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Finite Element Analysis of Magnetostriction Force in Transformer Based on an Anisotropic Magnetostriction Model

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Abstract – This paper presents a dynamic model of 2-D magnetostriction in electrical steel sheet (ESS) under rotating flux magnetization conditions and its implementation in finite element method (FEM). For an arbitrary waveform of magnetic flux density (B), the corresponding magnetostriction waveform can be predicted by the model. In order to apply the model to FEM easily, the model is based on trilinear interpolation method. As an example, the model is applied to a three-phase transformer constructed by highly grain-oriented electrical steel sheets and the numerical results by the magnetostriction model are discussed.

1. Introduction

It is well known that vibration in power transformer is mainly caused by magnetostriction force of core laminations [1]. It is also reported that around 40% of the accidents in power transformers are from mechanical problems of which more than half is caused by vibrations [2]. In the design of a power transformer, therefore, magnetostriction force should be taken into account not only to reduce acoustic noise but also to increase reliability.

A precise measurement of anisotropic magnetostriction data up to magnetic saturation level is still limited to non-oriented and grain-oriented materials. A highly grain-oriented ESS of which most power transformers are made nowadays is still in research because of the large size and high degree of alignment of its magnetic domains. A reliable model of the magnetostriction data has not been established yet either to be embedded in FEA although several models such as neural network approach, analogy of mechanical elasticity and isotropic magnetostriction curve have been developed [1]-[2].

In this paper, anisotropic magnetostriction data of a highly grain-oriented ESS is measured up to magnetic saturation level using a round-type two-directional single sheet tester (2-D SST) under both alternating and rotating field conditions. The data are, then, modeled based on Fourier series expansion and incorporated into a straightforward FEA to analyze the excitation force of vibration caused by magnetostriction.

2. Modeling of Anisotropic Magnetostriction of A Highly Grain-Oriented ESS

2.1 Measuring System

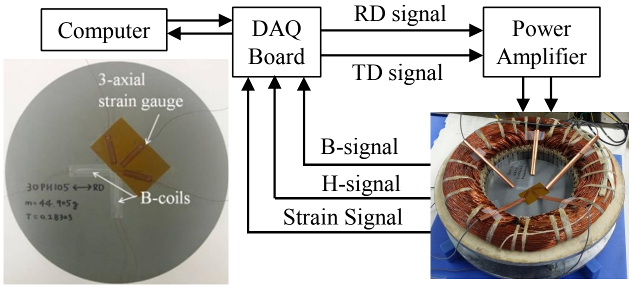
A highly grain-oriented ESS has bigger size and higher degree of alignment of magnetic domains than non-oriented and grain-oriented ones. This is known to enhance the magnetic properties along rolling direction (RD). This, on the other hand, also makes the measurement of magnetostriction as well as magnetic properties more difficult in 2-D SST because B-waveform control becomes more difficult.

This paper proposes, as shown in Fig. 1, a new round-type 2-D SST which is designed to have broader region of uniform field and allows a larger specimen (circular specimen with radius of 162.5mm) than the previous versions. In the measuring system, strain signals from the three-axial strain gauges are acquired when B-waveform is controlled to be elliptic. The normal strains (ε_x, ε_y) and shear strain (γ_{xy}) are calculated as follows:

$$\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\end{bmatrix}=\begin{bmatrix}\cos^2\theta_a & \sin^2\theta_a & \sin\theta_a\cdot\cos\theta_a\\ \cos^2\theta_b & \sin^2\theta_b & \sin\theta_b\cdot\cos\theta_b\\ \cos^2\theta_c & \sin^2\theta_c & \sin\theta_c\cdot\cos\theta_c\end{bmatrix}^{-1}\begin{bmatrix}\varepsilon_a\\ \varepsilon_b\\ \varepsilon_c\end{bmatrix} \qquad (1)$$

where θ and ε_a, ε_b, ε_c are angle from the RD and strains of each strain gauge, respectively. Magnetostriction along an arbitrary direction, ϕ, is obtained as follows:

$$\varepsilon(t,\varphi)=\varepsilon_x(t)\cos^2\varphi+\varepsilon_y(t)\sin^2\varphi+\gamma_{xy}(t)\sin\varphi\cdot\cos\varphi \qquad (2)$$



<Fig. 1> Magnetostriction measurement system.

