A study on the conversion relationship of noise perceived annoyance and psychoacoustic annoyance—a case of substation noise

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Abstract
The level of annoyance is an important basis to determine the acceptable degree of noise and develop noise standards. Psychoacoustic annoyance (PA) calculated by Zwicker’s model and perceived annoyance (such as mean annoyance, MA and the percentage of highly annoyed population, %HA) obtained through individual self-reports are widely used. PA and MA (or %HA) cannot be directly compared because the ranges of their values are different. Thus, the conversion relationship of PA and MA (or %HA) needs to be developed. As a case study, the model between PA and MA (or %HA) of substations noise was established and the rationality of model was verified. Results showed that the maximum value of the difference of MA (or %HA) between the calculation result of model and experimental result was less than 0.89 (or 15%). In this way, the perceived annoyance of substation noise samples can be determined by calculation without experiments.

Keywords
Perceived annoyance, psychoacoustic annoyance, mean annoyance, the percentage of highly annoyed population, conversion relationship, substation noise

Introduction
Including a series of negative emotions such as dissatisfaction, bother, and disturbance, annoyance is the direct perception of human body to noise.1,2 The level of annoyance is an important basis to determine the acceptable degree of noise and develop noise standards.3 Psychoacoustic annoyance (PA) calculated by Zwicker’s model4 and perceived annoyance obtained through individual self-reports are widely used. As the mainstream evaluation indices of noise annoyance obtained through listening experiments or socio-acoustics surveys,5 mean annoyance (MA) and the percentage of highly annoyed population (%HA) can characterize the level of perceived annoyance very well.

\[ MA = \frac{\sum_{i=0}^{10} (n_i \times i)}{\sum_{i=0}^{10} n_i} \]  

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\[ \%HA = \frac{10 \sum_{i=0}^{10} n_i}{\sum_{i=0}^{10} n_i} \]

where \( i \) (\( i = 0, 1, \ldots, 10 \)) is the \( i \)-th annoyance rating in the 11-point numerical scale; \( n_i \) is the number of subjects (or interviewees) choosing the \( i \)-th annoyance rating.

\( MA \) and \( \%HA \) can be obtained through listening experiments or socio-acoustics surveys in which the number of subjects (or interviewees) should meet statistical requirements and a large number of volunteers need to be recruited. In the process of experiments or surveys, the cost of manpower, equipment, and time is large. The method calculating \( MA \) or \( \%HA \) of noise by the prediction model can save the cost above. Previous studies have developed many prediction models of \( MA \) or \( \%HA \) for different types of traffic noise, industrial noise, community noise, etc., while these models used different acoustic parameters. Based on loudness (\( N \)), sharpness (\( S \)), fluctuation strength (\( F \)), and roughness (\( R \)), Zwicker\(^4\) established a psychoacoustic annoyance (\( PA \)) model suiting for different types of noise.\(^11,12\) However, Zwicker’s model did not consider the influence of tonality and to some extent underestimated the annoyance of tonal noise.\(^13\) Therefore, Di et al.\(^14\) improved Zwicker’s model through introducing tonality into \( PA \) model. Chen\(^12\) and Novakovič\(^15\) applied the improved Zwicker’s model to the annoyance evaluation of high-speed rail noise and vacuum cleaner noise, respectively, which indicated that \( PA \) calculated by improved Zwicker’s model had a high correlation with \( MA \) obtained through listening experiments.

\( PA \) and \( MA \) (or \( \%HA \)) cannot be directly compared because the ranges of their values are different. If the conversion relationships of \( PA \) and \( MA \) (or \( \%HA \)) of different types of noise are established, \( MA \) (or \( \%HA \)) will be quickly determined according to \( PA \) of noise. It can save the cost of listening experiments or socio-acoustics surveys and facilitate comparing the annoyance of different noises.

In order to study the conversion relationship of \( PA \) and \( MA \) (or \( \%HA \)), \( MA \) and \( \%HA \) of substation noise were obtained through listening experiments, and \( PA \) was calculated by the improved Zwicker’s model. The model between \( PA \) and \( MA \) (or \( \%HA \)) of substation noise was established through the logistic function,\(^16\) and the rationality of model was verified.

**Methods**

*Noise samples used in experiments*

Previous studies showed that low-frequency and tonal noise caused annoyance easily. Substation noise is a typical low-frequency and tonal noise.\(^17\) The spectrums of typical noise samples are shown in Figure 1. According to Figure 1, substation noise has an obvious peak value at the frequency of 100 Hz and its harmonic frequencies and the sound energy at the frequency of 100 Hz is dominant.

