RESEARCH ON ELECTROMAGNETIC VIBRATION OF THREE-PHASE TRANSFORMER CONSIDERING DYNAMIC STRESS

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To improve the calculation accuracy of transformer vibration, magnetization and magnetostriction properties under dynamic stress are considered in this paper. Firstly, the magnetization and magnetostriction under stresses are measured and the stress-characteristic multi-curves are extended to three-dimensional properties surfaces, which represent the properties data under continuous stress. Then the stress magnetization surface is used to simulate the permeability change caused by self-induced tension when calculating the magnetic field. Considering magnetostrictive effect, the dynamic stress-strain relationship is established and applied to the electromagnetic vibration calculation of the transformer. Finally, the electromagnetic vibration with or without dynamic stress properties was calculated, respectively. By analyzing the comparison between calculation and measurement results, it is shown that considering the dynamic stress can improve the numerical calculation accuracy of the electromagnetic vibration, which is conducive to more accurate vibration and noise assessment.

Keywords: Electromagnetic vibration, Transformer, Dynamic stress, Magnetostrictive effect.

1. Introduction

The electromagnetic vibration of cores affects transformer service life and the living environment of nearby residents. For the silicon steel，magnetization and magnetostrictive properties are the intrinsic properties, which determine the electromagnetic force and magnetostrictive effect and further determine electro-magnetic vibration of the transformer core [1]. Some papers have done many investigations on the electromagnetic vibration due to magnetostriction of transformer cores [2-4]. A dynamic magnetostriction model is applied to the numerical analysis to compute the vibration of a transformer core in [2]. The magnetostriction of two permanent magnet motors whose cores were made of different materials are measured in [3]. The vibration of transformers can be affected by many factors. The magneto-mechanical effects of transformers cores

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which is made in different structures were studied in [5] and the vibration of transformer under different excitation were analyzed and measured in [6]. The influence of operating temperature on core vibration characteristics is investigated [7]. The vibration of transformers under DC Bias is investigated [8-10].The magnetic and mechanical behaviors of steel materials are strong coupled, and mechanical stress affects magnetization and magnetostriction properties. Most studies focus on magneto-mechanical coupling and magnetostrictive effect, but few take the effect of stress on permeability and magnetostriction into account when calculating magnetic field and elastic mechanic. Studies on the effect of the stress on magnetic properties are shown in [11,12]. Therefore, it is necessary to consider the dynamic stress effects when the vibration of transformer due to magnetostriction is studied. The stress and its distribution of the reactor cores was calculated and analyzed in the previous researches [13-15], but the effect of dynamic stress on magnetic field and vibration is not considered.

The coupling between magnetic field and mechanical field is improved by considering dynamic stress in this paper. Based on the measurement of magnetization and magnetostriction properties under different stresses, the stress-magnetization and stress-magnetostriction surfaces are obtained, which is the data base of the calculation. In view of the coupling between magnetic and mechanical of transformer cores, the dynamic stress-strain relationship is developed and the electromagnetic vibration of cores of the three-phase transformer is analyzed and measured. The electromagnetic vibration calculation of transformer cores which take the dynamic stress into count is more accurate and will be significant on the optimization design of transformers and vibration and noise reduction in the future.

2. Magnetic properties measurement under stress

The properties of magnetization and magnetostriction under different stresses can be measured by a measurement system. The main part of the measurement is shown in Fig.1, which is suspended by an air pump to eliminate the external influence on magnetostrictive measurement. The system is mainly composed of SST single-chip magnetometer, laser interferometer and optical shockproof table.

