Optimal Design and Test Study on Sound Insulation Property of Exterior Wall Enclosure of Prefabricated Substation

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Abstract. In this paper, based on the fabricated wall panel used in original modular indoor substation, the optimal design of sound insulation property is conducted according to the relevant theoretical basis of sound insulation properties of wall panels, and the reverberation room method is used to test and study original and new wall panels. The study shows that the sound insulation of the sandwich panel after optimization has been greatly improved in both medium, low and high frequency areas, with obvious optimal design effect, and also there are significant engineering application value and social benefits in the noise control of substation.

1. Introduction
Substation plays a key pivotal role in the process of power transmission in China[1]. In recent years, with the rapid development of urban construction and the constant rise of social power consumption, many substations gradually penetrate into densely populated areas, and there are more and more substations in urban areas. The impact of substation noise on surrounding residents has been widely concerned by the society[2]. Transformer noise is the main source of indoor substation noise. The noise frequency range is mainly medium-low frequency and also a little high-frequency noise[3-5]. Substation noise control methods mainly include sound insulation, sound absorption, vibration isolation, etc.[6] In terms of indoor substation construction, modular construction of substation has become the mainstream of substation design in China. With unified design depth and construction standards, construction efficiency is improved and construction cost is reduced. However, the enclosure of modular fabricated indoor substation is mainly composed of aluminum-magnesium-manganese sandwich panel and other lightweight walls, so the control ability of power equipment noise is limited. Due to the lack of noise control scheme matching with the modular construction of indoor substation, the noise reduction reconstruction project can only be carried out for a substation in urgent need of noise control, thus greatly increasing the construction cost. Therefore, it is of significant engineering application value and social benefit to design a modular wall structure of high sound insulation for indoor substations, control the noise radiation of equipment in the substation, develop a modular wall structure of high sound insulation at a lower cost and with significant noise reduction effect compared with noise reduction transformation, and adapt the noise control scheme with modular construction to form a unified customized engineering solution.

In this paper, based on the fabricated wall panel used in original modular indoor substation, the optimal design of sound insulation property is carried out according to the relevant theoretical basis of
sound insulation properties of wall panels, and the reverberation room method is used to test and study original and new wall panels, so as to compare and analyze their sound insulation property. Finally, a kind of prefabricated wall panel with optimized sound insulation properties for substations is proposed.

2. Theoretical basis

2.1. Sound insulation mass law

In terms of a single-layer uniform wall, if the boundary conditions are not taken into account, that is, it is assumed that the wall panel is infinite, and the wall panel is considered to be a compliant mass without stiffness and damping, we can theoretically get the formula of sound insulation of the wall panel when the sound wave is vertically incident.

\[
R = 20 \log m + 20 \log f - 43
\]  

(1)

Where, \( R \), \( m \) and \( f \) are the sound insulation of the wall panel (in dB), density of the wall panel (in kg/m\(^2\)) and frequency of the incident acoustic wave (in Hz) respectively. If the incident acoustic wave direction is irregular, the above sound insulation formula can be modified as follows,

\[
R = 20 \log m + 20 \log f - 48
\]  

(2)

According to Formulas (1) and (2), the sound insulation of the wall panel increases with the increase of the density of the wall panel and the frequency of incident acoustic wave. The sound insulation of the wall panel increases by 6dB if the density of the wall panel or the frequency of incident acoustic wave is doubled. The greater the density of the wall panel is, the greater the sound insulation is. This is the mass law. As the formula is obtained under assumed conditions, actually, the increase of sound insulation of wall panel is no more than 6dB when the density of the wall panel or the frequency of incident acoustic wave is doubled. According to the study of a large number of sound insulation tests, the sound insulation of wall panel increases by 5.4dB when the density of wall panel is doubled and 3.6dB when the frequency of incident acoustic wave is doubled.

2.2. Features of frequency of sound insulation

According to the mass law, the sound insulation increases with the increase of the frequency of incident acoustic wave under conditions for certain density of single-layer uniformity walls. But in practice, the relation between the sound insulation of wall panels and the frequency of incident acoustic wave is affected by resonance and coincidence effects, as shown in figure 1. The features of frequency of sound insulation of the single-layer uniformity wall is related to density, stiffness and damping of the wall panel.

