Coherence Analysis and Tests of Vibration and Noise Caused by Indoor Substation

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Abstract. Structural vibration and noise of indoor substation is getting more and more extensive attention. The 110kV urban indoor substation and its associated building are taken as the research object. The vibration and noise signal of testing points are acquired in the building and transformer room. Time domain analysis and frequency analysis for the test data are carried out. By test and analysis, vibration and noise characteristics are obtained. The transformer vibration and its noise were transmitted with obvious attenuation in the structural floor slab. The vibration transmission into the lower floor slab is higher than that of into the higher one. If the floor is far from the transformer room, the vibration and noise and the low frequency characteristic are weak and thus the attenuation is no longer significant. It is necessary that indoor substation equipment of vibration and noise transmission can be controlled.

1. Introduction
The substations play a key role in the electric power transmission process in China. In recent years, with the rapid development of urban construction and the increasing social power consumption, many urban indoor substations have been gradually installed in the densely populated areas and more and more urban substations have been established in cities and towns. Because the urban substations have been built adjacent to residential areas or with office buildings seamlessly, the influence of vibration and noise of the urban substations upon residents has become more and more socially concerned. The urban indoor substation of 110kV, 220kV and even higher voltage classes have been numerously established in cities such as Beijing, Shanghai and Xi’an etc. across China, which has caused out of limits in environmental impact assessment on vibration and noise of some substations[1][2]. The channels of noise transmission by air in the associated equipment of underground or urban indoor substations can be effectively cut off through setting up materials with good isolation performance and sound absorption performance as well as walls or barriers [3-5]. However, as the urban substations tend to be established adjacent to or seamlessly with nearby buildings, the structural vibration and solid-state noise caused by the substation equipment cannot be neglected besides the noise transmission in air. In addition, the vibration and noise of transformer substations are featured by low frequency and uninterrupted operation, which has caused the researches on the structural vibration and solid-state noise of the substations to receive more and more wide attention from scientific and technical personnel at home and abroad[6][7].
2. Tests of Vibration and Noise

2.1. Condition of the substation
The urban indoor substation of 110kV be designed and installed with 3 sets of main transformers with unit capacity of 50MVA. It was seamlessly built with the office building. The mixed structure of steel-concrete frame was adopted as the building structure. The underground part had two floors. The basement floor 1 (BF1) included the cable inter-layers. The basement floor 2 (BF2) included a ventilator room, an electric reactor room, a capacitor room, and a warehouse etc. The over-ground floor 1 included 3 main transformer rooms (skip-floor F1-F3) and a switch gear room; the over-ground floor 2 and 3 included GIS rooms mainly. The over-ground part of the building included 8 floors (F4-F8) of office area with floor height of 4.0m and total building height of 32m. Figure 1 shows the layout plan of the first floor. Figure 2 shows the layout plan of the fourth to eighth floor (F4-F8).

Fig. 1 Test Points in First Floor              Fig. 2 Test Points in Fourth to Eighth Floor

2.2. Arrangement of Test Points
In order to obtain the characteristics of the frequency spectrum in main functional areas, such as the transformer room and office room, the following test contents were conducted according to the structural layout of the urban indoor substation and conjoined buildings.

2.2.1. Vibration and Noise Test of Transformer Room .The main vibration and noise source within the substation came from 1#, 2# and 3# main transformer rooms located in the first floor. The test points of vibration and noise were arranged in transformer oil tank wall surface, transformer foundation, ground surface and wall. The vibration and noise level in the main transformer room was tested. Two cross sections were set around the transformer in each main transformer room and then tested. Figure 1 shows the layout plan of test points in the main transformer room, in which▲represents the test points of vibration and noise of simultaneous acquisition in floor slab; and●represents the test points of oil tank wall and wall vibration.

2.2.2. Coherence Test of Vibration and Noise in Each Floor .The test points of vibration and noise were set up in each floor so as to control the vibration and noise characteristics of floor slab in the building structure. The key task was to analyse the coherence test of transformer vibration response so as to further obtain the vibration transmission routes and attenuation rules of the building structure. In addition, for locations such as corridor, passageway, and equipment room, the test points of vibration and noise were selectively set up on the floor slab and wall to test the vibration and noise level and analyse the frequency spectrum characteristics. Figure 2 shows the layout plan of test points in the office room, in which▲represents the test points of vibration and noise of simultaneous acquisition in floor slab; and●represents the test points of oil tank wall and wall vibration.
3. Analysis on Test Results

3.1. Vibration Characteristics in Transformer Room

This paper only analyses the data of different test points in 1# and 3# main transformer rooms. Figure 3 shows the layout map of test points in 1# main transformer room. The vibration acceleration and indoor noise were collected from the transformer oil tank, foundation, indoor floor slab and wall. The basic characteristics of indoor vibration and noise of transformer room could be obtained through the time-domain analysis of signals and Fourier spectrum analysis. Figure 4 and Figure 5 show the time-domain and spectrogram of test points from vibration transmission lines about 1# and # 3 main transformers respectively.

