Dynamic Characteristics of Transformer Housing under Rigid/ Flexible Foundation

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Abstract. This paper presented the dynamic characteristics of transformer housing under rigid/flexible foundation conditions based on finite element method. The deformation and stress distribution were analyzed due to interior excitations. The dynamic response for different stiffness coefficients was also investigated. Results show the maximum deformation of the housing occurs at the top of high pressure bushing with the value of 132.6 μm. And the maximum equivalent stress occurs at the junction between the steel bar and the supporting steel frame with the value of 18.5 MPa. The velocity, stress and deformation at the measuring point show a periodic response, besides the response frequency is consistent with the exciting force. Foundation stiffness has a great influence on the dynamic response of the transformer housing. The amplitude of equivalent stress decreases with the decreasing foundation stiffness, while the amplitude of deformation shows an opposite trend.

1. Introduction
Transformer is one of the key equipments in the power grid system. Its vibration and noise characteristics directly affect the safe operation of the transformer and the external environment. With the voltage level of substations is getting higher and higher by years, a large number of transformers will been put into use, these transformers will cause environmental vibration and electromagnetic noise in the normal power supply process, which will inevitably have adverse effects on the external environment. Vibration and noise has become an important index to examine transformer products. As one of the hot issues in the world, more and more attention has been paid to the vibration and noise of transformer [1-2].

The noise caused by transformer body vibration comes from the core and winding. The noise caused by the core is because that the silicon steel piece will be slightly changed in size under the action of alternating magnetic field. It is called magnetostrictive effect. The noise caused by the winding is induced by the electromagnetic force caused by the flow of current in the winding. In the transformer, the vibration produced by the core and winding is transmitted to the oil tank through the transformer oil and the parts such as the support and positioning of the device body, and the noise is radiated to the outside.
Song theoretically analyzed the vibration and transmission mechanism of power transformer, and simulated the coupling of circuit, magnetic field and solid mechanics of transformer winding vibration under the condition of load test by using finite element analysis. The results show that there is only 100 Hz component in the high frequency and frequency domain distribution of vibration signal under the condition of load test [3]. Taking the three-phase three-column power transformer as the research object, Wei and others studied the vibration characteristics, stress-strain and stress-strain of the core and winding under different load conditions by establishing the equivalent electric-magnetic-solid coupling model of the transformer. The results show that the vibration of transformer under zero-load or light load mainly lies in the vibration of the core, and the vibration of the core can even be regarded as the result of magnetostriction of the silicon steel piece. The contribution of winding vibration to transformer vibration should not be ignored when the transformer load is large [4]. Yao established the magnetic field-structure field coupling model of transformer by ANSYS finite element analysis software, and analyzed the relationship between the maximum stresses of accumulative effect and winding deformation of transformer inner and outer windings affected by short circuit impact [5].

The above references are focus on the internal vibration source, but there is few research on the dynamic characteristics of transformer housing under the action of internal load, especially considering the influence of support foundation stiffness on the dynamic characteristics of transformer housing. In this paper, the dynamic response of transformer housing under alternating load is studied based on finite element method. Considering the influence of support stiffness, the dynamic response characteristics of housing under different foundation stiffness are compared and analyzed.

2. Finite Element Modeling for Transformer Housing

Fig. 1 shows a three-dimensional model of a typical 10kV transformer. Its body is a housing tank with two sets of symmetrical heat dissipation fins around it, with a set of high and low voltage insulation joints on the top. The bottom is supported by steel structure, fixed by bolts and foundations.

![Figure 1. Three-dimensional model of transformer](image1)

![Figure 2. Finite element mesh model](image2)

2.1. Finite Element Model Mesh

Mesh partitioning is an important part of dynamic computing. The rationality of mesh quality and layout has a great influence on the accuracy and convergence rate of the calculation. The free partition method is used to mesh the computational model, and the mesh size is constrained at the same time. After the grid independence test, the grid size of the transformer is determined to be 0.01 m, and the number of grids is about 380000. Figure 2 shows the grid partition diagram of the finite element model of transformer.
2.2. Boundary condition setting

Fig. 3 shows the diagram of the boundary condition setting of the computational model. Fig. 3 (a), (b) shows the unsupported foundation model and the supported foundation model respectively. The unsupported foundation means that the foundation stiffness is infinite and only the effect of load on transformer housing is considered. The 100 Hz periodic vibration of the core caused by magnetostriction is the important share of the load on the transformer and the main cause of the transformer vibration. It is simplified here to simulate the periodic load acting on the bottom of the housing. As shown by load B in Fig.3, the amplitude and frequency of periodic load are 10 kN and 100 Hz respectively. In addition, the transformer housing is subjected to structural self-weight, where gravity loads are applied to the whole housing, as shown by load C in Fig.3.

