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Subjective annoyance caused by indoor low-level and low frequency noise and control method

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Abstract: The influence of low-level noise has not been widely noticed. This paper discovered that low-level and low frequency noise(A-weighted equivalent level $L_{eq} < 45$ dB) causes higher probability of subjective annoyance. The fuzzy mathematic principle was applied to deal with the threshold level of subjective annoyance from noise in this study; there is preferable relationship between the indoor noise and noise annoyance at low frequency noise level. Study indicated at the same centered noise level, the change of annoyance probability is mainly caused by the change of the frequency spectrum characteristic of the indoor noise. Under low noise level environment, without change of the medium-low frequency noise, the slight increase of medium-high frequency noise level with the help of noise sheltering effect can significantly reduce the noise annoyance. This discovery brings a new resolution on how to improve the environmental quality of working or living places. A noise control model is given in this study according to the acoustic analysis.

Keywords: low-level noise; subjective annoyance; threshold level; structural noise; indoor noise; noise control

Introduction

It was believed that only high-level noise could cause noise pollution. The influence of low-level noise has not been widely noticed. This research discovered that under certain conditions the low-level noise, especially low frequency noise, may even cause higher annoyance response.

The probability of noise annoyance from structural noise, caused by trunk-style electric power transformers, which were placed in the basement of residential buildings, studied in this paper. During the research, we found that many annoyance responses were fed back from the environment of lower sound level of the noise. The noise of lower sound level occurs when the low-frequency sound transmits through the structure of the building and then radiates inside the rooms of each floor of the entire residential building.

This paper focuses on the study of the subjective annoyance and structural sound. The former is caused by low-level and low-frequency noise while trunk-style electric power transformer generates the latter. In our example late, the transformers were placed in the basement of residential buildings. A technical evaluation model of subjective annoyance is discussed in this paper. This research also provided suggestive measures to prevent pollutions from structural noise in the modern city public facilities (water pump rooms, elevator rooms, power rooms, etc.). At the end, this paper presents a preventive design with the practical results based on the development of this study.

1 Subjective annoyance of low-level and low-frequency noise

1.1 Probability of subjective annoyance caused by noise

The level of subjective annoyance caused by noise is an important factor to evaluate the quality of sound environment. The grade of annoyance due to a certain noise usually can only be described by listeners themselves. Those descriptions are fuzzy and not quantified in most of the time—different people have different subjective responses on the grade of annoyance. Many scholars have been researching noise nuisance from the perspective of source of noise (types of noise source, noise-energy, frequency, etc.), sound-acceptors(age, history of noise exposure, etc.), and sound medium(building structure, weather condition, etc.), and so on. They have confirmed that subjective annoyance relates to not only sound level and frequency but also the physiological and mental factors of sound acceptors as well.

To quantify people's descriptions of subjective annoyance, this study provided people five different options to describe the noise annoyance under the low frequency and low-level noise environment when they filled out the questionnaires. The noise annoyance was divided by five options into five categories—highly, strongly, significantly, a little and not at all, respectively. The study found that people's responses to noise are complicated and diverse. The respondents of our questionnaire were very confident when they indicated highly annoying or not at all annoying in the questionnaire. But people are lack of confidence to identify and judge what amount of noise constitutes the grade scores of a little annoying, significantly annoying and strongly annoying. In this paper, we introduced the concept of annoyance probability to describe the average level of subjective annoyance response from the survey participant under a particular sound environment. The principle of fuzzy mathematics is also fully utilized to calculate the annoyance probability in this paper.

The membership function of noise annoyance of the people's subjective response to environmental noise is shown

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$$F = \sum \frac{\mu_j}{\nu_j} = \frac{1}{\nu_1} + \frac{0.75}{\nu_2} + \frac{0.5}{\nu_3} + \frac{0.25}{\nu_4} + \frac{0}{\nu_5}. \quad (1)$$

Eq. (1) is a typical format of the equation about membership function in fuzzy mathematics, where μ_j is the value of the membership function of each appraisal level ν_j. Here we quantifies the degree of confidence in responses of highly annoying (ν_1), strongly annoying(ν_2), significantly annoying(ν_3), a little annoying(ν_4) and not at all annoying (ν_5) grades as 1.0, 0.75, 0.50, 0.25, 0 at a equal interval. The annoying probability can be calculated as follows:

$$P_i = \sum_j \mu_j \alpha_{ij} \Big/ \sum_j \alpha_{ij}, \quad (2)$$

where P_i is the annoyance probability of i-th center sound level; α_{ij} is the number of people surveyed who selected jth evalutation grade under ith central sound level.