![Figure 1. Features of frequency of sound insulation of the single-layer uniformity wall](image-url)
3. Design of a composite sandwich panel with optimized sound insulation

3.1. Structure of a sandwich panel before optimization
At present, the building enclosure of modular substations is mostly made of sandwich panels, and its cross-section is shown in figure 2.

![Figure 2: Schematic diagram of the cross-section of a sandwich panel before optimization](image)

The applicable materials and dimensions of all parts of the sandwich panel before optimization are shown in table 1.

| S/N | Name                  | Material                                      | Dimensions (thickness, mm) |
|-----|-----------------------|-----------------------------------------------|----------------------------|
| 1   | Upper panel           | Aluminum-magnesium-manganese panel            | 0.8                        |
| 2   | Lower panel           | Aluminum-zinc coated steel sheet              | 0.6                        |
| 3   | Sandwich layer        | Rock wool (unit weight, 120kg/m³)             | 100                        |
| 4   | Polyurethane edging   | Polyurethane                                  | -                          |

Before optimization, the structure of the metal sandwich panel is as follows: the upper panel is an aluminum-magnesium-manganese panel, the lower panel is an aluminum-zinc coated steel sheet, and the middle sandwich layer is a rock wool strip. The upper and lower panels are adhered with the sandwich layer by an adhesive and two sides of edging of sandwich panel are filled by polyurethane. The current technical plan for lightweight sandwich panel can meet the requirements of modular construction of substations. The installation is convenient and quick, but the capacity of controlling noise of substation equipment is limited, thus making it difficult to meet the requirements of the sound insulation property of enclosure for substation.

3.2. Optimal design of sound insulation of sandwich panels
We have carried out optimal design of sound insulation for current metal sandwich panels in use. First, the sandwich layer is improved, and it is transformed into the 1 + 2 structure of sandwich layers. Where, the sandwich layer 1 is made of the fiber cement board with thickness of 10mm, which can significantly strengthen the stiffness and density of the sandwich layer, thereby greatly enhancing the sound insulation property of the sandwich panel wall structure. In addition, the fiber cement board is with excellent fire-proof insulation and humidity resistance, and is not easily deformed and warped, so it is very applicable to the enclosure of substation. The sandwich layer 2 is made of rock wool strip with thickness of 90mm. As a porous sound absorption material, the rock wool is used as the sandwich layer to play the roles of elastic medium and damper, so as to reduce vibration, thus further improving sound insulation property. Then, the upper and lower panels are made of aluminum-zinc coated steel sheet with thickness of 0.8mm, so as to enhance the stiffness of the metal surface, thus improving the sound insulation property of the sandwich panel and facilitating uneasy deformation during gluing adhesion with the sandwich layer made of fiber cement board and rock wool. Finally, the sandwich panel is adhered with the sandwich layers 1 and 2 by adhesive, and the two sides of the sandwich panel are subject to polyurethane edging, and its section is shown in figure 3.
1 - Upper panel, 2 - Lower panel, 3 - Sandwich layer 1, 4 - Sandwich layer 2, 5 - Polyurethane edging

Figure 3. Schematic diagram for section of a sandwich panel with optimal sound insulation

The applicable materials and dimensions of all parts of the sandwich panel with optimal sound insulation are shown in table 2.

Table 2. Applicable materials and dimensions of all parts of the sandwich panel with optimal sound insulation

| S/N | Name               | Material                        | Dimensions (thickness, mm) |
|-----|--------------------|---------------------------------|-----------------------------|
| 1   | Upper panel        | Aluminum-zinc coated steel sheet| 0.8                         |
| 2   | Lower panel        | Aluminum-zinc coated steel sheet| 0.8                         |
| 3   | Sandwich layer 1   | Fiber cement board              | 10                          |
| 4   | Sandwich layer 2   | Rock wool (unit weight, 120kg/m³)| 90                          |
| 5   | Polyurethane edging| Polyurethane                    | -                           |

For this type of multi-layer composite sandwich panel structure with fiber cement board and rock wool, its upper and lower panels are made of the thickened aluminum-zinc coated steel sheets with high stiffness, and the sandwich layer is in the combination form of fiber cement board and rock wool. This type of sandwich layer is used to improve the density and the sound insulation property and enhance the overall stiffness of the sandwich panel structure. The above-mentioned designs not only ensure that the overall structure of the multi-layer composite sandwich panel is with sufficient mechanical strength, stability and safety, but also optimize its sound insulation properties. Next, we will further test and analyze the sound insulation properties of such sandwich panel with optimal sound insulation by conducting tests.