![Figure 3. Boundary condition setting schematic](image)

(a) Unsupported  (b) Supported

2.3. Test points arrangement

The dynamic response of the deformation, stress and velocity of the transformer housing under the excitation force is monitored by setting the test points on the wall of the housing. The locations of the test points are shown in Fig.4. The test point 1 is located on the top of the heat dissipation fin on the side of the housing and the test point 2 is located at the center of the bottom of the housing.

![Figure 4. Test Point Arrangement](image)

(a) Test Point 1  (b) Test Point 2
2.4. Material Parameters Setting
The material of transformer housing is Q345, its elastic modulus is 206 GPa, Poisson's ratio is 0.28, density is 7850 kg/m$^3$, yield limit is 345 MPa, ultimate tensile strength is 475MPa.

3. Calculation result and analysis

3.1. Deformation dynamic response of transformer housing
Fig. 5 is a deformation cloud diagram of transformer housing at different times in an excitation period (T). At the initial moment, the maximum deformation occurs at the bottom of the housing under the action of gravity, as shown in Fig. 5 (a), the value is 16.5μm. At the moment of T/4, the excitation force and gravity in the same direction to aggravate the housing deformation. The maximum deformation also occurs at the bottom of the housing, as shown in Fig. 5 (b), the value is 66.2μm. At the moment of T/2, the maximum deformation point occurs on the top of the high-voltage insulating sleeve, as shown in Fig.5(c), the value is 132.6μm. The maximum deformation at the moment of 3T/4 also occurs on the top of the high-voltage insulating sleeve, as shown in Fig. 5 (d), the value is 113.8μm.

3.2. Stress response of transformer housing
Fig.6 shows the stress distribution of transformer housing at different moments in an excitation period (T). The maximum stress at the initial time is located at the junction of the bottom of the housing and the braced steel frame. As shown in Fig. 6 (a) and the value is 4.8MPa. At the moment of T/4, the maximum stress also appears at the junction of the housing bottom and the braced steel frame, as shown in Fig.6 (b), and the value is 18.5MPa. At the moment of T/2, the maximum value occurs on the top of the housing cover, as shown in Fig.6 (c), which is 4.7MPa. The maximum stress at the moment of 3T/4 occurs at the junction of the bottom of the housing and the braced steel frame, as shown in Fig.6(d), whose value is 17.2MPa.

Figure 5. Deformation cloud diagram of transformer housing at different times
3.3. Analysis of dynamic response of test points

Fig. 7 is a diagram of velocity, deformation and stress response at the test point 1 (side of the housing) and point 2 (bottom of the housing). It can be found that the parameters of two points show periodic dynamic response, and the frequency is consistent with the load frequency is 100Hz. The velocity amplitudes fluctuate around 0.028 m/s and 0.045m/s at the test point 1 and 2 respectively. The amplitude of vibration at the test point 1 fluctuates around 13μm, and the amplitude of deformation at the test point 2 fluctuates near 70μm. The amplitudes of stress response at the point 1 are all less than 1MPa. The amplitudes of stress at the point 2 fluctuate around 6MPa. The velocity, deformation and stress response amplitude of the test point 2 under the action of periodic load are larger than that of the test point 1.
3.4. Influence of flexible bracing Foundation on dynamic response

Figure 7. The velocity, deformation and stress response on test point 1 and 2

Figure 8. Equivalent stress and global deformation distribution cloud map (Young's modulus E is 0.206 GPa)
Fig. 8 shows the cloud diagram of the equivalent stress and total deformation distribution of the transformer housing when the Young's modulus E of the supporting foundation is 0.206 GPa and the total deformation distribution of the transformer housing at the moment of T/4. At the same time, under the action of gravity and co-directional excitation force, the value of housing deformation and equivalent force reaches the peak point, and the maximum equivalent stress appears at the joint of housing bottom vertical reinforcement and braced steel frame. See Fig.8 (a), and its value is 11.7MPa. The maximum total deformation occurs at the bottom of the housing, as shown in Fig.8 (b), and its value is 114.9μm.