1.2 Subjective response to low-frequency and low-level noise

1.2.1 Survey and measurement

In order to establish the subjective response regarding low-frequency and low-level noise, this survey was conducted in residential buildings where residents were influenced by low frequency and low-level noise from transformer room located in the basement of their residential buildings. The three buildings we selected in this study are all seven-storey with 3 units in each floor, a total of 63 units and 203 residents. The basic information of the residents is given in Table 1.

Table 1 The basic information of the residents

Age	Below 16	16 to 30	30 to 50	50 to 70	Above 70	Total
Number of residents	57	41	54	28	23	203
Gender	Male	Female				
Number of residents	98	105				203
Occupation	Public servant	Teacher/doctor	Worker	Student	Others	
Number of residents	24	33	44	48	54	203

The survey was conducted among residents of these three buildings by giving them the designed questionnaires. The participants were required to select the level of subjective annoyance response under a certain sound environment. The questionnaire also contained the general questions of the basic information about the respondents as well. In the meanwhile, the A-weighted equivalent sound level of 2 min in indoor and octave bands was conducted. During the indoor survey, all doors and windows were closed, and air-conditions and any other consumer electric appliances whichever create noises were shut down. Measure and survey were conducted in the both conditions when the electric transformers (the source of low-frequency structural noise) were on or not running at the basement of the buildings. The main items of sample questionnaire are as follows:

Transformer(run or stop)

L_{eq}, dB, 2 min

The level of subjective annoyance you feel now

Highly annoying

Strongly annoying

Significantly annoying

A little annoying

Not at all annoying

Your basic situation

Gender

Occupation

Age

Health

1.2.2 Results of survey and data analysis

A-weighted equivalent sound level of 2 min was measured in the low-level noise indoor environment, 32.7 to 40.8 dB in daytime, and 29.1 to 38.4 dB in nighttime. These data were divided into 4 groups as the group of 29.0—32.0 dB, 32.1—35.0 dB, 35.1—38.0 dB and 38.1—41.0 dB respectively. The grades of sound level were marked according to their respective center sound level, says, 30.5 dB, 33.5 dB, 36.5 dB and 39.5 dB. The results of surveys are shown in Table 2.

The information about the number of people who selected each level of annoyance was also included. The probability of annoyance at each center sound level is shown in Table 2.

Table 2 Subjective annoyance of low - level noise indoor

Central sound level, dB	The state of sound sources	The number of people who select each level annoyance(in the day)					Probability of annoyance, %	The number of people who select each level annoyance(at night)					Probability of annoyance, %
		ν_1	ν_2	ν_3	ν_4	ν_5		ν_1	ν_2	ν_3	ν_4	ν_5	
30.5	Off	–	–	–	–	–	–	0	0	1	15	14	14.2
	On	–	–	–	–	–	–	2	7	11	6	3	49.1
33.5	Off	0	0	1	9	19	9.4	0	0	8	10	8	25.0
	On	0	3	7	9	7	30.8	5	16	9	4	1	64.3
36.5	Off	0	0	6	10	9	22.0	1	2	6	3	5	36.8
	On	1	2	13	12	4	37.5	14	8	4	5	0	75.0
39.5	Off	0	2	10	11	10	28.5	–	–	–	–	–	–
	On	2	5	12	7	2	48.2	–	–	–	–	–	–

