

COVER PAGE

Document downloaded by @DAEL

Fri Nov 27 19:37:19 2026
For personal use

When automatic English translation is provided, only the original document is authentic.
The EAA cannot be held responsible of any translation error

Bibliographical reference

Proposed Revision to Emission Limits of Structure-Borne Noise from Fixture Transmitted into Room: An Investigation of People's Annoyance, Guo-Qing Di, Qi-Li Lin, Hang-Hai Zhao and Yan-Jie Guo, Acta Acustica **vol. 97** (Number 6), 2011, pp. 1034-1040

DOI
https://doi.org/10.3813/AAA.918483

ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 97 (2011) 1034 – 1040
DOI 10.3813/AAA.918483

Proposed Revision to Emission Limits of Structure-Borne Noise from Fixture Transmitted into Room: An Investigation of People's Annoyance

Guo-Qing Di, Qi-Li Lin, Hang-Hai Zhao, Yan-Jie Guo
Department of Environmental Science, Zhejiang University, 310028 Hangzhou, China. dgq@zju.edu.cn

Summary
In order to get more reasonable Emission Limits of Structure-Borne Noise from Fixture Transmitted into Room (ELSBNFTR), a subjective response experiment was carried out. In this experiment, the original samples (OS) were generated based on the current ELSBNFTR, while the adjusted samples (AS) were based on the proposed ELSBNFTR. Subjects were asked to make comparison between OS and AS on the basis of relative annoyance. The effect of Quality Assessment Index (QAI) on dealing with room noise complaints was discussed. As shown in the results, for each compared group, more than 72.0% of subjects chose "OS were more annoying than AS". The spectra of OS were more imbalanced, due to the higher proportion of low frequency noise energy, which led to a more rumbly character. It is proposed that QAI should be introduced into ELSBNFTR, in order to reduce complaints mainly caused by room noise (including structure-borne noise from fixture and background noise) with an imbalanced spectrum, while the structure-borne noise is still within ELSBNFTR. Besides, it is suggested that the evaluation of the difference values between room noise and background noise at different octave bands should be added in the procedure for the assessment of complaints, and 5 dB could be considered as a limit.
PACS no. 43.50.-x, 43.50.Ba, 43.50.Rq

1. Introduction

In the last decades, the rapid urbanization in China has led to growing concern about the effects of room noise [1]. According to Waye *et al.* [2], the A-weighted levels cannot provide good prediction for the subjective response of room noise. Therefore, several methods for room noise evaluation have been developed in different countries. Equal loudness contours were first measured by Fletcher and Munson in 1933 [3]. Then, a later study on equal loudness contours was carried out by Robinson and Dadson in 1956 [3], which became the basis for ISO 226: 2003 [4]. In 1957, Beranek [5] introduced the well-known Noise Criterion (NC) curves, which were developed from equal loudness contours and speech interference levels in a study on the office noise. Then, NC curves were revised, and Balanced Noise Criteria (NCB) curves were introduced [6]. One of the major improvements of this revision was the extension of the curves down to 16 Hz, and the other was the introduction of the concern about the imbalance in a noise spectrum. Blazier [7] published Room Criteria (RC) curves after investigating about 200 background noise environments. RC curves were adopted by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), as the preferred criteria in recognition of the mounting low frequency noise problem [8]. NC, NCB and RC were standardized by American National Standard Institute (ANSI) in Criteria for Evaluating Room Noise [9], where, NC and NCB were predominantly used in an occupied room, and RC in an unoccupied room. In 2008, extended NC curves (eNC) were standardized by ANSI, too [10]. Meanwhile, in Europe, Noise Rating (NR) curves, similar to NC curves, were initially proposed by Kosten and van Os [11]. Then, NR curves were developed by International Organization for Standardization (ISO) in 1971 to determine the acceptable indoor environment for hearing preservation, speech communication and annoyance. The definition of NR rating was provided by Standards Association of Australia [12], who then derived an additional formula method for calculation of the NR rating for a spectrum [13].

Fixture noise usually contains a great proportion of low frequency noise [14], and it is a major source of room noise [15, 16]. When fixture is inside the buildings, its noise can be transmitted into room by structure. Swiss Environmental Protection Act "EPA" provided the exposure limits of A-weighted levels for structure-borne noise [17]. In Australia, the design criteria for structure-borne noise were introduced in the Chatswood Interchange project, which were also described by A-weighted levels [18]. In

Received 31 December 2010,
accepted 16 August 2011.