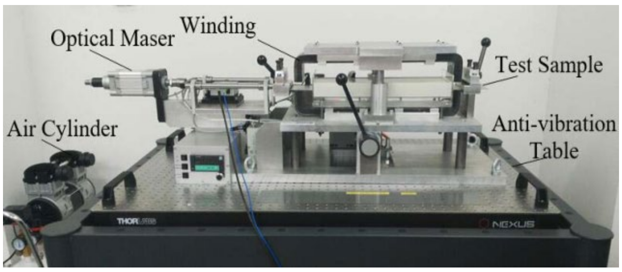
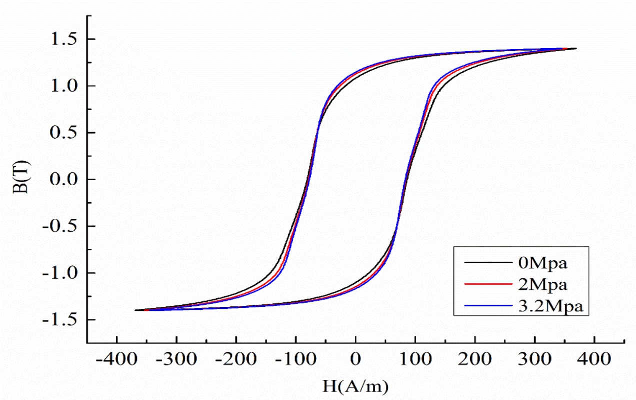


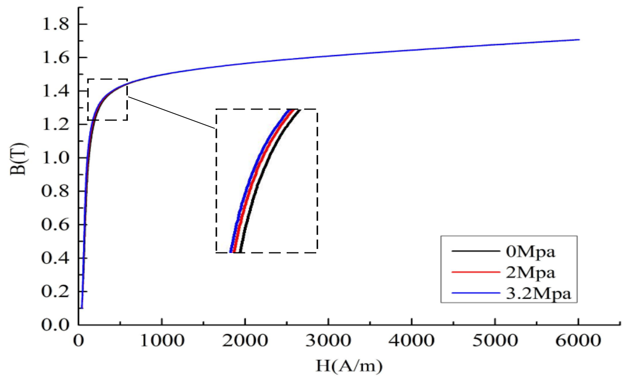
Fig. 1. Magnetization and magnetostriction measurement device

The magnetization and magnetostrictive curves are obtained by applying different stresses in the rolling direction. The tensile force applied on the silicon steel sample sheet is 0-140N. The measurement results of magnetic properties under different stress are shown in Figs. 2-3. The magnetization curve under the tensile stress of the data processing is shown in Fig. 2. With the increase of stress, the flux density of silicon steel samples increased slightly under the same magnetic field intensity. The corresponding series of magnetostrictive curves and the peak-peak curves were significantly reduced while the stress increase, which is shown in Fig. 3. The effect of stress on magnetostrictive curve is shown in the Fig. 3(a). The results showed that the magnetic flux density increases with the increase of tensile stress and the stress effect on magnetostriction is greater than that on magnetization, and the magnetostriction of ferromagnetic material can be reduced by applying tensile stress in the rolling direction.

Considering the influence of stress in calculation, the properties data under stress are extended to surface continuous data by linear interpolation. The surfaces of magnetization and magnetostrictive characteristics under stress are shown in Fig. 4.