In the substations of 500 kV, 750 kV, and 1000 kV, the sizes of single phase of the main transformer are 11 m (L) × 11 m (W) × 5 m (H), 13 m (L) × 13 m (W) × 6 m (H), and 19 m (L) × 19 m (W) × 8 m (H), respectively. As shown in Figure 2, noise sampling points were located at two sampling lines perpendicular to the main transformer. The distances between sampling point and transformer were 0.5 m, 1 m, 1.5 m, 2 m, 2.5 m, 3 m, 3.5 m, 4 m, 4.5 m, 5 m, 6 m, 7 m, 8 m, 9 m, 10 m, 15 m, 25 m, 30 m, 40 m, 50 m, 60 m, 70 m, 80 m, 90 m, 100 m, 120 m, 140 m, 160 m, 180 m, and 200 m, respectively. If the difference between the noise level at a certain sampling point and background noise level was less than 0.5 dB(A), noise of sampling points at further distance would not be sampled. It means that the noise at the farthest sampling point from transformer was close to background noise. During the sampling, the transformer was in normal operation and the weather was clear and windless.

![Figure 1](image1.png)

*Figure 1.* The spectrums of noise samples in the substations of 500 kV, 750 kV, and 1000 kV.
48, 50, and 47 noise samples in 500 kV, 750 kV, and 1000 kV substations were recorded by Artificial Head HMS IV.1 (Head Acoustics, Germany), respectively. A-weighted sound pressure levels of all noise samples were between 40 dB(A) and 80 dB(A). Hardly being disturbed by other noises, each sample with the duration of 5 s was extracted from original sample by ArtemiS 10.0 software.

These noise samples were divided into two groups (see Table 1). Noise samples in group I were used to establish PA–MA and PA–%HA models, and noise samples in group II were used to verify models. 45 noise samples for model verification came from 500 kV, 750 kV, and 1000 kV substations, and the distances of these sampling points away from the transformer were different. A-weighted sound pressure levels of these noise samples were between 45 dB(A) and 80 dB(A). All noise samples were sorted randomly for 3 times, and an interval of 7 s (5 s evaluation time +1 s warning tone of starting +1 s mute) was inserted between two adjacent noise samples, which formed a sequence of noise samples used in listening experiments.

**The calculation of noise psychoacoustics annoyance**

The Zwicker’s model improved by Di² (see equations (3)–(6)) was used to calculate PA of each noise sample

\[
PA = N_S \cdot \left(1 + \sqrt{w_S^2 + w_{FR}^2 + w_T^2}\right)
\]

\[
w_S = \begin{cases} 
  (S - 1.75) \cdot 0.25 \lg(N_S + 10) & S > 1.75 \text{ acum} \\
  0 & S \leq 1.75 \text{ acum}
\end{cases}
\]

\[
w_{FR} = \frac{2.18 \cdot (0.4F + 0.6R)}{N_S^{0.4}}
\]

\[
w_T = \frac{6.41 \cdot T}{N_S^{0.52}}
\]

where \(N_S\) is the percentile value of loudness, that is, the five percent exceedance level of loudness (in sone), \(S\) is the sharpness (in acum), \(F\) is the fluctuation strength (in vacil), \(R\) is the roughness (in asper), and \(T\) is the tonality (in tu).
Experimental site and equipment

Experiments were conducted in a soundproof room (3 m (L) × 2 m (W) × 3 m (H)) where the background noise was smaller than 25 dBA. The audio playback system used in experiments consists of a computer with ArtemiS 10.0 software, a digital equalizer (Head Acoustics PEQ V), a distribution amplifier (Head Acoustics HDA IV.1), and four high quality headphones (Sennheiser HD 600).

Experimental procedures

290 college students aged 20 to 25 (137 males and 153 females) with normal hearing were randomly recruited as the experimental subjects. Before experiments, subjects listened to experimental instructions. After calming down, subjects accepted noise exposure through headphones after a short rest. In the 11-point numerical scale specified by ISO 15666-2003, 0 represented not annoyed at all and 10 represented extremely annoyed. After each noise sample was played, subjects chose a number to evaluate the annoyance rating of noise.

Statistical analysis

In the evaluation data of noise annoyance, misjudgment data from subjects should be eliminated through testing. In this study, if the difference between any two evaluation values of the same sample is more than 2, three evaluation values of the same sample will be regarded as invalid data and be eliminated. MA and %HA of each noise sample were, respectively, calculated according to equations (1) and (2).