© S. Hirzel Verlag · EAA

2008, Emission Limits of Structure-Borne Noise from Fixture Transmitted into Room (ELSBNFTR) were proposed in China, which were standardized in Emission Standard for Community Noise (GB 22337-2008) [19] and Emission Standard for Industrial Enterprises Noise at Boundary (GB 12348-2008) [20]. The standards provided ELSBNFTR of the A-weighted levels, taking Code for Design of Sound Insulation in Civilian Construction (GBJ 118-88) [21] as a reference. Then, ELSBNFTR of the sound pressure levels (SPLs) of 31.5, 63, 125, 250 and 500 Hz octave bands ($L_{31.5}$, L_{63}, L_{125}, L_{250}, L_{500}) were defined based on the NR reference curves, while the NR ratings were given by equation (1) [22]. However, Leventhall *et al.* [23] found that NR curves were not suitable in cases when the spectra had high SPLs in low frequency bands. In some studies on room noise, it was noticed that a rapidly falling spectrum, which followed the NR curve, could still cause complaint about low frequency noise annoyance [24]. In this case, ELSBNFTR of $L_{31.5}$ and L_{63} might be too high. Moreover, according to Design of Sound Insulation in Civilian Construction, the relationship between the A-weighted levels and the NR ratings was given by equation (2). For the same A-weighted level (lower than 50 dB), since the NR ratings given by equations (1) and (2) were different by 5 units, the difference value between the SPLs of each octave band was also about 5 dB, in which case, ELSBNFTR of the SPLs of some octave bands might be too low. After an investigation in Beijing urban district, Wu [25] found that the structure-borne noise from fixture in over 50% of buildings exceeded ELSBNFTR of L_{250} and L_{500}. Thus, ELSBNFTR might not be suitable for predicting annoyance of room noise. For example, in some buildings, structure-borne noise from fixture was within ELSBNFTR, and $L_{31.5}$ or L_{63} was close to ELSBNFTR, however, people still complained about the room noise disturbance; while in some other buildings, though L_{250} or L_{500} was over ELSBNFTR, people could hardly experience the annoyance of noise [26].

$$NR = \begin{cases} L_A - 10, & L_A \le 50, \\ L_A - 7, & L_A > 50, \end{cases} \quad (1)$$

$$NR = L_A - 5, \quad (2)$$

where NR is NR rating (dB), L_A is A-weighted level (dB).

Although some criteria have been proposed for room noise, there is rare report on structure-borne noise from fixture transmitted into room (SBNFTR). In order to get more reasonable ELSBNFTR, a subjective response experiment was carried out, based on the current ELSBNFTR, while other criteria were also taken as reference. The results could provide science basis for ELSBNFTR revision.

2. Methods

2.1. Noise samples

Random noise (pink) was filtered into five octave band noise samples in software (Head AcoustiAS ArtemiS 10.00), whose center frequencies were 31.5, 63, 125, 250 and 500 Hz, respectively. The original samples (OS) were composed by the octave band noise samples, with the SPLs equal to the current ELSBNFTR (see Table I). The duration of each noise sample was 5 sec [27, 28].

Table I. The SPLs of the current ELSBNFTR (C) and the proposed ELSBNFTR (P) at 31.5–500 Hz octave bands.

Group		$L_{31.5}$	L_{63}	L_{125}	L_{250}	L_{500}
1	C	82	67	56	49	43
	P	77	64	56	51	47
2	C	79	63	52	44	38
	P	74	60	52	47	43
3	C	76	59	48	39	34
	P	71	57	48	43	39
4	C	72	55	43	35	29
	P	68	53	43	39	35
5	C	69	51	39	30	24
	P	65	49	39	35	31

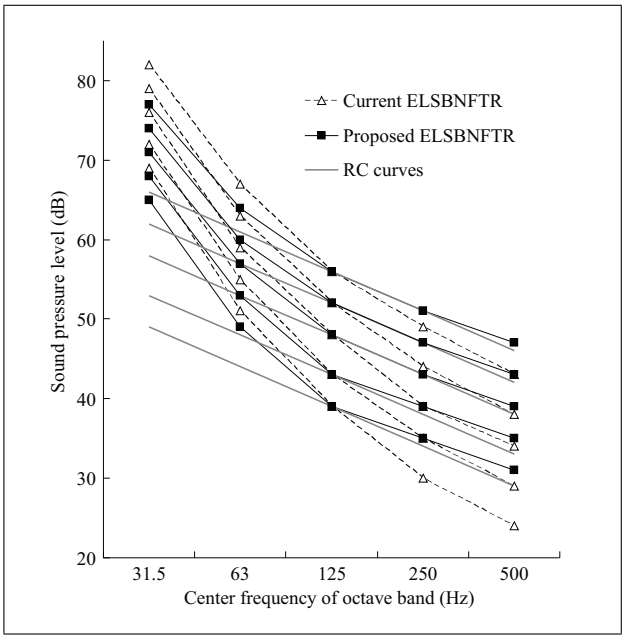


Figure 1. The current ELSBNFTR and the proposed ELSBNFTR compared with RC curves at 31.5–500 Hz octave bands.