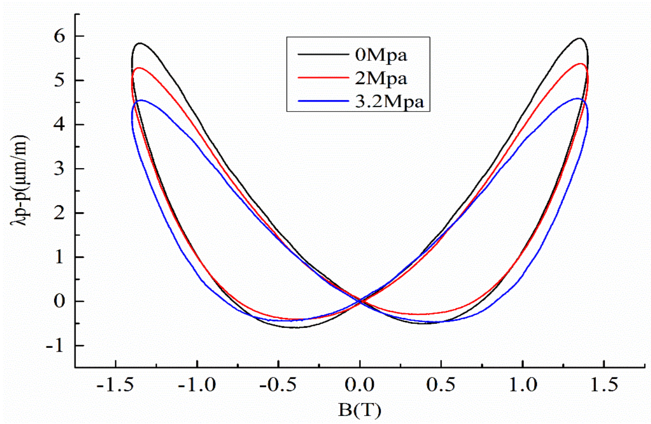


(a) Hysteresis loops

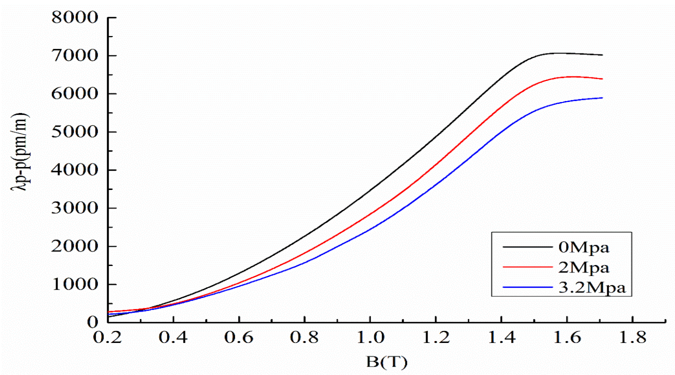


(b) Basic magnetization curve

Fig. 2. Magnetization of silicon steel under different stress

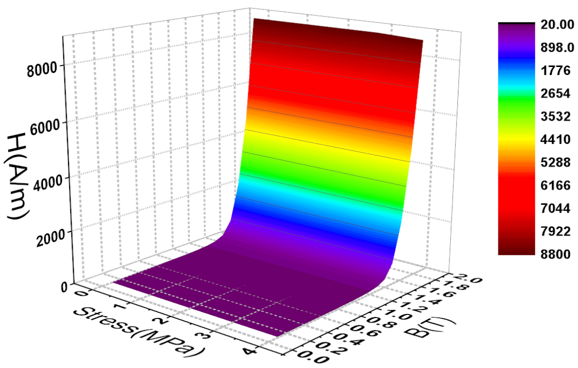


(a) Magnetostriction loops

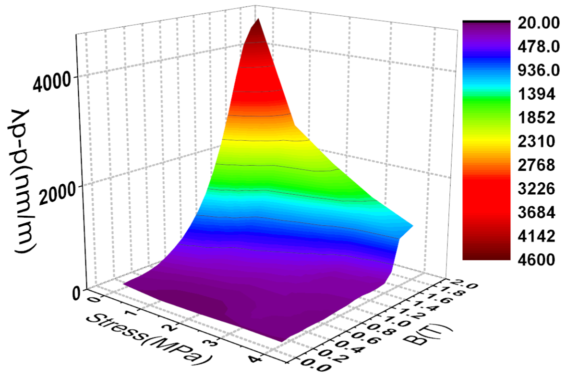


(b) Magnetostriction curves

Fig. 3. Magnetostriction under different stress



(a) Magnetization properties under stress



(b) Magnetostriction properties under stress

Fig.4 Surfaces of magnetization and magnetostriction properties

3. Magneto-mechanical coupled numerical model

In elastic mechanics, energy method is a common method in numerical analysis, it is based on the variational method in mathematics as an analytical method. In the magneto-mechanical system of the core, the energy function includes the strain energy, magnetic field energy, current potential energy, work done by magnetostrictive force and the work done by Maxwell force. Then the total energy functional of the core is:

$$\begin{aligned} I = &\int_{\Omega_2}\left(\frac{1}{2}\boldsymbol{\varepsilon}^T\cdot\boldsymbol{\sigma}\right)\mathrm{d}V + \int_{\Omega_1}\left(\int_0^B \boldsymbol{H}\cdot d\boldsymbol{B}\right)\mathrm{d}V - \int_{\Omega_1}\boldsymbol{J}\cdot\boldsymbol{A}\mathrm{d}V \\ &-\int_{\Omega_2}\boldsymbol{f}_{ms}\cdot\boldsymbol{u}\mathrm{d}V - \int_{\Gamma}\boldsymbol{f}_{mw}\cdot\boldsymbol{u}\mathrm{d}V \end{aligned} \tag{1}$$