Theoretically, MA increases with the increase of PA. The range of MA is from 0 to 10. MA takes 0 when PA is less than a certain value, and MA takes 10 when PA is greater than another certain value. Thus, the conversion relationship of PA and MA is consistent with the logistic function. In this study, PA–MA models for substation noise were established through the logistic function shown in equation (7). Similarly, PA–%HA models were established through the logistic function shown in equation (8)

\[ MA = \frac{10}{1 + e^{-a(PA-b)}} \]  
\[ %HA = \frac{1}{1 + e^{-k(PA-m)}} \]

where PA is the psychoacoustic annoyance of a noise sample and a, b, k, and m are undetermined constants.

Figure 3. The fitted curve of PA–MA model.
Results and discussions

PA–MA and PA–%HA model for substation noise

PAIs and MAIs (or %HAs) of 100 substation noise samples used to establish models of PA–MA (or PA–%HA) are shown in Figure 3 (or Figure 4). According to the logistic function shown in equation (7), three models of PA–MA suiting for substation noise of different voltage levels (500 kV, 750 kV, and 1000 kV), Model 1 (see equation (9)), Model 2 (see equation (10)), and Model 3 (see equation (11)), and one model of PA–MA without distinguishing the voltage level of substations, Model 4 (see equation (12)), were established (see Figure 3). The coefficients of determination ($R^2$) of models of PA–MA were 0.97, 0.98, 0.95, and 0.96, respectively. Results above showed that four models of PA–MA all could well characterize the relationship between PA and MA whether or not the voltage level of substations was distinguished.

According to the logistic function shown in equation (8), three models of PA–%HA suiting for substation noise of different voltage levels (500 kV, 750 kV, and 1000 kV), Model 5 (see equation (13)), Model 6 (see equation (14)), and Model 7 (see equation (15)), and one model of PA–%HA without distinguishing the voltage level of substations, Model 8 (see equation (16)), were established (see Figure 4). The coefficients of determination ($R^2$) of models of PA–%HA were 0.94, 0.99, 0.93, and 0.96, respectively. Results above showed that four models of PA–%HA all could well characterize the relationship between PA and %HA whether or not the voltage level of substations was distinguished.

\[
MA_{500} = \frac{10}{1 + e^{-0.073(PA_{500}-20.910)}} \tag{9}
\]

\[
MA_{750} = \frac{10}{1 + e^{-0.086(PA_{750}-20.622)}} \tag{10}
\]

\[
MA_{1000} = \frac{10}{1 + e^{-0.073(PA_{1000}-20.798)}} \tag{11}
\]

\[
MA_{500-1000} = \frac{10}{1 + e^{-0.075(PA_{500-1000}-20.722)}} \tag{12}
\]

\[
%HA_{500} = \frac{1}{1 + e^{-0.112(PA_{500}-40.783)}} \tag{13}
\]

\[
%HA_{750} = \frac{1}{1 + e^{-0.196(PA_{750}-38.284)}} \tag{14}
\]

\[
%HA_{1000} = \frac{1}{1 + e^{-0.134(PA_{1000}-40.071)}} \tag{15}
\]
HA_{500}/C0 = 1000/

\begin{equation}
\frac{1}{1 + e^{-0.136/PA_{500-1000}-40.310}}
\end{equation}

where \( MA_{500}, MA_{750}, MA_{1000}, \) and \( MA_{500-1000} \) are the mean annoyance of noise samples from 500 kV, 750 kV, 1000 kV, and 500kV–1000 kV substations, respectively. \( PA_{500}, PA_{750}, PA_{1000}, \) and \( PA_{500-1000} \) are the psychoacoustic annoyance of noise samples from 500 kV, 750 kV, 1000 kV, and 500kV–1000 kV substations, respectively. \( %HA_{500}, %HA_{750}, %HA_{1000}, \) and \( %HA_{500-1000} \) are the percentage of highly annoyed population of noise samples from 500 kV, 750 kV, 1000 kV, and 500kV–1000 kV substations, respectively.

The verification of PA–MA and PA–%HA model

The rationality of models of PA–MA (or PA–%HA) was verified by 45 noise samples which were different from noise samples used to establish these models. The experimental results of 45 noise samples were shown in Figures 5 and 6.