2.2 Modeling of Magnetostriction

Anisotropic magnetostriction model under rotating magnet field can be mathematically described by an analogy of mechancal elasticity introduced by Lundgren [3]. The model can be expressed as

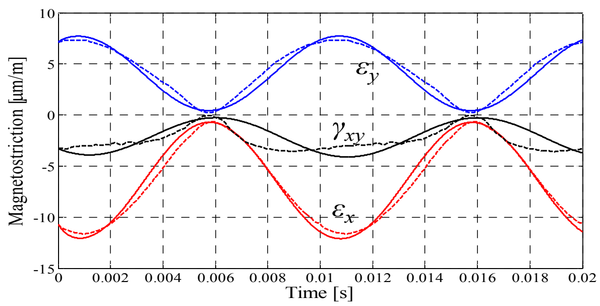
$$\frac{d}{dt}\begin{bmatrix}c_x\varepsilon_x\\ c_y\varepsilon_y\\ c_{xy}\gamma_{xy}\end{bmatrix}+\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{bmatrix}=\begin{bmatrix}\frac{1}{P_x} & -\frac{\xi_x}{P_y} & 0\\ -\frac{\xi_y}{P_x} & \frac{1}{P_y} & 0\\ 0 & 0 & \frac{1}{D_{xy}}\end{bmatrix}^{-1}\frac{1}{2\mu_0}\begin{bmatrix}B_x^2\\ B_y^2\\ B_{xy}\end{bmatrix} \qquad (3)$$

where ε_x and ε_y are the magnetostriction along the RD and the transverse direction (TD), and γ_{xy} is the shear strain. Magnetostricion generally depends on the magnetic force, so $B_x^2/2\mu_0$, $B_y^2/2\mu_0$ and $B_xB_y/2\mu_0$ are considered as magnet stress, where B_x and B_y are the components of instantaneous flux density in the RD and TD, and μ_0 is the permeability. of free space. Therefore, a set of magnetic parameters $\{P\}$ can be introduced to obtain components of magnetostriction, where P_x, P_y and ξ_x, ξ_y are the magnetic modulus and magnetic Poisson's ratio along the RD and TD, respectively; D_{xy} is the shear magnetic modulus. The phase shift between the magnetic stress and magnetostriction can be expressed as a first-order differential equation, with time constants c_x, c_y and c_{xy} for defining the width of butterfly loops.

For highly grain-oriented materials, the vector magnet properties is quite different under different magnet field, and micro-structure of highly grain-oriented SST is very complex, so the magnetostriction also present different properties under different magnetic field. It means that under different magnetic fields, the set of magnetic modulus and time constants in (1) will be different under different magnet fields. So firstly the rotating magnetic field is parameterized, as in [4], using maximum magnetic flux density, B_{max}, inclination angle, ϕ and axis ratio, α. Then the sets of magnetic modulus and time constants can be optimized according to the corresponding measured magnetostriction waveforms. Then we can get a serious sets of magnetostricion parameters at different magnetic fields. In this paper, the magnetostriction parameters $\{P\}$ is optimized by PSO method. Meanwhile, the results and the corresponding B_{max}, ϕ, α are saved into a database. So the magnetostriction parameters $\{P\}$ are the function of the corresponding B-waveform shown as follows:

$$\{P\} = f(B_{\max}, \varphi, \alpha) \tag{4}$$

Therefore, in this model a magnetostriction property database is developed, and the database includes a series of parameters of B-waveform and the magnetostriction parameters. The inputs of the model are the geometric parameters of arbitrary ellipse B-waveform. Then these parameters fed to the input of trilinear interpolation with the database together. The calculations resulted by the interpolation are the magnetostriction parameters $\{P\}$ of the corresponding magnetostriction waveform. At last, the magnetostrition waveforms can be calculating using (3). Fig. 2 compares measured and modeled magnetostriction waveforms under elliptical magnetization at B_{max}=0.7T, ϕ=30 deg, and α=0.3.