where $\int_{\Omega_2}\left(\frac{1}{2}\boldsymbol{\varepsilon}^T\cdot\boldsymbol{\sigma}\right)\mathrm{d}V$ is strain energy, Ω_2 is mechanic field domain, the stress and strain in the formula meet the Piezomagnetic equation, $\int_{\Omega_1}\left(\int_0^B \boldsymbol{H}\cdot\mathrm{d}\boldsymbol{B}\right)\mathrm{d}V$ is magnetic field energy, Ω_1 is magnetic field domain, $\int_{\Omega_1}\boldsymbol{J}\cdot\boldsymbol{A}\mathrm{d}V$ is current potential energy, the fourth and fifth terms in the functional are respectively the work done by the magnetostrictive force and the maxwell force. Ignoring the mass and damping terms in the core structure field, the matrix form of the ferromagnetic-mechanical coupling model is

$$\boldsymbol{S}\boldsymbol{A} = \boldsymbol{J} \tag{2}$$

$$\boldsymbol{K}\boldsymbol{u} = \boldsymbol{f}_{mw} + \boldsymbol{f}_{ms} \tag{3}$$

where $\boldsymbol{S}$ is electromagnetic matrix, K is mechanical stiffness matrix, $\boldsymbol{A}$ and $\boldsymbol{u}$ are the magnetic vector position and displacement to be solved in the model, respectively.

From the Maxwell formula in the electromagnetic field theory, the Maxwell stress tensor in the common frequency magnetic field is:

$$\boldsymbol{T} = \boldsymbol{BH} - \frac{1}{2}\mu_0 \boldsymbol{H}^2 \boldsymbol{I} \tag{4}$$

The Maxwell force can be calculated from the surface integral of the stress Tensor $\boldsymbol{T}$ on any closed surface S:

$$\boldsymbol{f}_{mw} = \int_S \boldsymbol{T}\mathrm{d}S = \int_S \begin{bmatrix} B_x H_x - \frac{1}{2}BH & B_x H_y & B_x H_z \\ B_y H_x & B_y H_y - \frac{1}{2}BH & B_y H_z \\ B_z H_x & B_z H_y & B_z H_z - \frac{1}{2}BH \end{bmatrix} \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \mathrm{d}S \tag{5}$$

where $B_i\left(i = x, y, z\right)$ is component of the magnetic flux density at the surface.

When the silicon steel sheet is in an alternating magnetic field, it will periodically elongate or contract and then it vibrates. On the contrary, the stress or strain generated by the external mechanical field will also change the electromagnetic properties of the material. Both magnetostriction and reverse magnetostriction can cause energy exchange between magnetic energy and elastic properties of the system. When the magnetic energy increases, part of the increased magnetic energy will be converted into elastic properties, which will change the stress and strain. On the contrary, when the elastic properties increase, part of the increased elastic performance will also be converted into the magnetic energy of the silicon steel sheet, thus satisfies the piezoelectric magnetic equation:

$$\boldsymbol{\varepsilon} = \boldsymbol{\sigma}/E_\sigma + d\boldsymbol{H} \tag{6}$$

$$\boldsymbol{B} = \mu_\sigma \boldsymbol{H} + d\boldsymbol{\sigma} \tag{7}$$

where $\boldsymbol{\varepsilon}$ is the strain of the ferromagnetic material, $\boldsymbol{\sigma}$ the applied stress, E_σ the elastic modulus of material, d magnetostrictive coefficient, μ_σ magnetic conductivity under stress.

The magnetostrictive coefficient meets the following formula:

$$d = \left.\frac{\partial \boldsymbol{\varepsilon}}{\partial H}\right|_\sigma \tag{8}$$

In laminated iron, magnetic field strength and stress interact with each other. The magnetic field produces force, and the force also changes the magnetic field. Magnetic field and force field are coupled to each other. It can be expressed as:

$$\boldsymbol{SX} = \boldsymbol{F} \tag{9}$$

where $\boldsymbol{S}$ is stiffness coefficient matrix, $\boldsymbol{X}$ magnetic vector position and vibration displacement matrix, $\boldsymbol{F}$ the current and the external force matrix.

