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Design and Analyze the Optimum Operating Point between Magnetic Flux Density and Vibration Noise of Transformer Cores

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Abstract: Base on the magnetization and magnetostriction measurement, this paper proposed a generalized 3D finite element numerical model, which can be used to analyze electromagnetic vibration of laminated cores including electromagnetism and magnetostriction effects. And then the acoustic field around the transformer was analyzed and tested, the results showed the model and analysis method were feasible. The work is helpful to estimate vibration noise level and then optimized design, choose suitable silicon steel and size in the design stage, which can reduce product development cycle and test cost.

Keywords: Operating point, magnetic flux density, vibration noise, acoustic field, magnetostriction.

1. INTRODUCTION

Energy saving and noise reduction must be the development trend of power transformers. Improving the magnetic flux density in cores can reduce the size of transformers, which will reduce the cost for the equipment and materials such as silicon-iron, copper, carbon steel, and insulation material. However, the vibration noise of cores will boost as the magnetic flux density increases. So, it is the part that needs optimization due the high cost and low vibration noise related with final product.

Electromagnetic vibration noise of power transformers under no load, especially dry transformers, mainly caused by silicon steel magnetostriction (MS) under the nominal operating flux density 1.5T-1.8T [1, 2]. Several papers have analyzed the vibration of cores due to magnetostrictive effect in 2D, some based the Principle of virtual work [3], and others based the equations of elasticity method in a similar way as thermal stresses [4-6]. The aim of this paper was to investigate a feasible way to determine the operating point of transformer cores within the vibration noise limit set by the government.

In this paper, the magnetic and MS characteristics of the oriented silicon steel both in the rolling direction (RD) and transverse direction (TD) were firstly measured which is necessary to the vibration analysis of transformer cores. Because the vibration of laminated cores due to MS is not only in the plane of the sheets, but also out-of-plane [7, 8], so a 3D numerical model including MS effects and magnetic anisotropy was developed, which was used to analyze the magnetic flux density and deformation of laminated cores. The acoustic field was also analyzed based on the total sound power emitted by the cores and windings. Finally, the noise level was investigated through analysis and measured results, which confirmed the reliability of the presented model and analysis method and provided a way to determine the optimum operating point of transformer cores between the magnetic flux density and vibration noise level in the design progress.

2. METHODES OF ANALYSIS

2.1. Magnetization and Magnetostriction Measurement

In order to measure the magnetization curves of silicon steel sheet of the transformer prototype, standard samples with 30mm*300mm were respectively cut 0°and 90° intervals from RD of the oriented steel. The strips, cut at each angle, stacked in 25cm Epstein Frame, then the magnetic anisotropy were tested according to GB/T 3655-2008. The hysteresis loops of one type grain oriented steel in RD from measurement were shown in Fig. (**1a**). Magnetostriction is the intrinsic characteristics of laminated core and is dependent on the magnetic induction. To analyze the vibration of the transformer cores including MS effects, the MS strains both in RD and TD are obtained with a 100mm*500mm sample piece by a heterodyne laser vibrometer, which meet the international standard IEC/TR62581 [9]. The alternating magnetization MS butterfly curves in RD under different induction values B_{RD} as demonstrated by Fig. (**1b**).

To simplified calculation program, the hysteresis and butterfly characters under alternating magnetic were ignored in this paper. Considering magnetic anisotropy of the grain oriented steel, magnetization and MS curves in RD and TD, used to analyze the magnetic field and vibration due to MS of transformer cores, were measured and shown in Fig. (**2**).

