Magnetostrictive Characteristics in Grain-Oriented Laminated Cores Magnetized with a DC Biased Magnetic Field

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The presence of direct current (dc) biased magnetic field intensifies the vibration and noise in the transformer cores due to magnetostrictive effect in the electrical steel laminations. The magnetostrictive property in laminated cores is measured on a modified Epstein frame and the difference of magnetostriction strain between a single steel sheet and laminated cores is illustrated. The effect of dc biased magnetic field on magnetostriction in laminated cores is investigated and the vector relation between principal strain and magnetic flux density is made clear by means of experimental data. A simple magnetostriction model is proposed to simulate the magnetostriction under dc bias in a single-phase transformer core model and its validity is verified.

***Index Terms*—DC bias, Epstein frame, laminated core, magnetostriction**

I. Introduction

Direct current (dc) bias is an abnormal phenomenon which may occur in the operation of a power transformer [1]. The presence of dc biased magnetic field may intensify vibration and noise in transformer cores since the resultant of alternating magnetization and dc bias changes the magnetostrictive property of the core material then causes the deformation of laminated cores. Some significant research work has been conducted on the measurement of magnetostrictive properties in a single grain-oriented (GO) steel sheet with the magnetization patterns of alternating or rotational magnetic field [2]-[5]. Very recently, by taking the effect of dc bias into consideration, the magnetostrictive property of a single GO steel sheet [6] or a ferrite toroidal [7] has been investigated based on experimental tests. However, a single sheet test cannot fully explain the magnetostrictive strain and audible noise in the electrical steel laminations used in the construction of transformer cores especially when the transformer works under dc biased fields.

In this paper, based on a modified Epstein frame, the magnetostrictive characteristics and its anisotropy in laminated cores magnetized with alternating field combined with a dc bias are measured, and the effects of dc biased field on principal strain of magnetostriction are investigated. The discrepancy of magnetostriction strain on a single steel test and a laminated one is illustrated. An estimated model is employed to explain the vector relationship between principal strain and magnetic flux density, and the magnetostriction in the lamination under dc bias is simulated and measured.

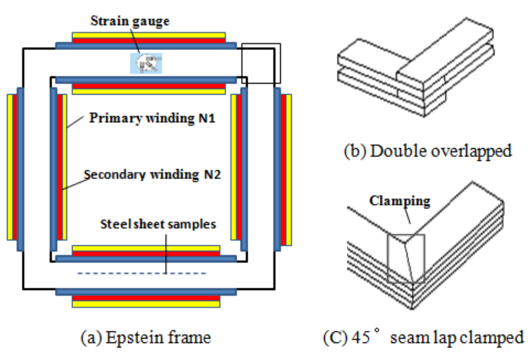


Fig.1 Epstein frame setup

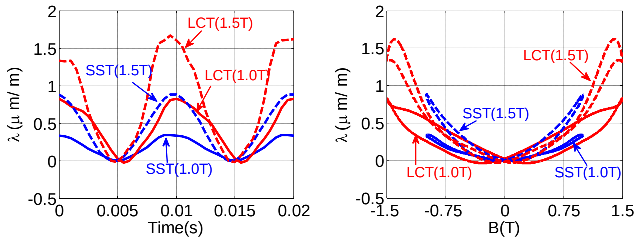
II. Magnetostriction in Laminated Cores

A. Measurement System

Fig.1 shows an Epstein frame with two kinds of different overlap designs in joint regions, in which the primary and secondary windings consist of four coils in series with the total 700 turns and a rosette foil type of triaxial strain gauge, KFG-10-120-D17-11, is stuck to the surface of electrical steel sheet to obtain an in-plane magnetostriction in an arbitrary direction as shown in Fig. 1(a). One kind of overlap designs is referred as a standard Epstein frame design with a double overlapped shown in Fig. 1(b) and 7 pieces of laminated steel sheets on each limb with 0.3m length and 0.03m width are not clamped together. The measurement results on the standard Epstein frame is similar to one in a single steel sheet due to the unclamped design and hereinafter regarded as a single sheet test (SST). The other is a modified Epstein frame design with a 45° seam lap assembling in Fig. 1(c) and the steel sheets are clamped at the mitered corners to simulate the practical transformer cores. The measurement on the modified Epstein frame is referred as a laminated core test (LCT).