In formula (2) and (3), there is no direct coupling between the magnetic field and the structural force field, they are established by magnetostrictive interpolation, which has a difference with the physical processes that the actual permeability and magnetostriction will change at the same time, and it cannot reflect the nature of the core material. The formula (9) is obtained by combining the magnetic vector position and displacement into a stiffness coefficient matrix by strong magnetic-mechanical coupling.

Without considering stress effect, the functional relationship between the field strength and the flux density of silicon steels is $H(B)$. When considering the effect of stress on the magnetic field, the magnetic field strength of the steel is not only a function of flux density, but also a function of stress. At this time, the function relationship is $H(B,\sigma)$.

Only use the magnetostrictive characteristic curve under different stresses, that is, after considering the magnetostrictive effect, the relationship between stress and strain is:

$$\sigma=\beta\left(\varepsilon-\lambda\left(B\right)\right) \tag{10}$$

where β is elastic modulus of material, λ the magnetostriction of the material.

The stress of the laminated core is constantly changing, it cannot consider the impact of the dynamic stress. When it is considered, the formula above will be modified to:

$$\sigma=\beta\left(\varepsilon-\lambda\left(B,\sigma\right)\right) \tag{11}$$

The stress $\boldsymbol{\sigma}$ is both the independent variable and the dependent variable, numerical calculations will be terminated due to the occurrence of cyclic variables. To avoid the termination of the numerical calculation, a new variable is added to replace the magnetostriction. The added new variable is solved by ordinary differential equation.

λ_σ is defined as the magnetostriction varied with the stress and μ_σ denotes the permeability under the stress. They can be obtained by calculating based the characteristic data under stress.

$$\frac{\partial\lambda_\sigma}{\partial t}=\lambda\left(B,\sigma\right)-\lambda_\sigma \tag{12}$$

$$\mu_{\sigma_i}=B(\sigma_i)/H(\sigma_i) \tag{13}$$

where $\boldsymbol{\sigma}_i$ means under the i stress.

4. Calculation and measurement

A SG-10 three-phase transformer is used as the prototype in this paper, and its parameters are shown in Tab. 1. The magnetic and mechanical fields of the transformer are analyzed by the finite element software-COMSOL, which is good in solving multi-physical field problems.

Table 1 Transformer parameters

Parameter	Value
Rated capacity (kVA)	10
Rated voltage (V)	380/220
Rated current (A)	8.8/15.2
Impedance voltage (%)	4
No-load current (A)	<1.4
Material type	30Q130
Material density(kg/m^3)	7650
Young's modulus	200E9
Poisson's ratio	0.26

Firstly, a geometric model of the transformer is established, and the excitation and boundary conditions are set, which uses the parameters of the silicon steel material and the working condition parameters of the transformer in Table 1. Then, the magneto mechanical coupling model derived from the energy method in the previous chapter is introduced to realize the coupling solution between multi-physical fields. Finally, the iterative calculation is carried out through the Newton-Raphson method, and the data results meeting the requirements are output. Considering the effect of dynamic stress on magnetization and magnetostriction properties, the calculation process of magnetic field and vibration is shown in Fig. 5.