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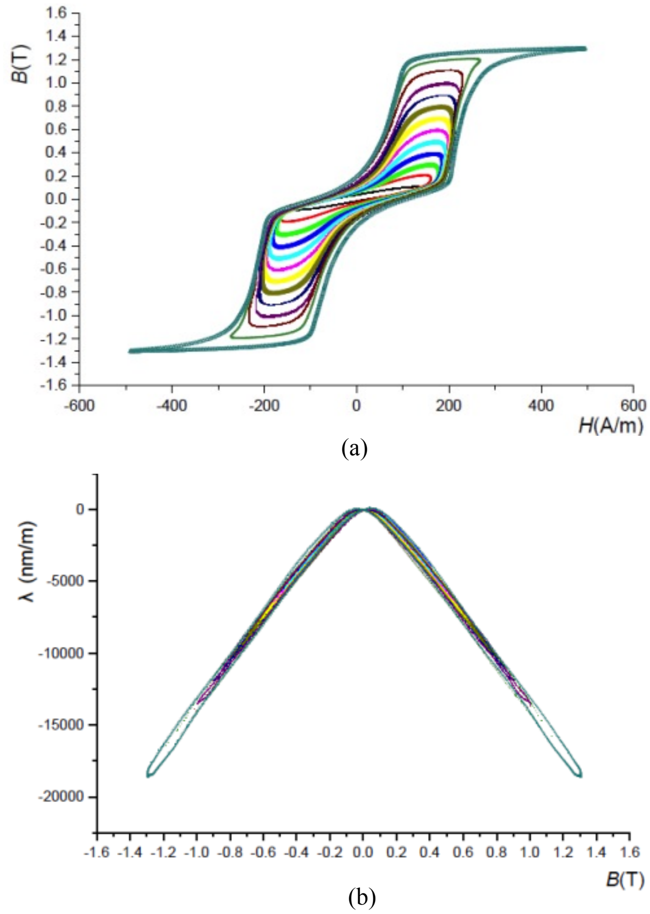

Fig. (1). AC magnetic characteristics curves of one type grain oriented steel in RD with 50Hz. (a) Hysteresis loops. (b) Magnetostricon butterfly curves

2.2. Functional Energy of Cores

Based on previous researches [8], the MS behavior of silicon steel materials follows piezomagnetic laws which is rewritten as:

$$\begin{cases} \varepsilon_i = s_{ij}^H \sigma_j + d_{ni} H_n & \left| i, j = 1,...6 \right. \\ B_m = d_{mj}\sigma_j + \mu_{mn}^{\sigma} H_n & \left| m, n = 1,...3 \right. \end{cases} \quad (1)$$

where s^H, $\boldsymbol{d}$, μ^{σ} are the tensors matrix of constant-H compliance, MS coefficients and constant-σ permeability matrix, ε and σ, the tensors of strain and stress, $\boldsymbol{B}$ and $\boldsymbol{H}$, the vectors of magnetic flux density and magnetic field, respectively.

The total energy functional of the transformer cores include mechanical energy, magnetic energy and magnet-mechanical coupling energy. It can be expressed as follows:

$$\begin{aligned} I = &\int_{\Omega_2} \left(\frac{1}{2} \boldsymbol{\sigma}^T \boldsymbol{s}^H \boldsymbol{\sigma} \right) dV + \int_{\Omega_2} \left(\boldsymbol{\sigma}^T \boldsymbol{dH} \right) dV + \\ &\int_{\Omega_1} \left(\frac{1}{2} \boldsymbol{H}^T \mu^{\sigma} \boldsymbol{H} \right) dV - \int_{\Omega_1} \boldsymbol{J} \cdot \boldsymbol{A}\, dV - \\ &\int_{\Gamma_1} \boldsymbol{f}_{\Gamma} \cdot \boldsymbol{u}\, dV - \int_{\Omega_2} \boldsymbol{f}_V \cdot \boldsymbol{u}\, dV \end{aligned} \quad (2)$$

where $\boldsymbol{A}$ is the magnetic vector potential, and $\mathbf{B} = \nabla \times \mathbf{A}$. $\boldsymbol{U}$ is the mechanical displacement. f_V and f_{Γ} are the external volume force and boundary surface force of the transformer cores. Ω_1 and Ω_2 are the analysis domain of magnetic and mechanical.