In order to explore more reasonable ELSBNFTR, the method to revise current ELSBNFTR was discussed in this paper. Then, the adjusted samples (AS) were composed by the octave band noise samples, with the SPLs equal to proposed ELSBNFTR (see Table I).

1. The current ELSBNFTR and five RC curves with same L_{125} are shown in Figure 1. The spectra of current ELSBNFTR in 31.5 to 125 Hz octave bands were falling more rapidly than those of the RC curves. According to Schomer and Bradley [29], it would cost too much on the application of RC curves. Thus, it was unnecessary to utilize the RC curves strictly at low frequencies.

Considering the basic condition of China, it was proposed that $L_{31.5}$ and L_{63} of current ELSBNFTR should decrease moderately. As a result, the spectra of proposed ELSBNFTR in 31.5 to 125 Hz octave bands were still falling a little more rapidly than those of the RC curves. Therefore, this revision not only helped to improve the quality of room environment, but also gave consideration to the expense of application of ELSBNFTR.

2. As mentioned above, the current ELSBNFTR of L_{250} and L_{500} might be too strict. Proposed ELSBNFTR of L_{250} and L_{500} were defined based on the NR reference curves, while the NR ratings were given by equation (2). In 125 to 500 Hz octave bands, the spectra of proposed ELSBNFTR were similar to the RC curves, which had been accepted by many experts (e.g., [5, 6, 24, 29, 30]).
3. The A-weighted levels of the current ELSBNFTR and the proposed ELSBNFTR with same L_{125} had no apparent change.

A-weighted levels and loudness levels of noise samples are shown in Table II. L_A of OS and AS in each compared group differ within 0.6 dB, and the loudness levels differ within 1.4 phon.

2.2. Subjects

Forty-five students, 26 males and 19 females, 22–27 years old, were recruited for this study. Before the experiment, the hearing test was performed with the use of an audiometer, and all of subjects had normal hearing [31].

2.3. Apparatus

Noise samples were presented binaurally by an audio playback systerm, which consisted of four headphones (Sennheiser HD-600), a distribution amplifier (Head AcoustiAS HDA IV. 1), a digital equalizer (Head AcoustiAS PEQ V), and a laptop (Samsung NC 10).

2.4. Listening test protocol

This experiment was performed in a soundproof room ($4\times4\times3\,m^3$). Four people were tested in the same time. In the experiment, OS and AS with same L_{125} formed a compared group. Two noise samples in same compared group were played back six times in random order. Subjects were asked to compare the subjective annoyance induced by OS and AS of each group [32], and to give their assessment scores according to the following rule: if the former noise sample is more annoying than the later, then the score is "1"; if the later one is more annoying, the score is "-1"; if they achieve the same annoying effect, the score is "0" [33]. Misjudgment is inevitable when subjects make a decision on the assessment scores. One compared group had six assessment scores by each subject. If more than 4 of these assessment scores were unanimous, the result for this compared group could be accepted, or the result should be deleted.

Table II. A-weighted levels and loudness levels of noise samples.

Group		L_A (dB)	Loudness level (phon)
1	OS	48.9	65.4
	AS	48.5	64.0
2	OS	45.2	60.8
	AS	44.7	59.6
3	OS	41.6	55.9
	AS	41.0	55.1
4	OS	37.4	49.6
	AS	37.1	49.7
5	OS	33.9	43.4
	AS	33.3	43.7

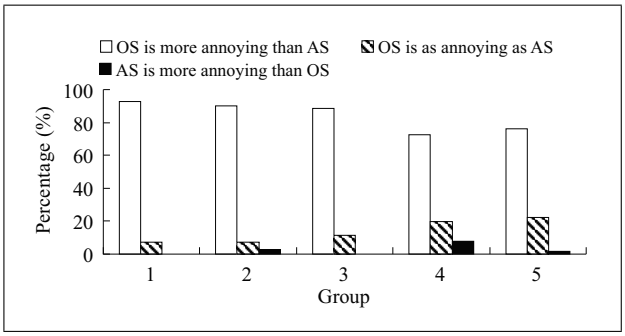


Figure 2. The percentage of subjects making comparisons of the original samples (OS) and the adjusted samples (AS) on the basis of relative annoyance.

After evaluation, a face to face interview was carried out. In the interview, every subject was asked to describe what characteristic influences the annoyance of noise samples most.

