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Annoyance response to low frequency noise with tonal components: A case study on transformer noise

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ABSTRACT

In order to study how acoustical factors influence annoyance responses to low frequency noise with tonal components, this research has selected 220 kV and 500 kV transformer noises as examples and an 11-point numerical scale as an evaluation tool, in which the percentage of highly annoyed (%HA) and mean annoyance (MA) are chosen to represent annoyance caused by noises. Results show that a logistic curve is well suited for describing the exposure–response relationship between the A-weighted equivalent sound pressure level (L_{Aeq}) and %HA (or MA) of the transformer noise. With the same L_{Aeq}, 220 kV transformer noise is more annoying than 500 kV transformer noise in terms of %HA and MA, which is related to different sharpness, roughness and tonality of the noises caused by transformers of the two voltage levels. Based on stepwise regression analysis, multiple linear regression models are further developed by using L_{Aeq} and roughness as acoustical parameters to predict the %HA and MA of transformer noise. Compared with the linear regression model that considered only L_{Aeq} values, multiple linear regressions can efficiently account for the different annoyance ratings of the two transformer noises at the same L_{Aeq} values.

1. Introduction

Low frequency noise is a relative term, and there is no definite boundary among low, middle and high frequency noises. In general, low frequency noise is defined as a noise with a frequency range of 20–250 Hz [1–3]. However, since the actual environmental noise has a wide range of frequencies, it is not advisable to define types of noise (i.e., low, middle and high frequency noise) merely according to noise frequency [4]. Therefore, noise whose low frequency sound energy is dominant in the total sound energy is usually defined as low frequency noise [5]. Noise induced by transformer of 50 Hz alternating current has apparent sound energy at 100 Hz and its harmonic frequencies, is typical low frequency noise [6].

Some laboratory subjective evaluations have already been carried out to study annoyance responses to low frequency noise and the prediction model. It has been reported that A-weighted equivalent sound pressure level (L_{Aeq}) and loudness may not be valid annoyance indicators of low frequency noise to some extent [3,7–9]. Apart from L_{Aeq} and loudness, there are also other acoustical characteristics contributing to subjective annoyance. For example, there can be significant difference in psychological effects when subjects are exposed to noise samples with the same L_{Aeq} but different in other acoustical characteristics [10–16]. Alayrac et al. [17] have studied noise annoyance induced by a variety of industrial sources including transformers. It has been demonstrated that among annoyance indicators such as L_{Aeq}, loudness level (L_N) and $I_{A,1/3oct,100Hz}$ (A-weighted level after excluding the 100 Hz component level), the acoustical indicator $I_{A,1/3oct,100Hz}$ appears to be the best annoyance predictor of low frequency noise with a main component at 100 Hz. Zwicker and Fastl [18] have proposed a nonlinear calculation model based on several psychoacoustic parameters (i.e., loudness, roughness, sharpness and fluctuation strength) to predict psychoacoustic annoyance, which has no upper limit. In addition, many researchers have set up linear regression models by using psychoacoustic parameters to evaluate and predict auditory unpleasantness and annoyance [19–21], etc.

For annoyance responses to low frequency noise with tonal components, researchers have drawn different conclusions through experimental studies. Landström et al. [22] have analyzed the relationship of noise annoyance with exposure levels and tonal components in low, middle and high frequency sound environments. It is suggested that the frequency characteristics and the sound level of the noise affect the strength of the effect of tones on annoyance. Noise with tonal components is more annoying than the others with the same B-weighted level, and annoyance is

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further increased when the noise contains several tones. Also, Jeon et al. [23] have tried to enhance indoor acoustic comfort by varying spectral envelope of air-conditioning sounds, and pointed out that sounds without tonal components are much more preferred over sounds with tonal components. Besides, in cases with and without tonal components, the subjects have a more favorable impression of sounds which have a larger energy at 250–630 Hz. In contrast, the research of Alayrac et al. [17] has indicated that with the same $L_{Aeq,}$ the higher the emergence of the 100 Hz tonal component of transformer noise, the lower the subjective annoyance.

In order to study subjective annoyance of low frequency noise with tonal components, a case study on transformer noise, which was selected because of its representativeness of such type of noise and broad impact on residents' annoyance, was conducted and noise annoyance was investigated through laboratory subjective evaluation based on binaural recordings of 220 kV and 500 kV transformer noises by using an 11-point numerical scale. The effects of different acoustical parameters on noise annoyance were examined, and appropriate prediction models were developed to efficiently differentiate noise annoyances caused by transformers of different voltage levels with the same L_{Aeq}.