2.3. Anisotropy Analysis

Magnetic permeability $v=(v_x\ v_y\ v_z)^{\mathrm{T}}$, in coordinate system v_x, v_y were obtained by interpolation from measured magnetization curves of B_xH_x and B_yH_y, which is $B_{RD}H_{RD}$ or $B_{TD}H_{TD}$ determined the core position in the coordinate system. v_z=v_0 in lamination thickness direction for the silicon steel sheet were coated with insulating layer.

Based on Eq. (1), the strain of transformer core caused by magnetostriction can be obtained as follows:

$$\boldsymbol{\varepsilon}' = \boldsymbol{d} \bullet \boldsymbol{H} = \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{pmatrix}^{\mathrm{T}} \begin{Bmatrix} H_x \\ H_y \\ H_z \end{Bmatrix} \quad (3)$$

MS coefficient matrix d, in which d_{11}, d_{22} can be obtained from measured MS characteristic curves $\lambda_x(B_x)$ and $\lambda_y(B_y)$. If

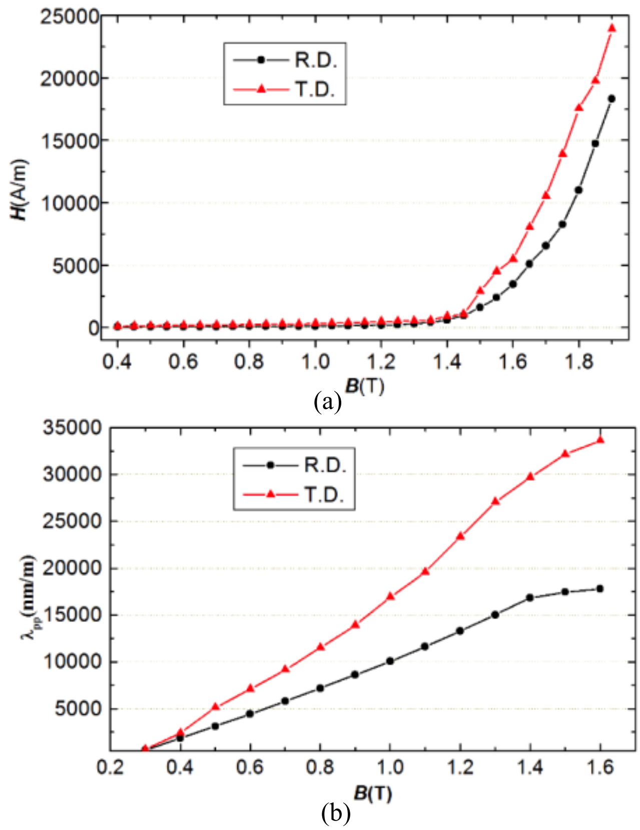

Fig. (2). The magnetization curves and peak-to-peak MS values in RD and TD of the type grain oriented steel. (a) Magnetization curves. (b) Peak-to-peak MS values.

shearing strains of the steel lamination is neglected, there is $d_{ij}=0$ (i=4,5,6, j=1,2,3). The MS coefficient in the normal direction is assumed as $d_{33}=(d_{11}+d_{22})/2$. Using the Hooker's law, we can get $d_{21}=d_{31}=-\alpha d_{11}$, $d_{12}=d_{32}=-\alpha d_{22}$, $d_{13}=d_{23}=-\alpha d_{33}$, where α is the Poisson ratio.

So, the magneto-mechanical coupling energy of transformer cores is given as:

$$\int_{\Omega_2} \sigma^{\mathrm{T}} \boldsymbol{dH} \mathrm{d}V =$$

$$E^{\alpha}\int_{\Omega_2}\begin{pmatrix}(1-\alpha)\varepsilon_x+\alpha\varepsilon_y+\alpha\varepsilon_z\\ \alpha\varepsilon_x+(1-\alpha)\varepsilon_y+\alpha\varepsilon_z\\ \alpha\varepsilon_x+\alpha\varepsilon_y+(1-\alpha)\varepsilon_z\\ (1-2\alpha)\gamma_{xy}/2\\ (1-2\alpha)\gamma_{yz}/2\\ (1-2\alpha)\gamma_{zx}/2\end{pmatrix}^{\mathrm{T}}\begin{pmatrix}1 & -\alpha & -\alpha\\ -\alpha & 1 & -\alpha\\ -\alpha & -\alpha & 1\\ 0&0&0\\ 0&0&0\\ 0&0&0\end{pmatrix}\begin{pmatrix}d_{11}H_x\\ d_{22}H_y\\ d_{33}H_z\end{pmatrix}^{\mathrm{T}}\mathrm{d}V \quad (4)$$