3. Results and discussion

3.1. Annoyance of noise samples

Figure 2 shows the results of subjective evaluation. For each compared group, more than 72.0% of subjects chose "OS were more annoying than AS" , e.g. for Group 2, 90.1% of subjects described that OS was more annoying; 7.2% described that OS was as annoying as AS; only 2.7% described AS was more annoying.

In the interview after experiment, 33 out of 45 subjects expressed that the noise annoyance level was mostly influenced by the rumbly character of noise samples; 5 expressed by other character; the rest expressed unknown.

According to Swiss EPA, protection from structure-borne noise is based on experience gained evaluating low-frequency sound [17]. Besides NR curves and RC curves, some curves were taken as reference in the process of ELSBNFTR revision, e.g. NCB curves, LFNR curves, RNC curves, PNC curves and RC curves. One of each kind of curves was picked for comparison (see Table III). This table shows that $L_{31.5}-L_{500}$ of the current ELSBNFTR is 42 dB, which is 10–24 dB more than those of other curves. It is indicated that the current ELSBNFTR has a

Table III. Comparison of room noise criteria curves (dB SPL).

Criteria curve	$L_{31.5}$	L_{63}	L_{125}	L_{250}	L_{500}	$L_{31.5}$–L_{500}
Current ELSBNFTR	76	59	48	39	34	42
Proposed ELSBNFTR	71	57	48	43	39	32
NCB 35	71	58	50	44	40	31
LFNR 30	52	52	47	40	34	18
RNC 30	66	57.7	49.3	41	36	30
PNC 35	62	55	50	45	40	22

Table IV. Some acoustical parameters of noise samples.

Group	Noise sample	$L_C - L_A$ (dB)	LF (dB)
1	OS	30.3	16.5
	AS	25.9	7.6
2	OS	30.9	18.3
	AS	26.6	8.5
3	OS	31.5	18.3
	AS	27.3	9.5
4	OS	31.7	20.3
	AS	28.1	10.4
5	OS	32.2	22.2
	AS	28.8	11.3

more rapidly falling spectrum than others. The room noise with a rapidly falling spectrum implies a high proportion of low frequency noise energy, which might have an unpleasant quality [23].

The difference value between the C-weighted level and the A-weighed level ($L_C - L_A$) can be taken to predict the proportion of low frequency noise energy [34]. As shown in Table IV, $L_C - L_A$ of OS are 3.4–4.4 dB higher than those of AS, which means that the proportions of low frequency noise energy of OS are higher than those of AS. It is indicated the energy of low frequency noise might be an important factor that impacts the annoyance.

The energy-averaged levels of the spectral deviation in low frequency (LF) [35, 36] can be regarded as a scale to estimate the magnitude of subjective response to low frequency noise. As a function of spectrum imbalance, LF includes 16, 31.5 and 63 Hz octave bands. LF can be obtained by these steps as follows:

The first step is to determine the RC rating of RC reference curve,

$$RC = \frac{L_{500} + L_{1000} + L_{2000}}{3}, \tag{3}$$

in which RC is the RC rating (dB), and L_{500}, L_{1000}, L_{2000} are the SPLs of 500, 1000, 2000 Hz octave bands (dB), respectively. Then, LF can be expressed as

$$LF = 10\log\frac{10^{0.1\Delta L_{16}} + 10^{0.1\Delta L_{31.5}} + 10^{0.1\Delta L_{63}}}{3}, \tag{4}$$

in which ΔL_{16}, $\Delta L_{31.5}$ and ΔL_{63} are the difference values between L_{16}, $L_{31.5}$, L_{63} and the RC reference curve values at those octave bands (dB). In this experiment, since noise samples only consisted of 31.5, 63, 125, 250 and 500 Hz octave bands, RC was determined by L_{500} of noise samples. In addition, 16 Hz octave band is not included in the spectra of noise samples, thus equation (4) can be simplified as

$$LF = 10\log\frac{10^{0.1\Delta L_{31.5}} + 10^{0.1\Delta L_{63}}}{2}. \tag{5}$$

Table IV shows LF of each noise sample. The values of LF of OS are 8.8–10.9 dB higher than those of AS. It is indicated that the spectra of OS were more imbalanced, which was attributed to the higher proportion of low frequency noise energy. In that case, the spectra of OS might have a more rumbly character [37]. Besides, most subjects expressed that the noise annoyance level are mostly influenced by the rumbly character of a noise sample. Considering NR curves were developed only from equal loudness contours and speech interference levels, it might ignore the effect of spectrum imbalance, which leads to the "rumble" problem.