![Figure 8](image1.png)
(a) Equivalent stress distribution  
(b) Global deformation distribution

**Figure 9.** Equivalent stress and global deformation distribution cloud map (Young's modulus E is 2.06 GPa)

Fig.9 shows the cloud diagram of the equivalent stress and total deformation distribution of the transformer housing at the moment of T/4 when the Young's modulus e of the supporting foundation is 2.06GPa. The maximum equivalent stress occurs at the junction of the bottom of the housing and the braced steel frame, as shown in Fig.9(a), the value is 14.4MPa.. The maximum total deformation occurs at the bottom of the housing, as shown in Fig.9 (b), with the value of 76.3μm.

![Figure 9](image2.png)
(a) Equivalent stress distribution  
(b) Global deformation distribution

**Figure 10.** Equivalent stress and global deformation distribution cloud map (Young's modulus E is 20.6 GPa)
Fig. 10 shows the cloud diagram of the equivalent stress and total deformation distribution of the transformer housing when the Young's modulus $E$ of the supporting foundation is 20.6 GPa and the total deformation distribution of the transformer housing at the moment of $T/4$. The maximum equivalent stress occurs at the junction of the housing bottom vertical reinforcement and the braced steel frame, as shown in Fig. 10(a), the value is 16.3 MPa. The maximum total deformation appears at the bottom of the housing as shown in Fig. 10(b), and its value is 70.8 μm.

Figure 11. Equivalent stress and global deformation distribution cloud map (Young's modulus $E$ is 206 GPa)

Fig. 11 shows the cloud diagram of equivalent stress and total deformation distribution of transformer housing with Young's modulus $E$=206 GPa at the moment of $T/4$. The maximum equivalent stress appears at the junction of the bottom of the housing and the braced steel frame, as shown in Fig. 11(a), the value is 16.7 MPa. The maximum total deformation occurs at the bottom of the housing as shown in Fig. 11(b), with a value of 69.9 μm.

Table 1 gives the variation of equivalent stress and general shape variable with foundation stiffness. When the material with small Young's modulus is used as the supporting foundation of transformer, the equivalent stress of the housing decreases significantly and the deformation of the housing increases correspondingly, but with the continuous increase of the stiffness of the supporting foundation, the equivalent stress and the general shape variable tend to be fixed gradually. The influence of foundation stiffness gradually weakens.

| Elasticity Modulus (GPa) | Stress (MPa) | Change | Deformation (μm) | Change |
|-------------------------|-------------|--------|------------------|--------|
| 0.206                   | 11.7        | -36.8% | 114.9            | +73.6% |
| 2.06                    | 14.4        | -22.2% | 76.3             | +15.3% |
| 20.6                    | 16.3        | -11.9% | 70.8             | +7.0%  |
| 206                     | 16.7        | -9.9%  | 69.9             | +5.6%  |
| No base                 | 18.5        | 0%     | 66.2             | 0%     |

4. Conclusion
Based on the finite element method, the dynamic response characteristics of transformer housing are studied, and the effects of different stiffness foundations on the dynamic response of transformer are compared and analyzed. The results show that:
(1) During the loading period, the maximum deformation of the housing occurs at the top of the high pressure casing at 132.6μm, and the maximum equivalent stress occurs at the junction of the vertical reinforcement and the supporting steel frame at the bottom of the housing with a value of 18.5 MPa.

(2) The velocity, stress and deformation of the side and bottom of transformer housing show periodic response, and the response frequency is consistent with the load frequency. The amplitude of the dynamic response of the bottom of the housing is obviously larger than that of the side of the housing.

(3) The stiffness of the support foundation of transformer has a great influence on the dynamic response of the housing, and the equivalent stress response amplitude of the housing decreases with the decrease of the foundation stiffness, while the deformation response shows the opposite trend. The effect of the foundation stiffness on the dynamic characteristics of the housing decreases with the increase of the stiffness.

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