.F. Wang, "Subjective Evaluation Test and Objective Quantificational Description of Vehicle Interior Noise"