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 ($B_\text{r}$), 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 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 12.5mm) 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 ($\varepsilon_n$, $\varepsilon_o$) and shear strain ($\varepsilon_s$) are calculated as follows:

\[
\begin{aligned}
\begin{bmatrix}
\varepsilon_n \\
\varepsilon_o \\
\varepsilon_s
\end{bmatrix} &=
\begin{bmatrix}
\cos^2\theta & \sin^2\theta & \sin\theta \cos\theta \\
\sin^2\theta & \cos^2\theta & -\sin\theta \cos\theta \\
0 & 0 & 1
\end{bmatrix}^{-1}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z
\end{bmatrix}
\end{aligned}
\]

where $\theta$ and $\varepsilon_x$, $\varepsilon_y$, $\varepsilon_z$ are angle from the RD and strains of each strain gauge, respectively. Magnetostriction along an arbitrary direction, $\varepsilon$ is obtained as follows:

\[
\varepsilon(t, \phi) = \varepsilon_n(t)\cos^2 \phi + \varepsilon_o(t)\sin^2 \phi + \varepsilon_s(t)\sin \phi \cos \phi
\]
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, \( B_{\text{max}} \), inclination angle, \( \phi \) and axis ratio, \( a \). 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 magnetostriction parameters at different magnetic fields. In
this paper, the magnetostriction parameters \( \{ P \} \) is optimized by PSO
method. Meanwhile, the results and the corresponding \( B_{\text{max}}, \phi, a \) are
saved into a database. So the magnetostriction parameters \( \{ P \} \) are
the function of the corresponding B-waveform shown as follows:

\[
\{ P \} = f \left( B_{\text{max}}, \phi, a \right)
\]

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 trinomial interpolation with
the database together. The calculations resulted by the interpolation
are the magnetostriction parameters \( \{ P \} \) of the corresponding
magnetostriction waveform. At last, the magnetostriction waveforms
can be calculating using (2). Fig. 2 compares measured and modeled
magnetostriction waveforms under elliptical magnetization at
\( B_{\text{max}} = 0.7T \), \( \phi = 30 \) deg, and \( a = 0.3 \).

\[<\text{Fig. 2}\] \quad \text{Comparison of calculated and measured magnetostriiction 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 \( \{ B_{\text{max}}, \phi, a \} \) 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 156 \( \times \) V\text{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\text{L}\text{L}) is applied on
the winding which has 56 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.

\[<\text{Fig. 3}\] \quad \text{Distribution of magnetostriction forces at } t=0 \text{ 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]

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