3.2. Application of Quality Assessment Index (QAI)

Besides SBNFTR, there are various kinds of background noise in a room. In order to assess the effects of actual room noise (including SBNFTR and background noise), the impact of background noise should be considered. Many complaints were investigated, and it was indicated that the increase of SPL of some octave band was usually much higher than those of other octave bands, when a room was affected by SBNFTR, which was similar to Lu and Luo's conclusion [22]. In that case, sometimes even though SBNFTR is within ELSBNFTR, the spectrum of room noise is much imbalanced after combined with background noise. Noise monitoring results of a bedroom at night are illustrated in Figure 3, in which the evaluation limits are selected according to GB 22337-2008 and GB 12348-2008. $L_{31.5}$, L_{63}, L_{125}, L_{250}, L_{500} and the A-weighted level of the structure-borne noise from water pump do not exceed the current ELSBNFTR or the proposed ELSBNFTR, but residents still complain about the impact of room noise. Therefore, it is necessary to take RC Mark II Method [36] as a reference, which has been accepted by ASHRAE [38, 39], and introduce QAI to assess the spectrum imbalance of room noise. There are three steps in this method, as shown below:

Table V. Difference values between room noise and background noise ($SPL_R - SPL_B$, dB) at different octave bands.

Fixture	L_{16}	$L_{31.5}$	L_{63}	L_{125}	L_{250}	L_{500}	L_{1000}	L_{2000}	L_{4000}
Large kitchen ventilator	0.2	0.5	8.6	0.6	4.1	2.0	0.5	0.0	1.2
Evelator engine	3.5	4.6	2.0	6.4	6.9	3.5	1.7	1.7	1.6
Transformer	2.4	6.2	5.5	3.4	12.5	11.1	16.9	6.5	1.4
Air cooled refrigeration equipment	0.4	1.8	1.2	7.0	2.3	1.5	1.1	2.0	3.5

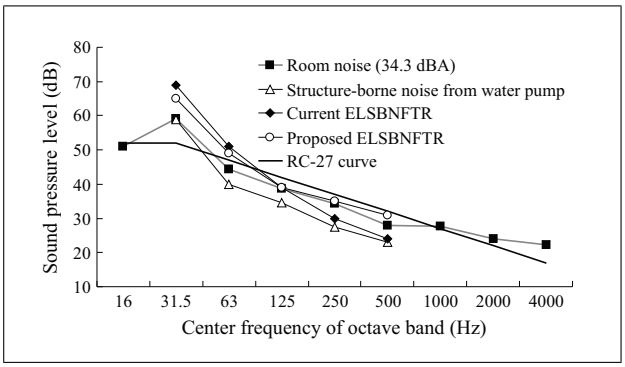


Figure 3. Noise monitoring results of a bedroom at night which is affected by the structure-borne noise from water pump transmitted into room.

1. The first step is to determine RC by equation (3). In the example illustrated in Figure 3, L_{500}, L_{1000} and L_{2000} are 28.0, 27.6 and 23.9 dB, respectively. Since RC given by equation (3) is 26.5 dB, the RC-27 curve is selected as the reference for spectrum evaluation.
2. The second step is to calculate energy-averaged level of spectral deviations from the RC reference curve in each of the three frequency groups, including LF (16, 31.5 and 63 Hz octave bands), MF (125, 250 and 500 Hz octave bands), and HF (1000, 2000 and 4000 Hz octave bands). The procedure is given by equations (4), (6) and (7).

$$MF = 10\log\frac{10^{0.1\Delta L_{125}} + 10^{0.1\Delta L_{250}} + 10^{0.1\Delta L_{500}}}{3}, \quad (6)$$

$$HF = 10\log\frac{10^{0.1\Delta L_{1000}} + 10^{0.1\Delta L_{2000}} + 10^{0.1\Delta L_{4000}}}{3}, \quad (7)$$

   where ΔL_{125}, ΔL_{250}, ΔL_{500}, ΔL_{1000} and ΔL_{2000} are respectively the difference values between the SPLs of 125, 250, 500, 1000, 2000 Hz octave bands and the RC reference curve values at those octave bands (dB). In the example, $LF = 3.4$ dB, $MF = -3.3$ dB and $HF = 3.1$ dB.
3. QAI is defined as the difference value between the maximum and minimum values of LF, MF and HF. In the example, $QAI = LF - MF = 6.7$ dB.

The sound, whose spectrum is quite balanced without the character of rumble, roar or hiss, can be classed as neutral [40]. Blazier [36] introduced 5 dB as the critical value of QAI. If $QAI \leq 5$ dB, the spectrum is identified as neutral. If $QAI > 5$ dB, the spectrum is identified as imbalance, when, if the maximum is LF, the spectrum is identified as a rumbly character; if the maximum is MF, the spectrum is identified as a roar character; if the maximum is HF, the spectrum is identified as a hissy character. In the example shown in Figure 3, QAI is 6.7 dB, and $LF > HF > MF$. Although the SPL of each octave band does not exceed ELSBNFTR (including the proposed ELSBNFTR), the spectrum of room noise is imbalanced with a rumbly character, which caused the complaint. Thus, it is suggested that QAI should be introduced into the evaluation procedure as an effective method in dealing with similar room noise complaints.