$$= E\int_{\Omega_2}\left(d_{11}\upsilon_x B_x\varepsilon_x + d_{22}\upsilon_y B_y\varepsilon + d_{33}\upsilon_z B_z\varepsilon_z\right)\mathrm{d}x\mathrm{d}y\mathrm{d}z$$

where, $E^{\alpha}=\dfrac{E(1-\alpha)}{(1+\alpha)(1-2\alpha)}$, and E is the Young's modulus of the cores.

After element discretization of functional I and element assembly, then matrix equation of the magneto-elastic system is given by

$$\begin{pmatrix}\boldsymbol{M} & \boldsymbol{D}\\ \boldsymbol{C} & \boldsymbol{K}\end{pmatrix}\begin{pmatrix}\boldsymbol{A}\\ \boldsymbol{u}\end{pmatrix}=\begin{pmatrix}\boldsymbol{J}\\ \boldsymbol{f}_v+\boldsymbol{f}_{\bullet}\end{pmatrix} \quad (5)$$

where $\boldsymbol{M}$ is the electromagnetic matrix, $\boldsymbol{K}$, the mechanical stiffness matrix, $\boldsymbol{C}$, $\boldsymbol{D}$, the coupling interactions between the magnetic field and mechanical deformation, and $\boldsymbol{C}=\boldsymbol{D}^T$. Magnetic- mechanical including MS is coupled by the C matrix.

2.4. Acoustical Analysis

Based on the vibration calculation, according to classical theoretical [10], the sound power of the test position radiated by cores can be expressed as:

$$W_i=\rho c\kappa_j\oint_S v_n^2 dS_c=\rho_0 c_0\kappa_j\sum_j v_{n,k}^2 S_{c,k}\cos\theta_i$$
$$=\rho_0 c_0\kappa_j\sum_j\left(\frac{\partial u_{n,k}}{\partial t}\right)^2 S_{c,k}\cos\theta_i \quad (6)$$

Table 1. Main parameters of the transformer.

Parameter Names	Values
Rated capacity	10(kVA)
rated voltage	1000/380(V)
rated current	5.77/15.2(A)
connection symbol	Yy0
no-load loss	72(W)
no-load current	2.0(%)

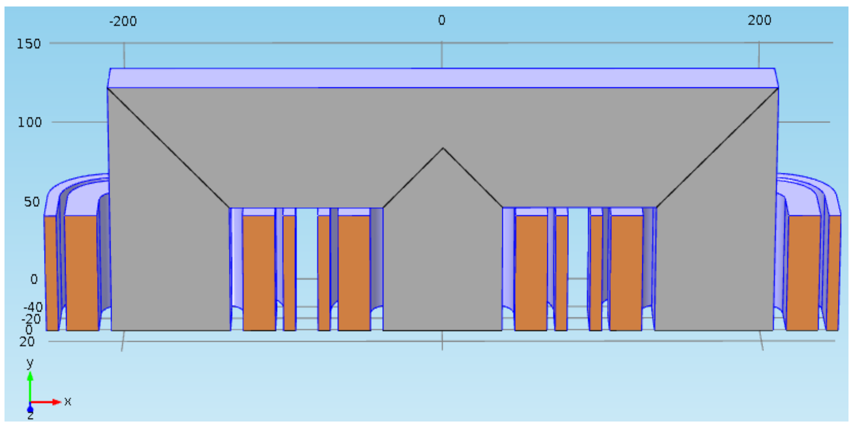

Fig. (3). Analysis model of the transformer.

where ρc is the characteristic impedance of the noise transmission medium, k_j the radiation coefficient of the j core surface, $cos\theta_i$ is the angle between the test point and the surface unit dS_{ci} of transformer cores.

