Finite Element Analysis of Magnetostriction Force in Power Transformer Based on the Measurement of Anisotropic Magnetostriction of a Highly Grain-Oriented Electrical Steel Sheet

Lixun Zhu, Hee-Sung Yoon, Hyun-Jin Cho, Doo-Jong Um, and Chang-Seop Koh, *Senior Member, IEEE*

College of ECE, Chungbuk National University, Chungbuk, 361-763, Korea, zhulixun@chungbuk.ac.kr

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.

***Index Terms*—Electrical steel sheet, magnetostriction, magnetostriction forces, transformer**

I. Introduction

It is well known that vibration in power transformer is mainly caused by magnetostriction force of core liminations [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.

Till now, the vibration caused by magnetostriction effects has been left aside while that by electromagnetic forces has been investigated extensively through finite element analysis (FEA). This is thought to be partly because of the difficulties in measurement and modeling of the magnetostriction data of an electrical steel sheet (ESS).

A precise measurement of anisotropic magnetostriction data up to magnetic saturation level is still limited to non-oriented and grain-oriented materials [3]-[4]. 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 [4]-[5].

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.

II. Measurement and Modeling of Anisotropic Magnetostriction of a Highly Grain-oriented ESS

A. 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 [5]. In the measuring system, strain signals from the three-axial strain gauges are acquired when B-waveform is controlled to be elliptic, and the corresponding H-waveform is needed for the electromagnetic modeling. The normal strains (ε_x, ε_y) and shear strain (γ_{xy}) are calculated as follows:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \cos^2\theta_a & \sin^2\theta_a & \sin\theta_a\cdot\cos\theta_a \\ \cos^2\theta_b & \sin^2\theta_b & \sin\theta_b\cdot\cos\theta_b \\ \cos^2\theta_c & \sin^2\theta_b & \sin\theta_c\cdot\cos\theta_c \end{bmatrix}^{-1} \begin{bmatrix} \varepsilon_a \\ \varepsilon_b \\ \varepsilon_c \end{bmatrix} \tag{1}$$

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:

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

Fig.2 shows the principal strains measured by using the developed round-type 2-D SST under rotation magnetic field when axis ratio is 0.1.

B. Modeling and FEA Implementation

The sinusoidal and elliptic B-waveforms are parameterized, as in [6], using maximum magnetic flux density, $B_{\max}$, inclination angle, φ, and axis ratio, α.

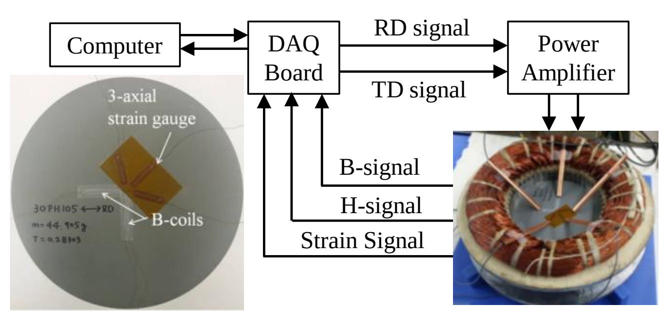


Fig. 1 Magnetostriction measurement system.

A magnetostriction (i.e., normal and shear strains) measured for an elliptic B-waveform is modeled and saved into a database based on Fourier series expansion as follows:

$$\varepsilon_k(\tau, B_{\max}, \varphi, \alpha) = \varepsilon_{k0}(B_{\max}, \varphi, \alpha) + \sum_{n=1}^{N}\left[R_{2n}^{k}(B_{\max}, \varphi, \alpha)\cos(2n\tau) + I_{2n}^{k}(B_{\max}, \varphi, \alpha)\sin(2n\tau)\right] \tag{3}$$

where the subscript k stands for x, y and xy, and N is the number of harmonic components taken into account.