According to data in Table 2, more probability of annoyance exists indoors even the sound level is lower. The level of low-frequency noise remains preferable connection with probability of annoyance indoors. This is identical to the conclusion made by Tesarz and Landström (Tesarz, 1997) about the noise in working environment. For the same central sound level, the annoyance probability was much more at the time when the transformer was on than when it was off. Our study showed when the transformer was on, the average annoyance was 18.9% higher than when it was off in the daytime, and 37.5% higher in the nighttime. Fig. 1 indicates the change of noise frequency spectrum when the transformer was on or not under the same central sound level 33.5 dB indoors. When structural noise of transformer exists, indoor noise level of the medium-low frequency has increased substantially. 4 dB, the peak increase of noise level was reached when the center frequency hit 125 Hz. We also discovered that the noise level did not change so much at the medium-high frequency above 500 Hz, it almost stayed as same as the background. Table 2 shows that the probability of annoyance indoors has been increased obviously when the pollution of the structural sound existed. Our study found that under the same central sound level, the change of the noise annoyance indoor is mainly caused by the change of the characteristic of the noise frequency spectrum. The enhancement of the medium-low frequency noise is caused by the structural sound transmission of the transformer. This conclusion is similar to the result of Persson's study (Persson, 1985). According to sound superpose theory, the indoor noise add level brought by the pollution of the structural sound of transformer can be calculated. The result of calculation is shown in Fig. 1 with fold line marked by triangles.

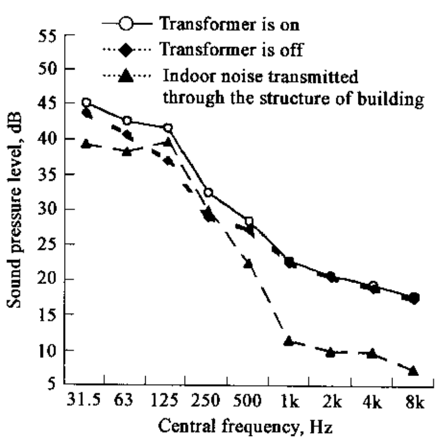

Fig.1 The comparison of frequency spectrum when the transformer is on or off

2 Characteristic analyze of low-frequency structural sound caused by the transformer and the example of related control

Fig.2 presents the comparison of the frequency spectrum of indoor noise between the daytime and the nighttime under the same center sound level of 33.5 dB. It indicated that the noise is almost invariable when the center frequency is below 250 Hz at the daytime compared with that of the nighttime. Once the medium-high frequency is above center frequency of 250 Hz, the sound level relatively increases. However, Table 2 shows that the probability of annoyance drops to 30.8% at the daytime from 64.3% at the nighttime. Therefore, in the environment of the low noise, without change of the magnitude of the medium-low frequency, the noise annoyance can be reduced through slightly strengthening the medium-high background noise under the masking effect of the noise.

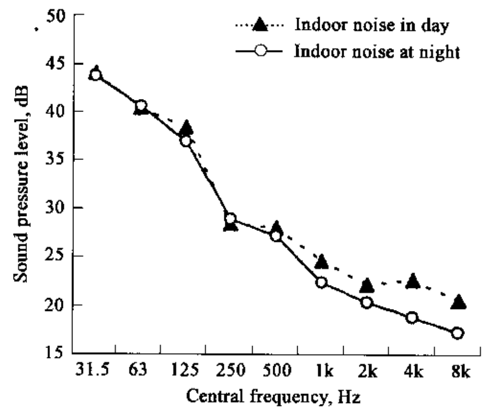

Fig.2 The comparison of the frequency spectrum of indoor noise between the daytime and the nighttime

2.1 Practical example for the control of low-frequency and low-level noise

2.1.1 Test of the characteristic of noise sources

The transformer room located in the basement of No.68 building in Jingfang Fifth Village in Hangzhou was selected for this practical example. Two sets of transformer of the model SB10-M-800/10 made by the Hangzhou Electric Equipment Production Company are laid in that room. The capacity of each transformer is 800 kV respectively. The noise outside and inside the transformer room was tested and analyzed with octave bands by dual channel spectrum analyzer (type BSWA VS302USB). The test results are presented in Table 3. The results indicated that each sound pressure level is higher than 45 dB when the central frequency is under 500 Hz. The noise of the transformer room met the feature of medium-low frequency, with the peak value of the frequency appeared around the frequency range of the central frequency of 250 Hz.

