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Comparison between measured and computed magnetic flux density distribution of simulated transformer core joints assembled from grain-oriented and non-oriented electrical steel

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The flux distribution in an overlapped linear joint constructed in the central region of an Epstein Square was studied experimentally and results compared with those obtained using a computational magnetic field solver. High permeability grain-oriented (GO) and low permeability non-oriented (NO) electrical steels were compared at a nominal core flux density of 1.60 T at 50 Hz. It was found that the experimental results only agreed well at flux densities at which the reluctance of different paths of the flux are similar. Also it was revealed that the flux becomes more uniform when the working point of the electrical steel is close to the knee point of the B-H curve of the steel.

I. INTRODUCTION

The cores of power transformers are one of the major sources of emitted noise. The majority of this noise is produced by in the corner joints. Flux distribution in the corner joints of transformer cores has a major effect on forces between laminations hence the vibration and resulting emitted noise. The flux behaviour and the transfer mechanism in the joints of transformer cores is well known^{1, 2}. Several investigations have been carried out recently on flux distribution³⁻⁵ which can be classified into two approaches: Empirical measurements and theoretical calculations. Empirical measurements of the flux distribution in the joints slightly changes the geometry hence the magnetic flux density distribution in a joint. Thus calculating the flux density distribution in the jointed regions is useful to verify the measurement. Besides, the inability of modelling the material parameters such as anisotropy and microstructures in software cause the computational models to become less representative of the real model therefore these models should be validated by means of empirical experiments. Researchers with similar approaches such as in Mechler⁴ and Tang⁵ works have not empirically validated their models whilst earlier experimental studies of the flux distribution in a jointed stack were not theoretically verified e.g. in Jones⁶ and Löffler⁷ works. Hence, it is essential to study the flux distribution using both methods. Furthermore, different values for flux density

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levels in different regions of the joints have been reported when similar methods were used. These variations might be due to using different materials or geometries which were used in each study⁸.

In this study, a detailed comparison between computed and measured magnetic flux density distribution of a linear joint is presented. Two types of materials were used to study the effect of the permeability of the materials on flux distribution.

II. METHODS AND MATERIALS

Epstein strips of 0.35 mm thick M140 grade grain oriented (GO) steel and M250 grade non-oriented (NO) electrical steel were used in this study. Magnetic properties of the NO steel were measured using an Epstein frame according to IEC 60404-2. The GO material was provided as 500×500 mm sheets, and its magnetic properties were measured with a single sheet tester according to IEC 60404-3. Then the sheets were cut into 300 mm × 30 mm Epstein strips and stress relief annealed. The variation of relative permeability of the two materials is shown in FIG. 1. This data was used as input characteristics to obtain the flux distribution in the model assembly using COMSOL Multiphysics software.

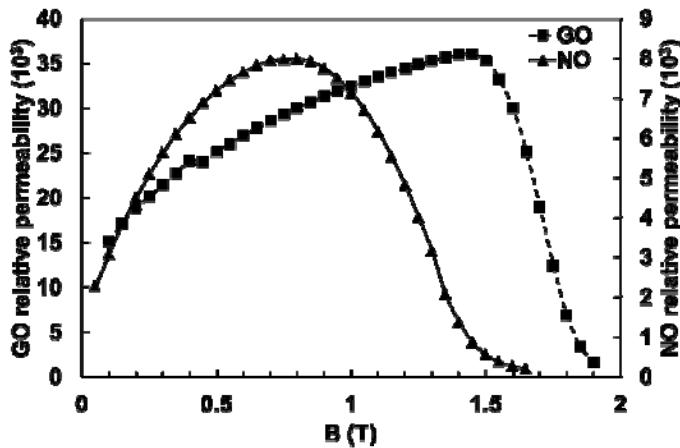


FIG. 1. Relative permeability characteristics of NO and GO materials measured using the Epstein frame and the single strip tester respectively