For the \( j \)-th (\( j = 1, 2, \ldots, N \)) noise sample used to verify a PA–MA (PA–%HA) model, \( |\Delta Y| \) of the \( j \)-th noise sample was calculated according to equation (17). \( |\Delta Y| \) was the absolute value of the difference of \( MA \) (or \%\( HA \)) between the calculation result of model \( (Y_{c,j}) \) and experimental result \( (Y_{e,j}) \) of the \( j \)-th noise sample. The maximum value of \( |\Delta Y| \) (\( j = 1, 2, \ldots, N \)) was denoted by \( |\Delta Y|_{\text{max}} \). For each PA–MA (PA–%HA) model, the arithmetic mean value \( (\overline{|\Delta Y|}) \) and the standard deviation \( (S_{|\Delta Y|}) \) of \( |\Delta Y| \) (\( j = 1, 2, \ldots, N \)) were calculated according to equations (18) and (19), respectively. The results of model verification are shown in Table 2.
\[ S_{\Delta Y} = \sqrt{\frac{1}{N} \sum_{j=1}^{N} \left( \frac{|\Delta Y|_j - |\Delta Y|}{|\Delta Y|} \right)^2} \]  

where \( Y_{c,j} \) is \( MA \) (or \( \%HA \)) of the \( j \)-th noise sample calculated by the \( PA-MA \) (or \( PA-%HA \)) model, \( Y_{e,j} \) is \( MA \) (or \( \%HA \)) of the \( j \)-th noise sample obtained through listening experiments, and \( N \) is the number of noise samples used to verify a \( PA-MA \) model.

As shown in Table 2, \( |\Delta Y|_{\max} \) of \( PA-MA \) models suiting for noise of 500 kV, 750 kV, and 1000 kV substations were 0.61, 0.89, and 0.88, respectively. When the voltage level of substations was not distinguished, \( |\Delta Y|_{\max} \) of the \( PA-MA \) model would be 0.85. Results above showed that \( |\Delta Y|_{\max} \) of each model was less than 1, the interval of adjacent annoyance rating of the 11-point numerical scale used in listening experiments. From the perspective of convenient application, the \( PA-MA \) model without distinguishing the voltage level of substations, that is, Model 4 (see equation (12)), can be directly used to determine \( MA \) of substation noise.

**Table 2. Results of model verification.**

| Model | Voltage level of substations (kV) | Evaluation index | \(|\Delta Y|_{\max}\) | \(|\Delta Y|\) | \(S_{\Delta Y}\) |
|-------|----------------------------------|------------------|-----------------|-------------|-------------|
| Model 1 | 500 | MA | 0.61 | 0.18 | 0.22 |
| Model 2 | 750 | MA | 0.89 | 0.21 | 0.31 |
| Model 3 | 1000 | MA | 0.88 | 0.24 | 0.32 |
| Model 4 | 500–1000 | MA | 0.85 | 0.26 | 0.21 |
| Model 5 | 500 | \%HA | 12.22% | 4.92% | 0.04 |
| Model 6 | 750 | \%HA | 14.01% | 6.22% | 0.03 |
| Model 7 | 1000 | \%HA | 13.50% | 5.75% | 0.04 |
| Model 8 | 500–1000 | \%HA | 14.44% | 4.80% | 0.04 |
When the voltage level of substations was distinguished, $\Delta Y_{\text{max}}$ of $P\text{A}-%HA$ models for noise of 500 kV, 750 kV, and 1000 kV substations would be 12.22%, 14.01%, and 13.50%, respectively. When the voltage level of substations was not distinguished, $\Delta Y_{\text{max}}$ of the $P\text{A}-%HA$ model would be 14.44%. Results above showed that $\Delta Y_{\text{max}}$ of all $P\text{A}-%HA$ models were less than 15%. In view of the convenience of application, the $P\text{A}-%HA$ model without distinguishing the voltage level of substations, that is, Model 8 (see equation (16)), can be directly used to determine $%HA$ of substation noise.

**Conclusions**

As a case study, the model between perceived annoyance (mean annoyance, $MA$ and the percentage of highly annoyed population, $%HA$) and psychoacoustic annoyance ($P\text{A}$) of substation noise was established and the rationality of model was verified. Results showed that the maximum value of the difference of $MA$ (or $%HA$) between the calculation result of model and experimental result was less than 0.89 (or 15%), and the mean value of the difference was less than 0.26 (or 7%). In view of the convenience of application, $P\text{A}–MA$ and $P\text{A}–%HA$ models without distinguishing the voltage level of substations can be directly used. In this way, the perceived annoyance of substation noise samples can be determined by model calculation, which can save the cost of listening experiments or socio-acoustics surveys. The results of this study can provide a basis for determining substation noise acceptability and developing substation noise standards.

$P\text{A}–MA$ and $P\text{A}–%HA$ models developed by this study are only suitable for substation noise. $P\text{A}–MA$ and $P\text{A}–%HA$ models for other types of noise can be developed through the method proposed by this study.

**Declaration of conflicting interests**

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