2. Description of experiments

2.1. Recording

Two typical outdoor transformers were selected, one from a 220 kV substation and the other from a 500 kV substation. Since transformers of different voltage levels are standardized and the equipment models, capacities and cooling methods of the chosen transformers are most common among transformers of the corresponding voltage levels in China, the characteristics of noises radiated from these two transformers are representative. The Artificial Head Measurement System HMS IV.0 (Head Acoustics, 2008) was used in the process of sample collection, and a digital video recorder was used to record the scene in the substations. The ear height was 1.5 m above the ground. The noise recording was made at different distances away from transformer tank wall, and the recording line was parallel to the firewall. The recording distance of 220 kV transformer noise was 1 m, 2 m, 3 m, 4 m, 5 m, 10 m, 15 m, 20 m, 25 m and 30 m, respectively, while 500 kV transformer noise was recorded at additional distances of 35 m, 45 m, 55 m and 65 m because of its relatively larger sphere of influence. During the recording, the cooling fan of the transformer was normally working, and there was no other noise source in the surrounding.

2.2. Test stimuli

The recordings were analyzed by using the ArtemiS 10.0 software (Head Acoustics, 2008). It has been proved that transformer noise is a steady noise since the fluctuation of the A-weighted level of each original noise sample within the measurement time is less than 2.3 dBA. Thus, a noise sample with the duration of 5 s was extracted from the original sample, with minimum interference by ambient noise. The final test stimuli contained three groups, each consisted of 24 noise samples in random orders, 10 for 220 kV transformer noise and 14 for 500 kV transformer noise, each corresponding to a distance from the transformer tank wall.

Spectral analyses of 220 kV and 500 kV transformer noise samples, which were recorded at a distance of 2 m from the transformer tank wall, were illustrated in Fig. 1. It can be seen that the low frequency sound energy of the two samples is prominent. A further calculation according to Eq. (1) showed that the proportions of low frequency (31.5–250 Hz octave bands) sound energy of all 24 noise samples are above 80%. Moreover, under the masking

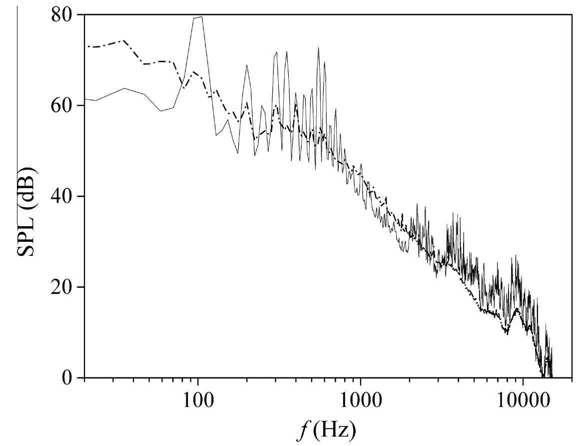

Fig. 1. Spectral analyses of transformer noises recorded at 2 m from the transformer tank wall. (———220 kV transformer noise, —·— 500 kV transformer noise.)

effect of the cooling fan noise, there are still a series of strong tonal components at 100 Hz and its harmonic frequencies in the 500 kV transformer noise, while the tonal components are much weaker in the 220 kV transformer noise due to the relatively lower sound pressure level (SPL) of its electromagnetic noise component.

$$\eta = \frac{10^{0.1L_{31.5}} + 10^{0.1L_{63}} + 10^{0.1L_{125}} + 10^{0.1L_{250}}}{10^{0.1L}} \tag{1}$$

in which η is the proportion of low frequency sound energy in the total sound energy of each noise sample (%); $L_{31.5}$, L_{63}, L_{125}, L_{250} are the SPLs of 31.5, 63, 125, 250 Hz octave bands (dB), respectively; and L is the total SPL (dB).

2.3. Apparatus and setting

The binaural audio playback system consists of four headphones (Sennheiser HD-600), a distribution amplifier (Head Acoustics HDA IV. 1) and a digital equalizer (Head Acoustics PEQ V), which has been calibrated at the calibration laboratory of the Head acoustics GmbH to make the difference of sound pressure level between nominal value and actual value lower than 0.05 dB. The experiment was performed in a soundproof room (4 m × 4 m × 3 m), where the background noise was lower than 25 dBA.

2.4. Procedure of subjective evaluation

A hearing test was performed by using an audiometer to test the hearing loss of each subject. 30 subjects were finally selected for subjective evaluation experiments, 15 males and 15 females, with a mean age of 24.1 ± 2.4. At most four subjects could receive noise exposure at the same time via headphones since the binaural audio playback system consisted of four sets of headphones. Before the experiments, subjects were asked to sit calmly on a chair, wear the headphone, and be ready for noise exposure. When the experiments began, a recorded video of the scenes in the substation was presented via a 40-inch television, and the following instruction was given before the arranged test stimuli, whose presentation orders were different for each subject group [24], was played back in their real SPLs.

> *"You will hear a series of transformer noises recorded from substations. Imagine you are in a substation and evaluate how much the noise annoys you."*