![Test Points of 1# Main Transformer](image1)

![Amplitude and Spectrogram in 1# Transformer](image2)

![Amplitude and Spectrogram in 3# Transformer](image3)

The analysis of the above Figure 4 and Figure 5 shows that there are regular attenuation on vibration amplitude in vibration transmission paths of the main transformer, including the decrease of vibration frequency amplitude and decrease of frequency spectrum composition. The main transformer body has the largest vibration amplitude and the 1# and 3# main transformers have relatively close vibration amplitudes. The vibration amplitude in floor slab of the main transformer room is slightly reduced. It can be seen from the spectrum of vibration signals that the two spectrum ranges are the closest. The vibration amplitude in the lower B1 floor slab of the main transformer is significantly higher than that of in the upper floor of the main transformer. This shows that the upwards-transmitted energy attenuation of the vibration is relatively higher.
Table 1. Vibration Amplitude and Z Vibration Level of Test Points in 1# and 3# Main Transformers

| NO. of Test Point | Effective Value (m/s²) | Vibration Level (dB) | 100Hz Z Vibration Level (dB) | Test Point Position |
|-------------------|------------------------|----------------------|-----------------------------|--------------------|
| F1V60             | 0.084                  | 98.82                | 64.26                       | 1# main transformer body (vertical ground) |
| F1V61             | 0.054                  | 94.59                | 73.32                       | Floor slab in 1# main transformer          |
| B1V10             | 0.019                  | 85.76                | 64.13                       | B1 floor slab in 1# main transformer       |
| F4V9              | 0.032                  | 70.21                | 46.22                       | Floor slab right above 1# main transformer |
| F1V1              | 0.050                  | 94.01                | 54.13                       | 3# main transformer body (vertical ground) |
| F1V3              | 0.036                  | 91.31                | 58.4                        | Ground surface in 3# main transformer      |
| B1V5              | 0.014                  | 83.25                | 61.45                       | B1 floor slab in 3# main transformer       |
| F4V4              | 0.003                  | 71.27                | 48.18                       | Floor slab right above 3# main transformer |

Table 1 shows the vibration acceleration amplitude and Z vibration level in the test points of 1# main transformers. In order to represent the vibration level [8][9], the vertical Z-vibration level is defined as follows:

\[
La = 20 \log_{10} \frac{a}{a_0} \quad (dB)
\]  

In which, \(a\) - Effective value of accelerated speed (root mean square value), \(a_0\) - Take 10-6m/s² as reference value. It can also be obtained that the vibration amplitude in transformer body is the largest in the main transformer room. The ground vibration amplitude in the adjacent floors decreases and the influence of vibration transmitted to the lower floor slab is higher than that of the upper floor slab.

### 3.2. Noise Characteristics in Transformer Room and Coherence Analysis

The coherent analysis can determine how much of the output response comes from input disturbance; in this way, the degree of correlation can be analysed between vibration and noise of urban indoor substation and floor slab vibration in building structure. Adopt the coherent function to describe the degree of correlation between the two signals at each frequency. The coherence function of the two stationary random vibration processes \(X(t)\) and \(Y(t)\) is defined as:

\[
\gamma_{XY}(\omega) = \frac{|G_{XY}(\omega)|^2}{G_X(\omega)G_Y(\omega)}
\]  

In which, \(G_X(\omega)\) and \(G_Y(\omega)\) refer to the auto-power spectrum and \(G_{XY}(\omega)\) refers to the cross-power spectrum. The coherence function can determine how much of the output signal \(Y(t)\) comes from the input signal \(X(t)\).

Similar to the vibration test, select several key test points from the 1# and 3# main transformers to conduct noise coherence analysis. Figure 6 and Figure 7 show the cross spectrum diagram and coherence function of the noise signals in the 1# main transformer room and the noise signal between adjacent rooms respectively. Figure 8 and Figure 9 show the cross spectrum diagram and coherence function of the noise signals in the 3# main transformer room and the noise signals between adjacent rooms respectively.
Table 2. Sound Pressure Value at Test Points about 1# and 3# Main Transformers

| NO. of Test Point | Effective Value (m/s²) | Value of Total Sound Pressure Level (dBA) | Test Point Position                          |
|-------------------|------------------------|------------------------------------------|----------------------------------------------|
| N4                | 0.0208                 | 60.37                                    | 1# main transformer room                     |
| N6                | 0.0248                 | 61.88                                    | Underground cable interlayer in 1# main transformer |
| N5                | 0.017                  | 58.59                                    | 1# main transformer room to the higher second floor |
| N1                | 0.0582                 | 69.28                                    | Ground surface in 3# main transformer        |
| N3                | 0.0462                 | 67.28                                    | Underground cable interlayer in 3# main transformer |
| N2                | 0.0485                 | 67.69                                    | Upper floor slab in 3# main transformer       |

For the vibration noise of the main transformer on the transmission paths, the coherence coefficient between noise signals in the main transformer room and those of in the adjacent room is larger and between 0.83 and 0.97, which indicates a transmission and causal relationship between the signals. However, the vibration noise of the 1# main transformer room and cable interlayer of basement floor
is less coherent, and the vibration noise of the basement floor is slightly greater than that of in the 1# main transformer room. The reason may be that the cable interlayer space is small and there is reverberation effect and the vibration noise of the 2# main transformer is large, which affects the vibration noise of the cable interlayer of the 1# main transformer. The vibration noise of the main transformer room to upper floor (F2) has obvious attenuation compared with the vibration noise of the main transformer room. This is consistent with the transmission characteristics of the noise, and the coherence coefficient between the two signals is high at 0.97, which indicates that there is a causal relationship in the transmission between the two signals.

4. Conclusion
Base on testing and analysing the vibration and noise in the urban indoor substation, there are regular attenuation on vibration amplitude in vibration transmission paths of the main transformer. It includes the decrease of vibration frequency amplitude and decrease of frequency spectrum composition. Frequency focuses from 100Hz to 500Hz. The vibration amplitude in the lower B1 floor slab of the main transformer is significantly higher than that of in the upper floor of the main transformer. This shows that the upwards-transmitted energy attenuation of the vibration is relatively higher. Through analysing the coherence test data of main transformer noise, the coherence coefficient between the two signals is larger and between 0.83-0.97, which indicates that there is a transmission and causal relations between signals. However, the noise signals do not fully conform to the attenuation rules because of factors such as room opening area, room structure, and other noise sources.

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