2.1.2 The routes of noise transmission

The routes of noise pollution caused by the transformer inside the house are as follows:

(1) The machinery vibration of the transformer sets is transmitted along the ground of the transformer room. It is further transmitted to the indoor metope of the house. The vibration of the metope stimulates the turbulence of the air again, which takes the air sound to ears of human.

(2) The noise of the transformer is transmitted to the wall of the room by the air and partially reflected on the wall. Some noise spread along the wall (called structural noise, some of those noise are absorbed by the wall in the process of spread) and continuously reach to the indoor metope of the each floor along the structural wall of the building. The vibration of the metope stimulates the turbulence of the air again, which takes the air sound to the ears of human.

(3) The doors and windows of the transformer room diffract the air sound. Those diffracted sounds are transmitted to the residential units via the doors and windows of the building.

Table 3 The spectrum analysis of transformer-room at night

Central frequency, Hz	Outdoor	Indoor
31.5	48	45.5
63	48.9	46
125	51.8	53.5
250	52.5	62
500	52.1	53.2
1k	43	45.1
2k	28.5	30
4k	19.5	19.8
8k	18.2	18.2
Sound pressure level in total	60.5	62.5
L_{eq}	53.7	55.2

Notes: the outdoor measuring points were outside the opening door of the equipment room, while the indoor measuring points were 20 cm away from to the radiator of the transformer of the equipment room

2.2 Identification and estimation of the relative source intensity of the noise source

The noise from the above three routes along with the original background indoor noise ultimately forms the indoor noise pollution. We can analyze and judge the relative magnitude of each component of the noise from the energy perspective to distinct the relative intensity of the noise. The analysis result will help us to take measures accordingly to better control noise.

(1) The sound intensity of the structural sound (also called solid sound), spread by the vibration of the transformer sets (through the form of the elastic wave) to the foundation and the various components joined with the foundation, should be calculated as: $I = \rho c u_e^2$ if the sound wave of the structural sound is considered as plain sound wave. According to the measure results from the vibration speed of the rigid ground connected with the transformer, the effective value of the vibration speed $u_e = 0.53$ cm/s; and the sound impedance of the concrete ground $\rho c = 3.65 \times 10^6$ kg/($m^2 \cdot s$). Therefore, the sound intensity of the structural sound $I \approx 103$ W/m^2. The effective area (which connects the two sets of transformer) of the rigid foundation is about 2 m^2, accordingly, the average sound power of the structural sound $\overline{W} = I \cdot s = 206$ W.

(2) The air sound caused by the vibration of the transformer shell spreads to the wall of the equipment room, as well inspires the vibration of the wall. Then the sound wave is spread by the components connected with the wall. Finally, sound wave reach to the indoor metope of the each floor along the structural wall of the building. Based on the practical measurement, the virtual value u_e of the vibration speed of the transformer shell is equal to 1.02 cm/s. If the vibration speed of the air particle is assumed equal to the vibration speed of the transformer shell, the sound intensity I of the air sound caused by the vibration of the transformer shell is about 0.043 W/m^2. According to the practical measure, the efficient radiated area of the two transformer shells is about 25 m^2. Based on this information, the average sound power $\overline{W}$ can be estimated as 1 W. If the sound energy of the air sound can be all switched to the structural sound, the maximum sound power of the structural sound is about 1 W.

(3) The diffraction sound spreading from the transformer room to the indoor: The air sound power caused by the vibration of the transformer shell is about 1 W, so the sound power of the diffraction sound spreading from the transformer room to the indoor is much less than 1 W.

According to the above analysis and estimation, in order to control the indoor noise pollution caused by the transformer sets, the most important section needs to be controlled is the structural sound spread caused by the vibration of the sets. The structural sound spread caused by the radiated air sound on the sets shell can be somewhat considered as well. And the effect of the diffraction sound of the equipment room can be almost ignored.

