Iron Loss Models under Static Stress for Non-Oriented and Grain Oriented Steel

Omar Saeed[1], Aroba Saleem[2], Tanvir Rahman[1], Richard Chromik[2], David A.Lowther[1]

[1]Department of Electrical and Computer Engineering, McGill University, Montreal, Canada
[2]Department of Mining and Materials Engineering, McGill University, Montreal, Canada

Frequency domain iron loss prediction models have been developed taking the effects of mechanical stress into account. Single Sheet Testers (SST) were used for non-oriented and grain oriented steels to apply up to 40 MPa stress (along a longitudinal direction) for frequencies ranging from 100 Hz to 1000 Hz. Both compressive and tensile stresses were applied. It was shown that the effects on core loss and magnetic permeability is greatest under compressive stress. Using the results of the experiments two modern frequency domain loss models were considered and modified to include the effects of stress. The variation of the model coefficients as a function of stress was studied and it was shown that the hysteresis component of the loss model varies significantly compared to the eddy loss component which is in line with expectations. The accuracy of the loss prediction models were found to be better than 97% for sinusoidal waveforms over the frequency range and for saturation levels up to 1.6 T.

***Index Terms*—Compressive Stress, electric machines, Iron Loss, Laminated steel, magnetic properties, single sheet tester.**

I. INTRODUCTION

STEEL laminations are widely used in electric machines as core materials. In real applications, these laminations are often subjected to stress, both tensile and compressive, during their manufacturing process such as cutting, clamping and shrink or press fitting, among others. Effects of static stress on the magnetic properties of materials caused by some of these processes can be quite significant. Also, in electric machines, the stator and rotor cores are subjected to cycles of stress under normal operations which may also have an impact on their performance. These, of course, are dynamic stress effects. Hence, for accurate prediction of electromagnetic device performances the effects of stress should be taken into account. These effects are generally quantified by measuring the changes to the magnetic permeability and the core loss in Epstein frame and SST magnetic measurement experiments [6].

Even though iron losses under compressive and tensile stress conditions have been studied previously [1, 2], adequate loss models have not been developed, particularly, for modern electromagnetic computational software. The main reason for this is that the calculation of dynamic stress effects on the electromagnetic field solution (magnetostriction) is time consuming and is not practical for application in commercial packages at present. Nevertheless, loss prediction models including static stress effects (due to manufacturing processes etc.) also need to be developed and these would be relatively easier to implement, from an algorithmic standpoint. Also, compared to the models presented in [2], in recent years, a number of advancements have been made on frequency domain iron loss models [5] which have not been modified to include the effects of mechanical stress. Because of these, in this work, we have carried out Epstein frame and SST experiments to measure the magnetic properties of grain oriented and non-oriented steels under compressive and tensile stresses. The experiments were conducted for frequencies from 100 Hz to 1 KHz and at induction levels past the saturation point, for sinusoidal waveforms only. Using the results of our measurements we have developed novel frequency domain loss prediction models that include the effects of compressive stress. The development of these models comprise the first step towards developing practical time domain models which can be used to calculate the effects of static stress in electromagnetic devices. The effect of tensile stress was not included in the models presented here because their effect on the magnetic permeability and the iron losses were found to be negligible. The first part of this paper discusses the iron losses obtained via the experimental setup under different levels of stress; both tensile and compressive. The second part of this paper shows the effect of compressive stress on the iron loss coefficients and ultimately proposes a model that includes the effect of frequency, magnetic flux density and compressive stress levels.

II. EXPERIMENTAL PROCEDURE

The Brockhaus Single Sheet Tester (SST) was used to obtain the iron losses and the magnetic permeability for both the non-oriented, 35WW300, and the grain oriented, M85-23P, steel laminations under various levels of stress. The measurements were done from 100-1000 Hz for sinusoidal excitations and for induction levels from 0.1 Tesla to 1.6 and 1.9 Tesla, respectively. Measurements were carried out up to a compressive stress of around 40 MPa and a tensile stress of about 40 MPa. The laminations were subjected to a number of cycles of stress to ensure consistency of measurements. The SST measurement results under zero stress were compared to that of the Epstein frame measurements to ensure accuracy of measurements.

III. ANALYSIS AND MODELING

Figure 1 shows the variation of iron losses with respect to stress (from compressive (negative) values to tensile (positive) values) at two different frequencies for the non-oriented steel (at B peak = 1 Tesla). It can be observed that the loss is more sensitive to compressive stress rather than tensile stress. The reason for this is that in contrast to tensile stress, compressive stress hinders the movement of the magnetic domains trying to align with the external magnetic field [1, 4] and hence, more energy is dissipated in that process resulting in higher losses. Similar observations have been confirmed previously in [2]. In each case, however, the effects of stress saturates. Based on this observation, for frequency domain loss prediction model development we have considered the effects of compressive stress only. Figure 2 shows an example of the effect of compressive stress on the magnetic characteristics and the loss in one of the samples, keeping the peak induction level fixed. Similar results have been obtained for both materials at various induction levels and frequencies. It can be seen that the permeability of steel reduces with respect to compressive stress levels.