3.3. Analysis of complaint cases

Many SBNFTR complaints have been investgated in China. The spectra illustrated in Figure 4 are some noise monitoring results of typical SBNFTR cases. The fixtures are large kitchen ventilator, elevator engine, transformer and air cooled refrigeration equipment, respectively. In the examples shown in Figure 4a–c, all of SBNFTR are within ELSBNFTR, but QAI of these room noises are 7.6, 7.6, 13.6 dB, whose spectra can be identified as rumbly character, roar character and hissy character, respectively. Thus, it is indicated that the imbalanced character caused the SBNFTR complaints. However, in the case illustrated in Figure 4d, SBNFTR are within ELSBNFTR, and QAI of room noise is 1.3 dB, whose spectra can be identified as neutral. In the field acoustical measurement, the annoyance of noise could be experienced by people, who described that they could distinguish SBNFTR easily. In Table V, the difference values between room noise and background noise at different octave bands ($SPL_R - SPL_B$) are given. It shows, at the octave band with center frequency of 125 Hz, $SPL_R - SPL_B$ of the example in Figure 4d reaches 7.0 dB. After analyzing lots of complaint cases, we found that when $SPL_R - SPL_B$ exceed 5 dB at any octave band, people would experience the noise annoyance. As shown in Table V, the highest values of $SPL_R - SPL_B$ among other examples reach 8.6, 6.9, 16.9 dB, respectively. Ordinarily, people in the room might have been accustomed to the background noise. After the fixtrue is turned on, if $SPL_R - SPL_B$ reaches high enough, SBNFTR would be distinguished easily. In that case, people would complain about the noise annoyance. Thus, it is suggested that the evaluation of $SPL_R - SPL_B$ should be added in the procedure for the assessment of complaints, and 5 dB could be considered as a limit.

4. Conclusions

A method for the revision of ELSBNFTR is proposed. Based on the current ELSBNFTR and the proposed ELS-