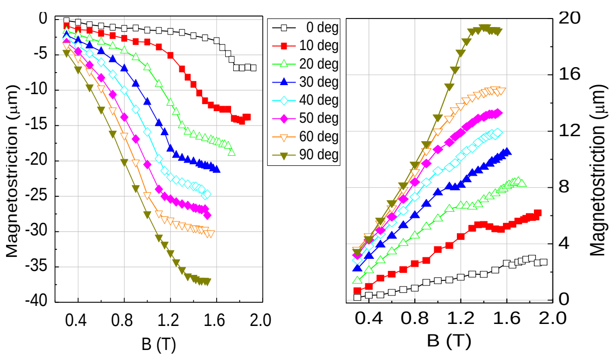
By utilizing the database, the magnetostriction for an arbitrary elliptic B-waveform is found through interpolation in ($B_{\max}$, φ, α) space. A non-elliptic B-waveform is approximated to an elliptic one by using the method presented in [6], and its corresponding magnetostriction is found.

C. FEA of Magnetostriction Forces

The magnetostriction force at k-th node in an element is computed as follows:

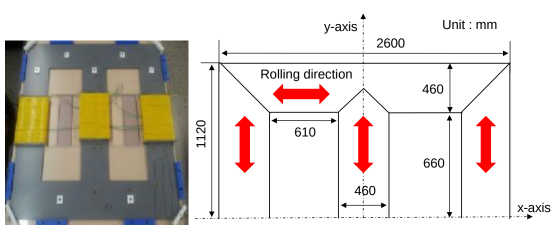
$$\begin{bmatrix} F_{k,x}^{e} \\ F_{k,y}^{e} \end{bmatrix} = \left[K^{e}\right] \begin{bmatrix} (x_k - x_m)\varepsilon_x \\ (y_k - y_m)\varepsilon_y \end{bmatrix} \tag{4}$$

where $[K^e]$ is mechanical stiffness matrix, (x_m, y_m) is center of an element, respectively, the subscript k is 1, 2 and 3 in first order triangular element.



(a) compressive strain (b) tensile strain

Fig. 2 Principal strains of a specimen 30PH105 with respect to inclination angle and magnetic flux density when α=0.1.



(a) model transformer (b) specifications

Fig. 3 Power transformer model of 30MVA made of a highly grain-oriented ESS (30PH105).

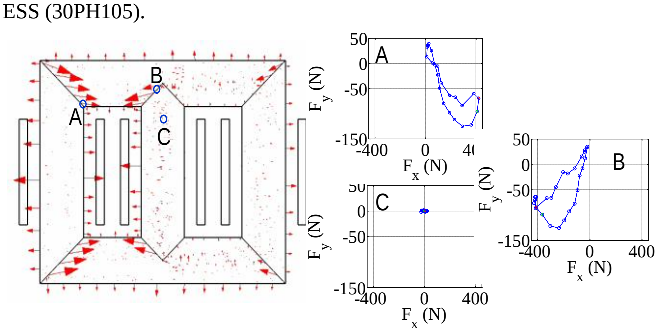


Fig. 4 Distribution of magnetostriction forces at ωt =0 in steady state.

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 ($B_{\max}$, φ, α) for each element and calculate the magnetostriction using (3),

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

III. Application to a Power Transformer

Fig. 3 shows a model transformer for a power transformer of 30MVA with 154 ($kV_{L\text{-}L}$). 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 ($V_{L\text{-}L}$) is applied on the winding which has 356 turns.

The measurement and FEA simulation were carried out without secondary winding with the assumption that the magnetostriction is only dependent on the exciting current. The FEA of magnetic field was accomplished by using (B, θ_B) formulation [7].

The distribution of the magnetostriction force at time ωt=0 after reaching steady state is shown in Fig. 4 together with force trajectories at some points. It is found that the transformer has quite big magnetostriction forces at joint areas of lamination where the magnetic flux is not always along the RD. On the other hand, the magnetostriction forces are negligible at the transformer legs where magnetic flux is always parallel to RD.

In the version of full paper, the measuring system as well as the numerical procedure will be explained in more detail. The numerical results will also be compared with experimental ones.

IV. References

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