Then we can get the sound pressure level L_p of the free sound field around the core:

$$L_{pi} = 10\lg(W_i / W_0) - \lg R_i - D \quad (7)$$

W_i is the sound power calculated by Eq. (6), W_0=10^{-12} W is the reference's value. R_i the distance from the measured point to the core.

3. RESULTS AND DISCUSSION

The numerical model and vibration tests were implemented on a dry power transformer and the main parameter of the transformer is shown in Table (**1**).

The magnetic-mechanical strong coupling was calculated by finite element of 1/4 according to the symmetry and the analysis model of the dry-type power transformer in the rectangular coordinate as shown in Fig. (**3**). The magnetic field and deformation of the transformer core can be obtained from numerical analysis. The magnetic flux distribution and deformation in different time is displayed in Fig. (**4**). It is evident that the deformation is bigger where with larger magnetic flux, which is consistent with the theoretical and Eq. (1).

According to China's national standard GB7328-87, the analysis and test points of the acoustic field are shown in Fig. (**5**). The no-load noise was measured by AWA6270 analyzer as shown in Fig. (**6**). Based the magneto-elastic analysis, the sound level around the dry transformer were calculated and the result in a moment as Fig. (**7**) shown, which including the windings in order to close the actual working and measuring condition.

Sound pressure level results of the points, shown in Fig.5, from analysis and measured were listed in Table **2** when the transformer cores were inspired by rated voltage. From the table we can see the maximal error between analysis and measurement is 3.37%, which in the range of 5% allowed by engineering. So, it's feasible to estimate the noise level emitted by cores and winding based the proposed model and method in the design stage. The optimum operating point of transformer cores can be achieved through changing flux density and material of cores considering product cost and noise limit.

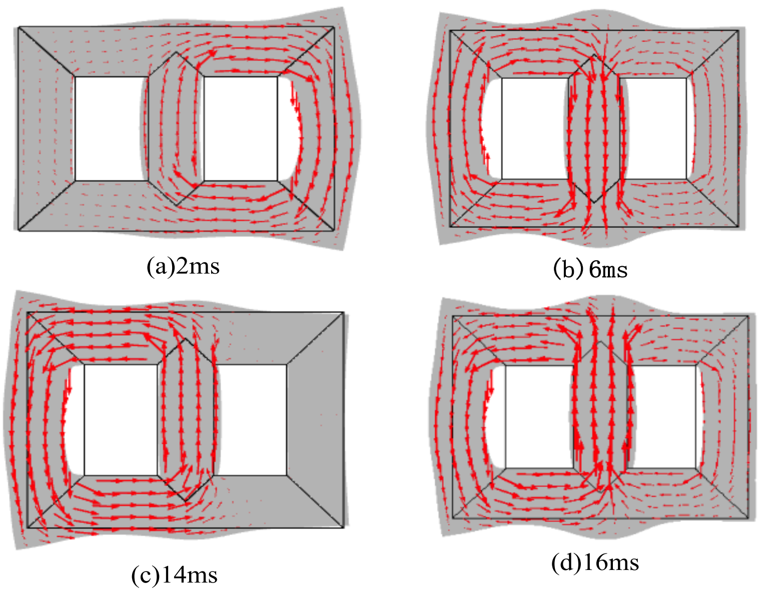

Fig. (4). Section view of magnetic flux and deformation distribution of the transformer core.