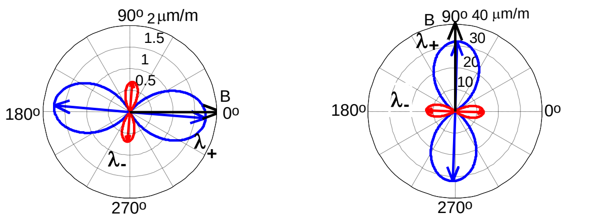
B. Difference of Magnetostriction Measured on a Single Sheet Test (SST) and a Laminated Core Test (LCT)

Fig.2 shows measured magnetostriction strain from SST and LCT when the specimen is magnetized along the rolling direction (RD) with peak magnetic induction B_{max} of 1.0T and 1.6T. From the figure, we can see that measured magnetostriction strain along the RD on LCT is nearly one time greater than that on SST. There are two factors resulted into the obvious increase of magnetostriction, one is the effect of external stress induced by the clamped design, and the other is that the magnetostrictive strain of laminated cores as a whole gets bigger. Therefore, the study of magnetostriction concentrated on a SST is not enough to represent the vibration and audible noise in transformer cores in practical applications.



(a) λ_{RD} vs. t (b) λ_{RD} vs. B

Fig.2 Magnetostriction in the RD measured from SST and LCT



(a) magnetized along the RD (b) magnetized along the TD

Fig.3 Elongated principal strain marked with blue line and contractive one with red line in laminated cores when the magnetic induction is 1.6T

C. Anisotropy of Magnetostriction in Laminated Cores

In order to investigate the principal strain of magnetostriction on LCT under different magnetizing directions, the samples are cut with 30° intervals from the RD to the transverse direction (TD). Based on the knowledge of plane strain, the elongated λ_+ and contracted λ_- principal strain can be calculated as

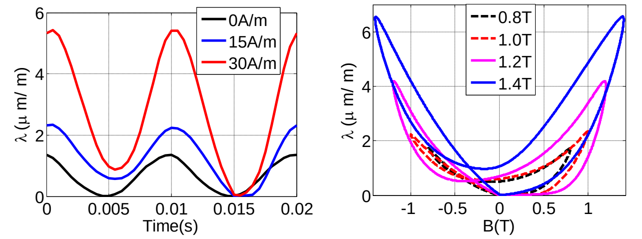
$$\lambda_+, \lambda_- = \frac{\varepsilon_x + \varepsilon_y}{2} \pm \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2} \quad (1)$$

where ε_x, ε_y are the linear strains and γ_{xy} is shear strain which can be obtained from a triaxial strain gauge measuring the strains at angles of 0°, 45° and 90° with respect to the RD.

Fig. 3 displays the variation of principal strain in one time period in the polar coordinate with 1.6T magnetic induction when the samples are magnetized along the RD and the TD, respectively. It can be seen that the maximum elongated principal strain with blue arrow line occurs at the same direction as the magnetization, but its value in the TD is nearly 18 times greater than one in RD with highly strong anisotropy of magnetostriction. The texture plays a significant role in this phenomenon and there is more 90° domain wall motion when the sample is magnetized along the TD, which results in high magnetostriction.

D. Magnetostriction in Laminated Cores with DC Biased Field

During the measurement, the excitation current in the primary windings in Fig. 1 is overlapped with a dc component, then the samples are magnetized by a resultant of alternating magnetic field and a biased one H_{dc}. Fig. 4 illustrates the variation of elongated principal strain λ_+ in laminated cores with the increase of dc biased field H_{dc} when the samples are magnetized along the RD. In Fig. 4(a), it can be seen that the waveform of λ_+ is not equal in a time period. When H_{dc} increases to 15A/m and 30A/m from 0A/m, respectively, the amplitude of elongated principal strain increases to 2.34μm/m



(a) λ_+ vs. t with 1.4T (b) λ_+ vs. B at H_{dc}=50A/m

Fig.4 Elongated principal strain λ_+ in laminated cores under dc biased field when the samples are magnetized along the RD

and 5.45μm/m from 1.21μm/m respectively. Fig. 4(b) shows the magnetostrictive elongation loops under alternating flux condition at B varying from 0.8T to 1.4T under a specific H_{dc} of 50A/m. It is apparent that the butterfly loops are asymmetrical under the condition of dc bias, and the left wing of the butterfly curve has a tendency to degenerate. More discussion on the effect of dc bias on magnetostriction will be presented in the extended paper.

III. Prediction of Magnetostriction under DC Biased Field in Laminated Cores

According to the magnetostrictive property under dc bias in the electrical steel laminations mentioned above, the vector relationship between elongated principal strain and magnetic flux density can be described as

$$\begin{cases} \lambda_+ = f(B_m, \theta_B) \\ \theta_{\lambda_+} = f(B_m, \theta_B) \end{cases} \quad (2)$$

where B_m and θ_B are the peak value and direction of applied magnetic induction, respectively, and $\theta_{\lambda+}$ is the direction of elongated principal strain. The proposed model is employed to simulate the magnetostriction distribution in a single-phase transformer core under different dc biased fields, and the detailed discussion will be given in extended version.

IV. References

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