In each experiment nine layers of strips were assembled with butt and lap joint configurations and a single step lap joint was set up in the center of one limb to simulate the 45° mitered transformer core corner joint in a linear fashion. The benefit of the linear joint is that it is easy to assemble accurately and the flux distribution can be studied without the influence of the material anisotropy and 90° transfer in actual joints so it reduces to a simple two-dimensional problem. Single turn search coils formed from 60 μm diameter enamel coated copper wire were installed at points along the strips in layer 5 to measure the distribution of the longitudinal component of localized flux density along the path AB (See FIG. 2 and FIG. 3). The search coils were glued to the strips in order to fix them in place were tightly wrapped around the strips. The layer of glue

was negligibly thick after gently spreading with a cotton bud to ensure that the search coils were not damaged. After positioning the search coils, to fix the strips in place, their edges were glued to adjacent layer as shown in FIG. 2. Since the glue is non-magnetic and non-conductive it would have no influence on the flux distribution. Also the stress imposed on the steel by the adhesive after it had set was negligible. The outcome of this process was a rigid limb of the Epstein square which consisted of nine layers as shown in FIG. 3. In this schematic diagram two perpendicular arms of the Epstein frame are also illustrated. The cross sectional area of the strips positioned at the back of the jointed strips are hatched. The photo of the experimental setup is shown in FIG 4. It comprises four rectangular cross section arms within which the Epstein strips are situated. Each arm wrapped by a 700 turn secondary coil on which is wound a 700 turn primary coil. The whole core was magnetized at 1.60 T, 50 Hz. An adaptive magnetic field was applied to the core in a way that the magnetic induction in the material was forced to be sinusoidal. Also the reported values of the magnetic flux densities for each search coils were averaged over five cycles in which all the measured peak values were within 0.05% of the target B value 1.60 T.

The relative permeability characteristics of the materials shown in FIG. 1 were used to carry out a static analysis of a 2D flux distribution model in the jointed stack region using COMSOL. The model was developed with the same joint geometry and dimensions as the experimental set up and solved at an overall limb flux density of 1.60 T. The localized flux density along the path AB in layer 5 was recorded. The schematic diagram of the model which was used in COMSOL is shown in FIG. 5. In order to minimize the number of finite elements a solid yoke was attached to the test zone to close the magnetic path. Magnetizing coils were placed on both sides of the studied region to help the uniformity of the flux in this region. The coils were driven by the current density which was input manually by the user. In COMSOL, the non-linear magnetic material can be implemented either with an analytic expression for the relationship between the B and the H fields, or with the help of a lookup table. In this investigation the measured data for relative permeability was inserted in B-H and H-B look up tables.

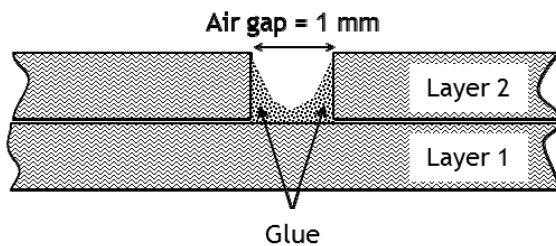


FIG. 2. Schematic diagram of the jointed area of the laminations in each layer which fixed by means of glue