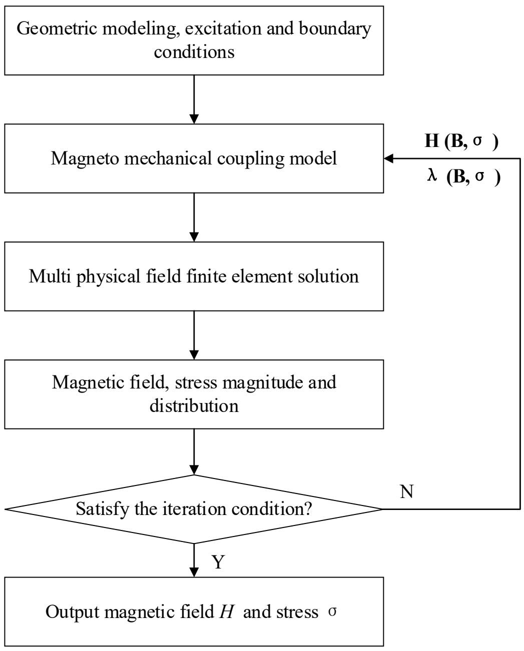


Fig. 5. Calculation flow chart

Based the Maxwell equations, the magnetic field of the transformer is firstly analyzed, which is also the basic of vibration calculation. Considering the transformer is running at power frequency (50Hz), the displacement current can be ignored, so the Maxwell equation can be expressed as:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} \tag{14}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{15}$$

where $\boldsymbol{H}$ is magnetic field intensity, $\boldsymbol{E}$ is electric field intensity, $\boldsymbol{B}$ is magnetic fiel-d density, and $\boldsymbol{J}$ is current density.

Magnetic field density $\boldsymbol{B}$ can be expressed by magnetic vector position $\boldsymbol{A}$ as: $\boldsymbol{B} = \nabla \times \boldsymbol{A}$. So the equation of magnetic vector can be expressed as:

$$\nabla \times \left(\mu_0^{-1}\mu_r^{-1}\nabla \times \boldsymbol{A}\right) = \boldsymbol{J} \tag{16}$$

where μ_0 and μ_r are the permeability of vacuum and the relative permeability.

The product of vacuum magnetic permeability and relative magnetic permeability can be represented by magnetic resistance: $\mu_0^{-1}\mu_r^{-1} = \upsilon$. So the magnetic vector equation under three-dimensional conditions is as follows.

$$\left.\begin{aligned}
\frac{\partial}{\partial y}\left[\upsilon_\sigma\left(\frac{\partial A_y}{\partial x}-\frac{\partial A_x}{\partial y}\right)\right]-\frac{\partial}{\partial z}\left[\upsilon_\sigma\left(\frac{\partial A_x}{\partial z}-\frac{\partial A_z}{\partial x}\right)\right]=J_x\\
\frac{\partial}{\partial z}\left[\upsilon_\sigma\left(\frac{\partial A_z}{\partial y}-\frac{\partial A_y}{\partial z}\right)\right]-\frac{\partial}{\partial x}\left[\upsilon_\sigma\left(\frac{\partial A_y}{\partial x}-\frac{\partial A_x}{\partial y}\right)\right]=J_y\\
\frac{\partial}{\partial x}\left[\upsilon_\sigma\left(\frac{\partial A_x}{\partial z}-\frac{\partial A_z}{\partial x}\right)\right]-\frac{\partial}{\partial y}\left[\upsilon_\sigma\left(\frac{\partial A_z}{\partial y}-\frac{\partial A_y}{\partial z}\right)\right]=J_z
\end{aligned}\right\} \tag{17}$$

where υ_σ means the magnetic resistance under stress which can be got by Eq.(13) based on magnetization measurement under different stress.

Then magnetic field distribution of the core can be calculated based the equations and the effect of stress on the distribution of magnetic field is considered by calling the characteristics of permeability under different stresses. The magnetic forces can be calculated by Eq.(5) while the magnetic field analysis.

The result of the magnetic flux analysis of the transformer prototype core is shown in Fig. 6. The magnetic flux of the transformer is about 1.7T.