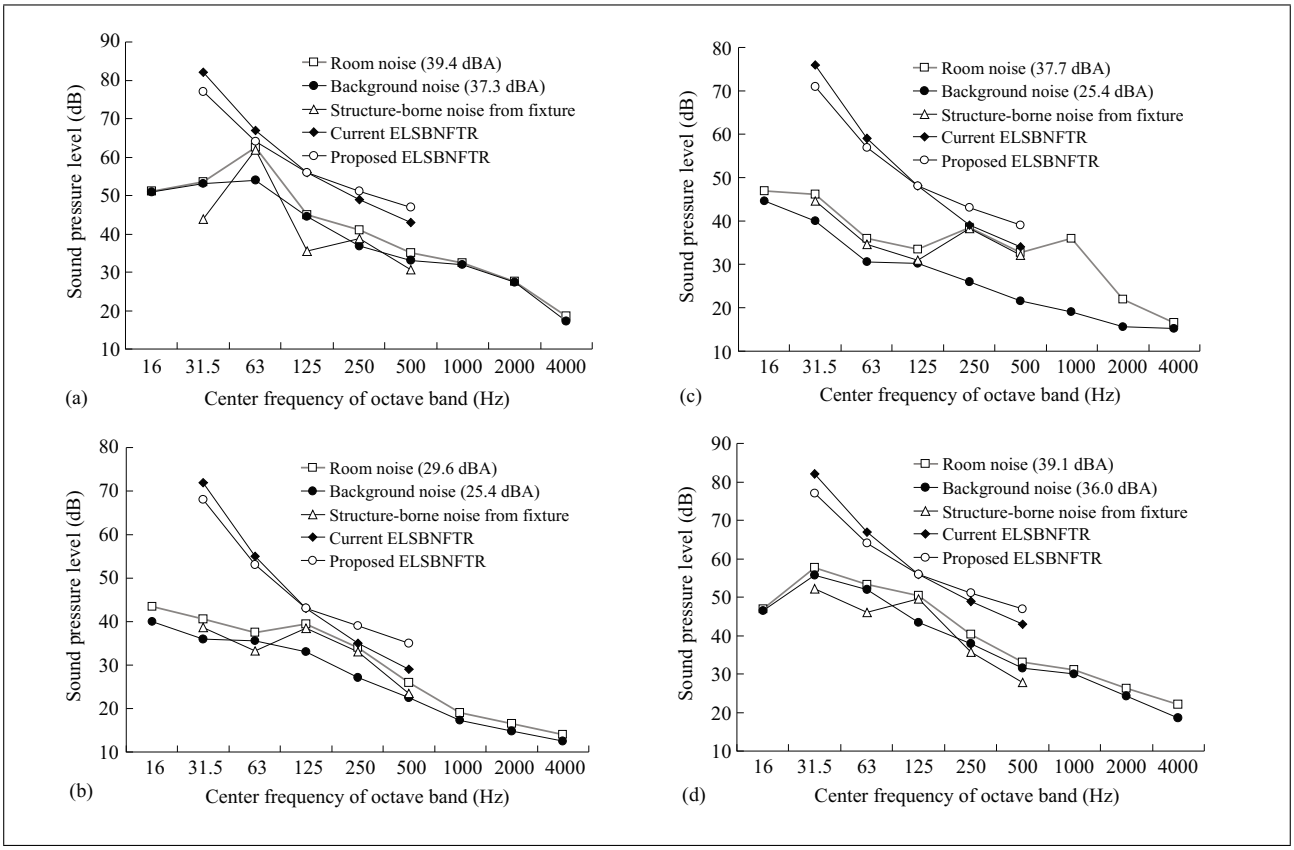


Figure 4. Noise monitoring results of some SBNFTR complaints. a. large kitchen ventilator; b. elevator engine; c. transformer; d. air cooled refrigeration equipment.

BNFTR, OS and AS were generated. For each compared group, more than 72.0% of subjects chose "OS were more annoying than AS". Moreover, the difference values between OS and AS in the aspect of A-weighted levels and loudness levels were relatively small, but $L_C - L_A$ and LF of OS were respectively 3.4–4.4 dB and 8.8–10.9 dB higher than those of AS. Attributed to the higher proportion of low frequency noise energy, the spectra of OS were more imbalanced. In that case, the spectra of OS might have a more rumbly character.

Noise with an imbalanced spectrum is particularly annoying to subjects. It is proposed QAI should be introduced into ELSBNFTR, in order to reduce complaints mainly caused by room noise (including structure-borne noise from fixture transmitted and background noise) with an imbalanced spectrum, while structure-borne noise from fixture is within ELSBNFTR. Besides, the evaluation of the difference values between room noise and background noise at different octave bands should be added in the procedure for the assessment of complaints, and 5 dB could be considered as a limit.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (No. 10604048) and the National Public Benefit Research Foundation (No. 200809142). We gratefully acknowledge the assistance of Qing-Pu Lu, who collected some of the data reported here.

References

[1] G. Q. Di, B. J. Zhang, Q. Shang: Subjective annoyance caused by indoor low-level and low frequency noise and control method. J. Environ. Sci. **17** (2005) 135–140.

[2] K. P. Waye, M. Björkman, R. Rylander: Loudness, annoyance and the dBA in evaluating low frequency sounds. J. Low Freq. Noise Vib. **9** (1990) 32–45.

[3] K. D. Kryter: The effects of noise on man. Academic Press, 2ed Ed., New York, USA, 1985.

[4] ISO 226: Normal equal-loudness-level contours. Inernational Organization for Standardization, 2003.

[5] L. L. Beranek: Revised criteria for noise in buildings. Noise Control **3** (1957) 19–27.

[6] L. L. Beranek: Balanced noise-criterion (NCB) curves. J. Acoust. Soc. Am. **86** (1989) 650–664.

[7] W. E. Blazier: Revised noise criteria for application in the acoustical design and rating of HVAC systems. Noise Control Eng. **16** (1981) 64–73.

[8] ASHRAE Handbook: HVAC application, sound and vibration control. Chapter 42. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1991.

[9] ANSI S12.2: Criteria for evaluating room noise. American National Standards Institute, 1995.

[10] ANSI S12.2: American national standard criteria for evaluating room noise. American National Standards Institute, 2008.

[11] C. W. Kosten, G. J. van Os: Community reaction criteria for external noises. Proc. NPL Symposium 12: The Control of Noise, London, UK, 1962.

[12] AS 1469: AcoustiAS-methods for the determination of noise rating numbers. Standards Association of Australia, 1973.

[13] AS 1469: AcoustiAS-methods for the determination of noise rating numbers. Standards Association of Australia, 1983.

[14] P. Yu, G. Q. Di, Y. F. Huang, B. J. Zhang: The analysis of noise frequency characters of facilities in urban residential area. China Environ. Sci. **26** (2006) 491–495.

[15] J. Bengtsson, K. P. Waye, A. Kjellberg: Sound characteristics in low frequency noise and their relevance for the perception of pleasantness. Acta Acustica united with Acustica **90** (2004) 171–180.