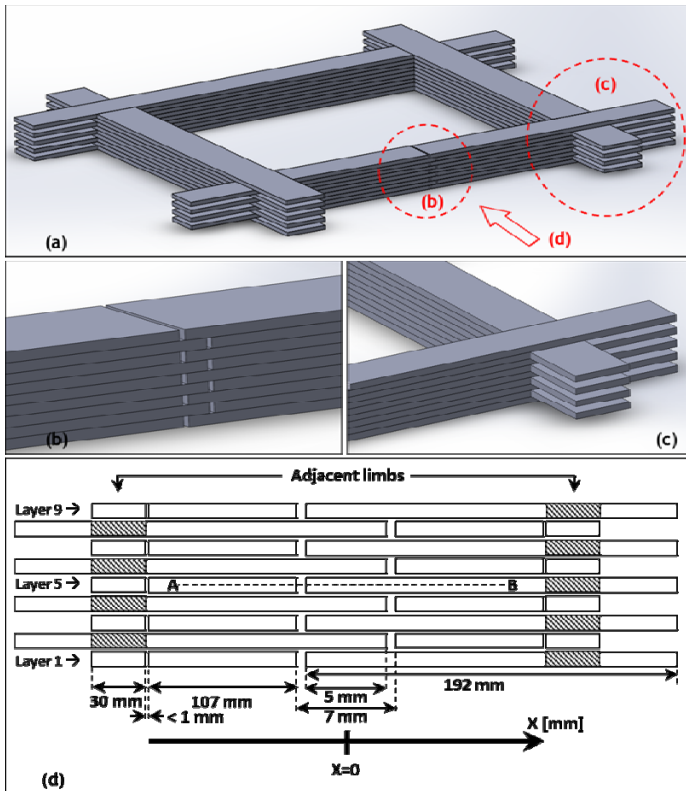


FIG. 3. Schematic diagrams of the jointed assembly in the Epstein frame showing (a) Full view of nine layers of the jointed assembly (b) Jointed region at the middle of the limb. The air gap length was 1 mm and the overlap length was 5 mm. (c) Four corners of the assembly are in butt lap joint configuration, hence the laminations are not overlapped in the corner joints so the assembly is the same as a conventional single phase transformer core with butt and lap outer corner joints (d) cross section of laminations in the jointed limb (front view of the assembly). Ends of laminations in adjacent limbs shown hatched. The origin of the x axis is placed at the centre of the overlap for future addressing purposes (The figure is not to scale).

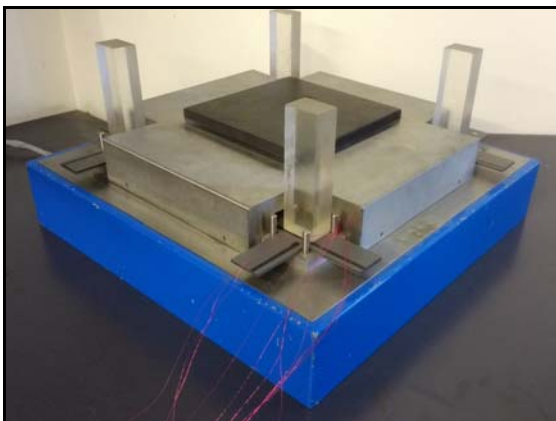


FIG. 4. The experimental setup comprising the standard Epstein frame with assembly of laminations inside the arms and four 100gr weights on four corners.

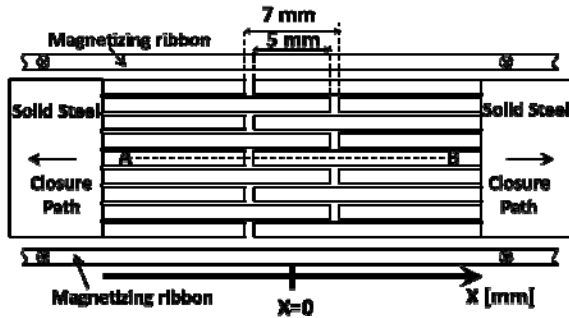


FIG. 5. Schematic diagram of the computational model in COMSOL including a cutline which is used to read the flux density of lamination 5.