4. Test methods and results

4.1. Test methods
In this document, the reverberation room measurement method is used for measurement of sound insulation properties of elements, that is, the test is performed according to the relevant provisions of GB/T 19889.3-2005/ISO 140-3:1995 National Standard of PRC - Acoustics - Measurement of Sound Insulation in Buildings and of Building Elements - Part 3: Laboratory Measurements of Airborne Sound Insulation of Building Elements.

Figure 4. Schematic diagram of reverberation room measurement method
The laboratory applying reverberation room measurement method is composed of two adjacent reverberation rooms (which shall be in the volume of no less than 50m³ respectively, and consist of a sound source room and a receiving room) and a control room. The part between such two reverberation rooms is gap filling wall, on which there are test holes for installation of test pieces, as shown in figure 4. According to the above-mentioned standard, the calculation formula of sound insulation is as follows,

$$ R = L_1 - L_2 + 10 \lg \frac{S}{A} $$

(3)

Where, $R$ refers to sound insulation (in dB); $L_1$ and $L_2$ respectively refer to the average sound pressure level in sound source room and receiving room (in dB); $S$ refers to the area of test pieces (in m²); $A$ refers to the sound absorption in receiving room (in m²).

4.2. Test results

Figure 5. Comparison of sound insulation characteristics curve between sandwich panels before optimization and sandwich panels with optimal sound insulation

Figure 5 shows the comparison of sound insulation characteristics curve between sandwich panels before optimization and sandwich panels with optimal sound insulation. The gray area shows the part of the sound insulation of the sandwich panel with optimal sound insulation in all frequency bands higher than that before optimization. According to the above figure, the sound insulation of the sandwich panel with optimal sound insulation in all frequency bands is better than that before optimization, where, the excessive sound insulation of the sandwich panel with optimal sound insulation at 1000Hz of its coincidence valley is the least. If 1000Hz is taken as the boundary, the average sound insulation of the sandwich panel with optimal sound insulation is 32.3dB in the medium-low frequency area of less than 1000Hz, which is 5.5dB higher than that before optimization. In the medium-high frequency area of more than 1000Hz, the average sound insulation of the sandwich panel with optimal sound insulation is 45.0dB, which is 12.7dB higher than that before optimization. Therefore, the sound insulation of the sandwich panel after optimization has been greatly improved in both medium, low and high frequency areas, with an obvious optimal design effect.

Table 3. Comparison of test results between sandwich panels before optimization and sandwich panels with optimal sound insulation

| S/N | Classification                          | Surface density (kg/m²) | Weighted sound insulation ($R_w$, dB) |
|-----|----------------------------------------|-------------------------|--------------------------------------|
| 1   | Sandwich panel before optimization     | 18.894                  | 31                                   |
| 2   | Sandwich panels with optimal sound insulation | 36.060                  | 39                                   |
In table 3, the test results are further compared, and it can be found that the density of the sandwich panel with optimal sound insulation is 36.060kg/m², which is 1.909 times that before optimization, and the weighted sound insulation reaches 39dB, which is 8dB higher than that before optimization, further proving a sound optimal design effect.

5. Summary
In this paper, based on the fabricated wall panel used in original modular indoor substation, the optimal design of sound insulation properties is performed according to the relevant theoretical basis of sound insulation properties of wall panels, and the reverberation room method is used to test and study original and new wall panels, so as to compare and analyze their sound insulation properties. According to the test results, the sound insulation of the sandwich panel with optimal sound insulation in all frequency bands is better than that before optimization, and the weighted sound insulation reaches 39dB, which is 8dB higher than that before optimization. The sound insulation of the sandwich panel after optimization has been greatly improved in both medium, low and high frequency areas, with obvious optimal design effects, and also there are significant engineering application value and social benefits in the noise control of substations.

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