The loss data obtained from the measurements are fitted to frequency domain prediction models to derive new formulae. Two general models which have been studied previously [5] for loss prediction without stress were considered in this work. They are shown below.

$$P_{Fe} = K_{hyst}B^2 f + K_{eddy}B^2 f^2 \qquad (1)$$

$$P_{Fe} = K_{hyst}B^{\alpha} f + K_{eddy}B^2 f^2 + K_{exc}B^{1.5} f^{1.5} \qquad (2)$$

Where, P_{Fe} is the iron loss, f is the frequency and B is the peak magnetic induction level. The physical interpretation of the two and the three terms models can be found in detail in [3, 6]. One of the main objectives of this work is to investigate the variations of the model coefficients when stress is included.

The iron loss coefficients K_{hyst}, K_{eddy}, α and K_{exc} in (1) and (2) are obtained by data fitting the results of the SST measurements. The algorithms for this are similar to those presented in [5]. The novel aspect of this work is that we have studied the accuracy of the models when stress effects are included, the behavior of the various loss components due to stress and derived appropriate models for the loss coefficients. Figure 3 shows that K_{hyst} is more sensitive to compressive stress than it is to frequency. This should be expected because stress should not affect the eddy loss components in materials. It was also observed that K_{hyst} can be fitted into a second order polynomial of stress, as shown in (3).

$$K_{hyst}(S) = A_{kh}S^2 + B_{kh}S + K_{hyst}(0) \qquad (3)$$

Where, A_{kh} , B_{kh} are model parameters and $K_{hyst}(0)$ is the iron loss coefficient under no stress. From Fig.4, it can be observed that the error between the iron loss, two term, model and the experimental data is minimal; less than 3%. It should be noted that Eq. 3 is different from that suggested by [2], one of the original findings in this work.

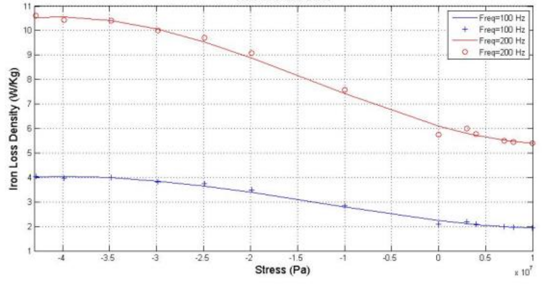

Fig. 1. Iron loss as a function of stress, non-oriented steel

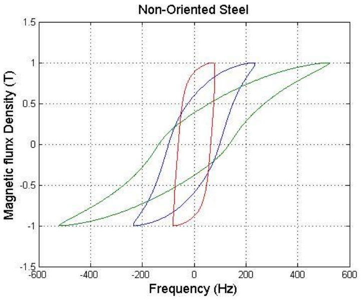

Fig. 2. Effect of compressive stress on the B-H Curve at 200 Hz and 1 Tesla

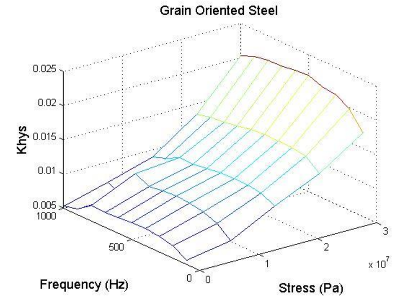

Fig. 3. K_{hyst} as a function of frequency and stress

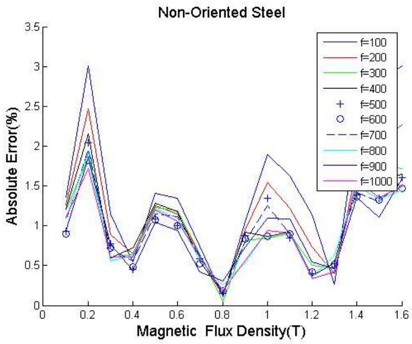

Fig. 4. Absolute Error vs Magnetic Flux Density at various frequencies (grain oriented steel -30 MPA)

IV. CONCLUSION AND FUTURE WORK

The iron loss and magnetic properties of two typical EM device steel were measured using SSTs. Using the experimental data novel frequency domain models for predicting iron losses under mechanical stress was developed.

V. REFERENCES

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