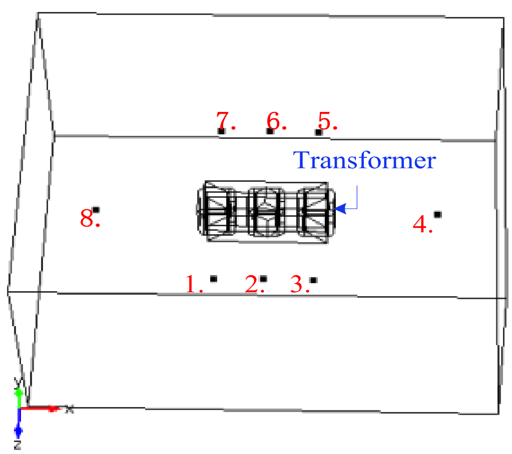

Fig. (5). The acoustic field and measuring points.

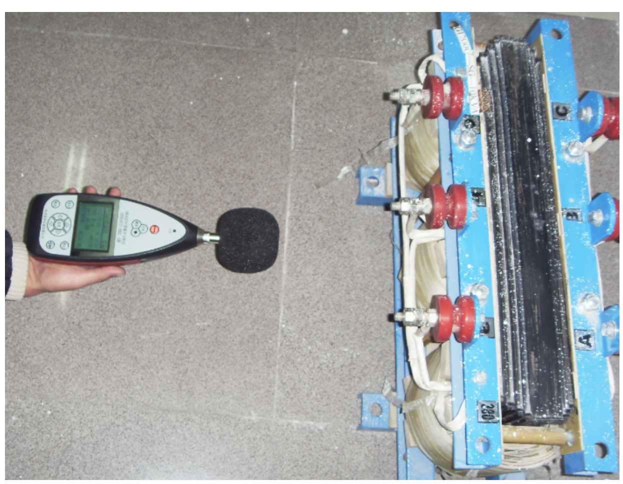

Fig. (6). Sound pressure level measurement.

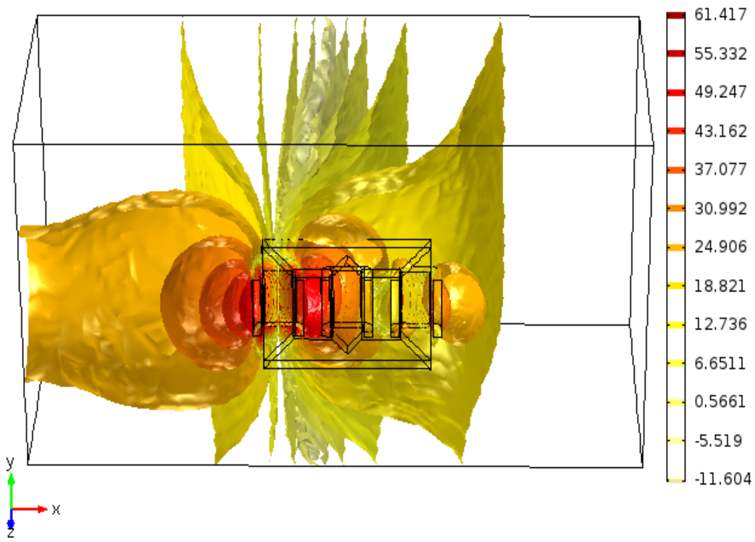

Fig. (7). Sound pressure level contour surface from analysis in a moment.

Table 2. The result of sound level from analysis and measurement.

Points	Analysis (dB)	Measurement (dB)	Errors (%)
1	28.8	29.8	-3.36
2	30.3	29.9	+1.34
3	27.6	28.1	-1.78
4	25.8	25.3	+1.98
5	29.6	30.3	-2.31
6	30.5	31.2	-2.24
7	30.1	30.8	-2.27
8	26.3	27.5	-4.36
Absolute mean	28.6	29.1	2.46

CONCLUSION

A numerical model and analysis method for predicting vibration and noise of transformer products is proposed in this paper, which is subject to solve the contradiction between cost and noise limits. Applying the model, the vibration noise of a transformer was analyzed and measured and the results confirmed the correctness of the model and feasible of the method. In a word, the work is helpful to design the optimum operating point of transformer cores, shorten new product development cycle and reduce costs.

CONFLICT OF INTEREST

There is no conflict of interest between financial contributions to the paper work.

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