2.2.1 Control measures

(1) In order to reduce the structural sound caused by the vibration of the transformer set, the vibration isolation is applied to the sets.

(2) In order to reduce the structural sound at the time the low-frequency air sound spreads along the wall, the structural sound absorption is installed on the metope and the roof of the transformer room.

2.2.2 Design of the parameters of the components

(1) Vibration isolator: four vibration isolators were installed according to the distribution of the quality weighted points of the transformer. The static load of the transformer (including the foundation) is 3785 kg, while the dynamical load is minimal and can be ignored. Therefore the load of each vibration isolator is 946 kg. If the safety factor is taken into account, load of 1000 kg for each isolator is a reasonable weight. The lowest perturbation frequency of the transformer is twice as many as the alternating current. In China, the civil frequency of the alternating current is 50 Hz, therefore, the fundamental frequency of the transformer vibration f is 100 Hz. According to the lowest interference frequency, the fundamental frequency of the structural sound is fixed at 100 Hz.

Under the standard condition, the sound spread speed in the concrete is 3048 m/s. Then the wavelength of the structural sound wave can be calculated as 30.48 m. The half wavelength of this sound wave is still much longer than the thickness of the wall. Accordingly it can be utilized to design the solid sound isolation set in low frequency sound range. The result of the sound isolation can be measured by the magnitude of the ratio of the vibration transferring. The ratio of the vibration transferring is as follows:

$$T_A = \sqrt{\frac{1 + \left(2\frac{C}{C_C}\frac{f}{f_0}\right)^2}{\left[1 - \left(\frac{f}{f_0}\right)^2\right]^2 + 4\left(\frac{C}{C_C}\frac{f}{f_0}\right)^2}}. \quad (3)$$

Here, f is the intense vibration frequency; f_0 is the inhere frequency of the vibration isolator; and C/C_C is the damping ratio.

$$\eta = \left(1 - \frac{C}{C_C}T_A\right). \quad (4)$$

Considering the large load's favorable vibration isolation ability for the low frequency vibration, the vibration isolators with pre-stressed force damping spring is selected here with the damping ratio of 0.08. The ratio of the vibration transferring can be calculated by taking all the parameters into the formula above. The ratio comes as 0.0016. The Formula (4) is selected to calculate the efficiency of the vibration isolation η. The η can reach as high as 99.838%. Four TJS-21type vibration dampers can be installed to reduce the structural sound caused by the vibration of the transformer sets.

(2) The sound absorption structure of the wall: According to the noise frequency spectrum in the transformer room listed in Table 4, the sound absorption structure with higher sound absorption coefficient to the medium-low frequency(especially in the frequency range where the 250 Hz central frequency is) were installed. The structural sound transmitted through metope of the house is reduced by the sound absorption. A sound absorption structure combined with tiny perforated board and porous sound absorption material are chosen here. The perforation aperture of the tiny perforated board(aluminum sheet) is 0.8 mm with 1% of the ratio of perforation, and 1 mm of thickness. A 10 cm air cavity is remained behind the board with 25 kg/m^3 silicate cotton filled in. 10 cm × 5 cm fireproof woods are acted as the keels in the cavity. The central space between the keels is 40 cm × 40 cm. Considering the entire design plan of the equipment room, this sound absorption structure is overspread on the whole aisle wall and the roof of the equipment room. The sound absorption coefficients of each part of the sound absorption structure are shown in Table 4.

Table 4 The sound absorption coefficient of each part of the sound absorbtion structure

Structure of sound absorption	Central frequencies, Hz				
	125	250	500	1 k	2 k
Tiny perforated board	0.24	0.71	0.96	0.40	0.29
24 kg/m^3 silicate cotton	0.25	0.55	0.7	0.75	0.88

2.3 The equation of noise reduce

The practical result of the noise control was tested after the above noise-reduce measures were taken. The test results are shown in Table 5.