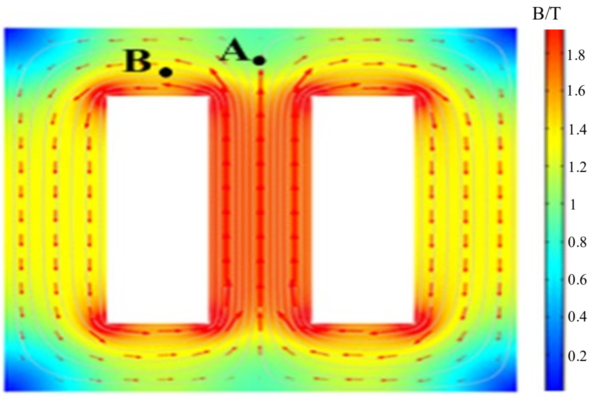
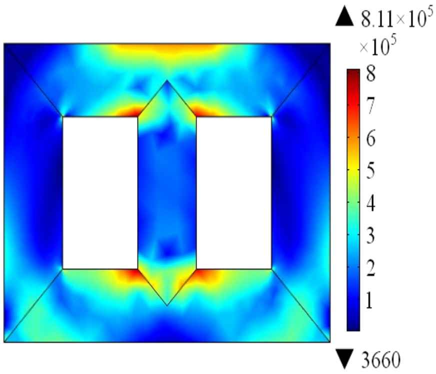


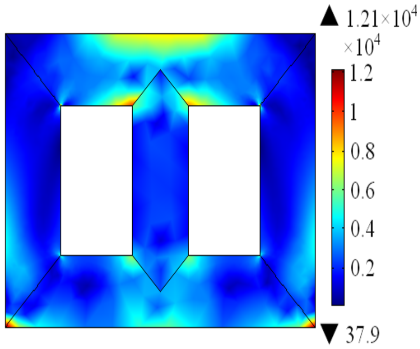
Fig. 6. Magnetic flux distribution of transformer cores

Then the vibration of transformer cores can be analyzed according the magneto mechanical coupling model in the third chapter, while the magnetostriction under stresses are invoked during the calculating. To compare the effects of dynamic stress, the stress of the core with and without considering the dynamic stress was analyzed, respectively. The overall stress distribution of the core under different conditions is shown in Fig. 7. The results show that the integral stress is smaller under considering dynamic stress effects due to smaller magnetostriction with tensile stress.

To verify the accuracy of electromagnetic vibration, two points A and B are selected to compare the analyzed and measurement results. The positions of A and B are also shown in Fig. 6.



(a) without considering the stress



(b) With considering the stress
Fig. 7. Equivalent stress distribution of iron core

To compare the effect of dynamic stress on vibration, the electromagnetic vibration of the core considering and not considering dynamic stress was calculated and the vibration of core is also measured by high precision vibration sensor. The vibration measurement system of the transformer prototype is shown in Fig. 8. The three-phase transformer prototype is placed on the vibration isolation table during the measurement to reduce interference and is supplied by a stable transformer. The calculate and measured results of the two points are shown in Fig. 9.

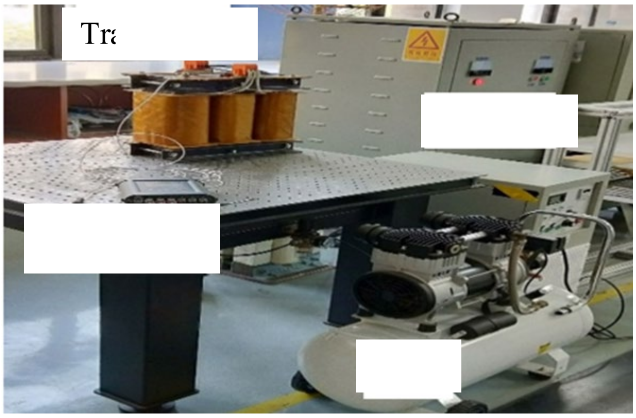
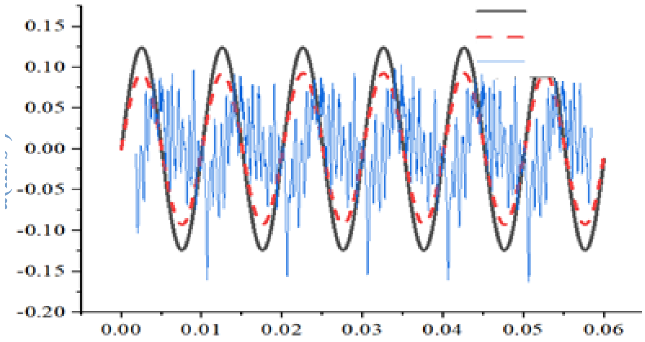