<Fig. 2> Comparison of calculated and measured magnetostriction waveforms (solid lines-measured, dashed lines-modeled)

2.4 FEA of Magnetostriction Forces

A straightforward FEA of magnetostriction is summarized as follows:

Step 1. After reaching steady state in FEA, calculate the B-waveform (i.e., distribution of magnetic flux density) in each element,

Step 2. Estimate the B-waveform parameters (Bmax, ϕ, α) for each element and calculate the magnetostriction using (3),

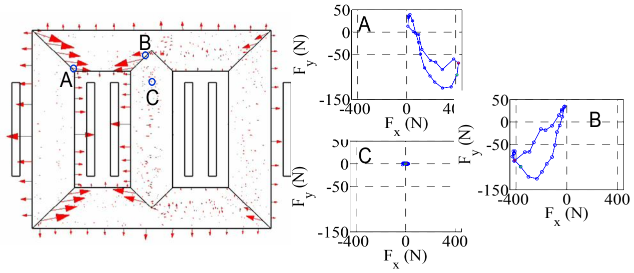
Step 3. Calculate the excitation force of vibration in each element.

3. Magnetostriction Force calculation of Three-Phase Transformer

3.1 Calculation model

a model for a power transformer of 30MVA with 154 (kV_{L-L}). It is made of highly grain-oriented ESS (30PH105) and has 6 laminations. In order to have same magnetic flux distribution with a real transformer, three-phase voltage of 100 (V_{L-L}) is applied on the winding which has 356 turns.

The nodal forces distribution of magnetostriction at t = 0 rad is shown in Fig. 3. Seen from the figure, the force at the edge is much bigger than that inside the core. Therefore, it can be concluded that the magnetostriction force has a contribution to the deformation of the core.



<Fig. 3> Distribution of magnetostriction forces at ωt=0 in steady state

4. Conclusion

This paper presents a dynamic model of 2-D magnetostriction in electrical steel sheet (ESS) under rotating flux magnetization conditions and its implementation in finite element method (FEM). The results of this study indicate low magnetostriction forces values in limbs, due to mere magnetostriction which is weak for alternating magnetization. All other regions - including limb ends - exhibit distinctly increased strain values which partly can be attributed to rotational magnetization and partly to forces. In all cases, the main direction of strain is given in RD. Maximum magnetostriction force values arise close to overlaps.

[References]

[1] K. Delaere, W. Heylen, R. Belmans, and K. Hameyer, "Comparison of induction machine stator vibration spectra induced by reluctance forces and magnetostriction," IEEE Trans. Magn., vol. 38, no. 3, pp. 969-972, Mar. 2002.

[2] Y. D. Kim, et.al. A Study on the Establish Evaluation Criteria for Noise and Vibration of Power Transformer (154kV/60MVA), Ministry of Knowledge & Economy, KOREA, Mar. 2009.

[3] S. Somkun, A. J. Moses, and P. I. Anderson, "Measurement and modeling of 2-D magnetostriction of nonoriented electrical steel," IEEE Trans. Magn., vol. 48, no. 2, pp. 711-714, Feb. 2012.

[4] M. Song, H. Yoon, H. Yang, and C. S. Koh, "A generalized Chua-type vector hysteresis model for both the non-oriented and grain-oriented electri¬cal steel sheets," IEEE Trans. Magn., vol. 47, no. 5, pp. 1146-1149, Sep. 2000.