[16] Y. F. Huang, G. Q. Di, Y. T. Zhu, Y. P. Hong, B. J. Zhang: Pair-wise comparison experiment on subjective annoyance rating of noise samples with different frequency spectrums but same A-weighted level. Appl. Acoust. **69** (2008) 1205–1211.

[17] T. Meloni: New Swiss legislation to protect persons from vibrations and structure-borne noise. J. Low Freq. Noise V. A. **29** (2010) 189–196.

[18] J. T. Nelson, M. Harrisson, M. Pettersson: Sructure-borne noise and vibration control for Chatswood Interchang. Notes on Numeical fluid mechanics and multidisciplinary design **99** (2008) 143–149.

[19] GB 22337: Emission standard for community noise. Ministry of Environmental Protection of P. R. C., General Administration of Quality Supervision, Inspection and Quarantine of the P. R. C., 2008.

[20] GB 12348: Emission standard for industrial enterprises noise at boundary. Ministry of Environmental Protection of P. R. C., General Administration of Quality Supervision, Inspection and Quarantine of the P. R. C., 2008.

[21] GBJ 118-88: Code for design of sound insulation in civilian construction. Ministry of Urban Construction and Environment Protection of P. R. C., 1989.

[22] Q. P. Lu, Q. P. Luo: Exploration and practice of the methods of environmental quality assessment for indoor noise. China Science and Technology Press, Beijing, China, 2007.

[23] H. G. Leventhall, P. Pelmear, S. Benton: A review of published research on low frequency noise and its effects. Department for Environment, Food and Rural Affairs, London, UK, 2003.

[24] N. Broner, H. G. Leventhall: Low frequency noise annoyance assessment by low frequency noise rating (LFNR) curves. J. Low Freq. Noise Vib. **2** (1983) 20–28.

[25] Q. L. Wu: Limits and evaluation methods of low frequency noise. Proc. Zhe, Su, Hei, Lu and Tianjin acoustical conference, Jinan, China, 2009.

[26] Q. L. Lin, X. H. Xu, Y. Zheng, X. Y. Liu, G. Q. Di: Investigation and research on subjective annoyance of indoor structure-borne noise from associated facilities. Tech. Acoust. **28** (2009) 160–162.

[27] N. Otto, S. Amman, C. Eaton, S. Lake: Guidelines for jury evaluations of automotive sounds. Sound Vib. **35** (2001) 1–14.

[28] D. X. Mao, W. Z. Yu, Z. M. Wang: Statistical validation and criterion for paired comparison data in sound quality evaluation. China Acta Acustica **30** (2005) 468–472.

[29] P. D. Schomer, J. S. Bradley: A test of proposed revision to room noise criteria curves. Noise Control Eng. J. **48** (2000) 124–129.

[30] L. L. Beranek, W. E. Blazier, J. J. Figwer: Preferred noise criterion (PNC) curves and their application to rooms. J. Acoust. Soc. Am. **50** (1971) 1223–1228.

[31] ISO 389-8: Acoustics. Reference zero for the calibration of audiometric equipment. Part 8: Reference equivalent threshold sound pressure levels for pure tones and circumaural earphones. International Organization for Standardization, 2004.

[32] R. Guski, R. Felscher-Suhr, R. Schuemer: The concept of noise annoyance: how international experts see it. J. Sound Vib. **223** (1999) 513–527.

[33] G. Q. Di, Z. G. Li, X. Y. Liu, X. Shi: Research on the simulation of the subjective annoyance of actual noise using combined pure tones. J. Low Freq. Noise V. A. **29** (2010) 25–31.

[34] A. Kjellberg, M. Tesarz, K. Holmberg, U. Landström: Evaluation of frequency-weighted sound level measurements for prediction of low-frequency noise annoyance. Environ. Int. **23** (1997) 519–527.

[35] W. E. Blazier: Sound quality consideration in rating noise from heating, ventilating and air-conditioning (HVAC) systems in buildings. Noise Control Eng. J. **43** (1995) 53–63.

[36] W. E. Blazier: RC Mark II: A refined procedure for rating the noise of heating, air-condition (HVAC) systems in buildings: Noise Control Eng. J. **45** (1997) 243–250.

[37] R. N. Vasudevan, C. G. Gordon: Experimental study of annoyance due to low frequency environment noise. Appl. Acoust. **10** (1977) 57–69.

[38] ASHRAE Handbook: Handbook, fundamentals. Chapter 7: Sound and vibration. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 2005.

[39] ASHRAE Handbook: Handbook, hvac applications. Chapter 47: Sound and vibration control. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 2007.

[40] A. Broner: Rating and assessment of noise. Proc. 2004 AIRAH 'Are you being heard?' acoustiAS conference, 2004.