Fig. 8. The vibration testing system

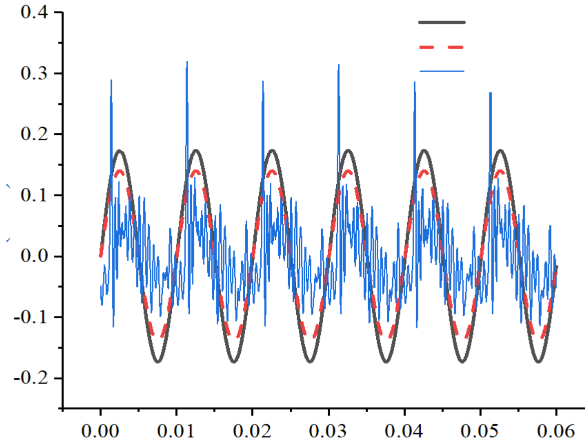
The blue curves in Fig. 9 are the vibration acceleration measurement results of point A and B, which showed that the vibration acceleration of B is a little larger than point A, that is because point B is close to the corners, and the point A is located on the upper side of the middle core and the flux density at point B is larger than that at point A, as shown in Fig.6. In addition, because the probe used in the measurement experiment is attached to the outside the core column, the vibration measurement results contain some harmonics for the influence of winding and so on.

The calculation results of point A vibration acceleration considering dynamic stress and not considering stress are shown in Fig. 9(a) in solid line and dashed line respectively, and the results of point B in Fig. 9(b). The results showed the sinusoidal distribution of the calculated vibration acceleration is weak when the dynamic stress is considered, and it is closer to the measured result. The calculated results are consistent with the magnetostriction of steel sheet reduction caused by tensile stress, because magnetostriction is the main cause of electromagnetic vibration of transformers.

The actual vibration measurement value is lower than the calculated value because the clamping force of transformer core structure is neglected in the analysis.



(a) Point A



(b) Point B

Fig. 9. Comparison of calculation and measurement of core vibration

5. Discussion and conclusion

Electromagnetic force and magnetostrictive effect are the cause of transformer core vibration. The magnetic and mechanical behaviors of steel materials are strong coupled, and the core vibration is intricately linked to mechanical stress because the magnetization and magnetostriction properties can be affected by stress. Based on the research on the relationship between mechanical stress and magnetic properties, the dynamic stress effects are considered in analyzing the core vibration in this paper. The main as follows:

First, the magnetization and magnetostrictive curves under different stresses are obtained by applying different stresses in the rolling direction, and the properties data under stress are extended to surface continuous data by linear interpolation.

Second, a SG-10 three-phase transformer is analyzed and measured. To compare the effects of dynamic stress, the stress of the core with and without considering the dynamic stress was analyzed, and the results show that the integral stress is smaller under considering dynamic stress effects due to smaller magnetostriction with tensile stress.

Third, two points are selected to compare the analyzed and measurement results to verify the accuracy of electromagnetic vibration. The results show that the sinusoidal distribution of the calculated vibration acceleration is weak when the dynamic stress is considered, and it is closer to the measured result.

This paper analyzed the core vibration considering the effect of mechanical stress on magnetic properties and the results show that the sinusoidal distribution of the calculated vibration acceleration is closer to the measured result. The research will be significant on transformer structure design and vibration and noise reduction.

Acknowledgement

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