Table 5 indicates that the noise at the master room just above the equipment room is reduced by 3.9 dB if the measure of set vibration isolation is taken in place. The noise can be further reduced by 1.1 dB if both measures of set vibration isolation and the sound absorption are established. The ratio of the effect between the two measures is 4:1. Therefore, vibration isolation should be the main method to eliminate the pollution of the structural sound of the transformer. However, the method of sound absorption of the equipment room should not be eliminated, especially in order to achieve the higher quality indoor environment. In addition, in the second survey to the residents after the noise treatment was completed, the subjective responses of the indoor noise annoyance generally declined to "a bit annoyance" or "not too annoyance". A good satisfaction feedback from residents is obtained. This sample treatment can prove, from the perspective of noise pollution control, that technically, the transformer room can be placed in the basement of the residential buildings and the office buildings. In the mean while, it provides the practical experience and technical guide for the design of the noise sensitive buildings as well.

Table 5 Comparison of pre-treatment and after-treatment

Measuring point	L_{eq} at night, dB			Notes
	Before treatment	After treatment	Noise reduction amount	
20 cm away from to the radiator of the transformer of the equipment room	55.2	49.1	6.1	Sets vibration isolation and sound absorption of the equipment room
Outside the opening door of the equipment room	53.7	46.1	7.6	Sets vibration isolation and sound absorption of the equipment room
The master room just above the equipment room	35.2	31.3	3.9	Sets vibration isolation
	35.2	30.2	5.0	Sets vibration isolation and sound absorption of the equipment room

3 Conclusions

Under the low noise environment indoor(L_{eq} < 45 dB), various low frequency components of the noise still can create great degree of annoyance. The level of low-frequency noise remains preferable connection with probability of annoyance indoors. With the level of the low frequency noise transmitted through the structure of building increasing, the annoyance probability increases substantially. In our example, for the same central sound level, the annoyance probability was much more at the time when the transformer was on than when it was off. When the transformer was on, the average annoyance was 18.9% higher than when it was off in the daytime, and 37.5% higher in the nighttime.

For the noise under the same central sound level, the change of the noise annoyance indoor is mainly caused by the change of the characteristic of the noise frequency spectrum, and the enhancement of the medium-low frequency noise produced by the structural sound transmission of the transformer.

Under the environment of the low noise, without change of the magnitude of the medium-low frequency, the noise annoyance can be reduced by slightly strengthening the medium-high background noise, and taking advantage of the masking effect of the noise as well. This discovery provided new lights to how to improve the quality of the indoor acoustic environment in the working and living places.

The low frequency noise is generally created by the structural sound spreading via the vibration. The vibration isolation associated with sound absorption can greatly eliminate the low frequency components of the noise. The structural noise will be reduced effectively by taking advantage of this technology.

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Introduction to author's research group

The research of the group is on the field of environmental physics, mainly on the study of basic theory of environmental acoustics, noise effect and its control, pollution of environmental electromagnetic, computing simulation of environmental pollution and environmental information processing.

In recent years, the group has carried out researches of environmental protection projects supported by Environmental Protection Bureau of Zhejiang or Hangzhou, China, such as "noise propagation of urban elevated road and its control", "the pollution and control of the social life noise", "the subjective annoyance caused by indoor low-level and low frequency noise and control method", "the computer simulation model and the control method of underground garage noise in urban residential areas" and "the status in quo and developing trend of electromagnetic pollution in cities".

With the process of urbanization in China, changes have happened both in manner of noise influence on people and sources of sound in residential areas. All kinds of noises generated by residential equipments have become the most important noise sources in urban. These equipments are equipped in urban living surroundings and mainly emit low frequency noise whose influence on people is stronger than that of middle/high frequency noise. Now the author is undertaking the project, study on the characters of low frequency noise in urban residential regions and its evaluation, supported by the National Natural Science Foundation of China.

In this project, the acoustic characters of low frequency noise in residential areas and their influence on people will be studied. Through subjective annoyance survey of sound receivers and laboratory psycho-acoustic research, relations between acoustic character and their influence on people will be established by mathematics model, the evaluation factor and method will be determined. Because the research aims to provide fundamental materials to improve noise evaluation system and draw a low frequency noise standard in residential areas, so the research is important to the improvement of urban noise environment quality in China.