III. RESULTS AND DISCUSSIONS

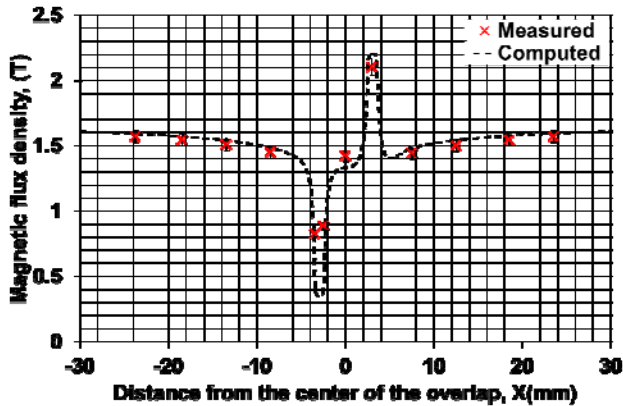
The measured and computed flux density distribution in both materials along layer AB at 1.60 T is shown in FIG. 4. The maximum difference between measured and simulated flux distribution at any point in the NO is less than $\pm 7\%$. In the GO material, measured and calculated flux density in the overlap regions agree well but the measured flux density is as much as 40% lower than the calculated value at $X < -2.5$ mm; and is up to around 10% higher than calculated at $X > 2.5$ mm. X is the distance from the mid-point of the overlap region as shown in FIG. 3.

The reluctance of an airgap is proportional to its length and inversely proportional to its cross-sectional area. If the length, width and height of the in plane airgap at the butt joint are considered to be 0.1, 30 and 0.35 mm then the reluctance of the in plane airgap in a fixed induction level would be a multiple of $(0.1 \div (30 \times 0.35))$ 9.5 while this value for the interlaminar air gap considering 0.016, 30 and 2 mm for length, width and height is $(0.016 \div (30 \times 2))$ 0.25 . This shows that the reluctance of an in plane airgap is approximately 38 times greater than that of interlaminar gap.

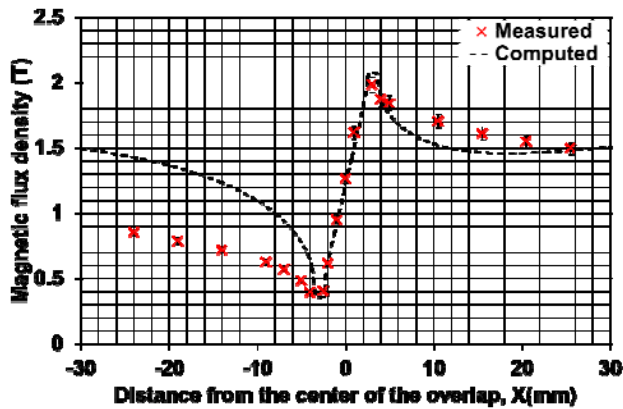
The MMF, hence the flux, drops in the airgap. The amount of this drop is proportional to the reluctance of the airgap. So in layer AB, the left butt joint is closer to the artificial airgap than the butt joints in adjacent layers. Thus the magnetic reluctance path per unit length of the $X < -2.5$ mm part in layer A is larger. Subsequently, the flux tends to pass more through the upper and lower adjacent layers, so the flux density at $X < -2.5$ mm in layer A drops. This non-uniformity is more significant for GO steel than for NO material at 1.60 T because the permeability of GO steel at 1.60 T is much higher than

that of the NO material at the same induction level. Higher permeability in the core results in a lower reluctance path which in turn produces the improper flux redistribution after the joint and increases the non-uniformity.

As shown in the FIG 6 there is a good agreement between measured and calculated results in the joint region. The airgap flux density in NO and GO steels are slightly less than 0.40 T. The flux density in the region which bridges the airgap in NO steel reaches 2.10 T and 2.20 T in the measured and simulated results respectively. These values for GO are 1.98 T and 2.08 T, which shows that the NO steel is in a state of deeper saturation in the bridge region.



(a)



(b)

FIG. 6. Longitudinal measured and calculated flux density distribution along layer A at 1.60 T (a) NO (b) GO

III. CONCLUSIONS

(1) The measured and computed flux densities in the airgap and the gap bridge region are similar for both steels despite their greatly different relative permeabilities. Further from the joint regions the measured and computed values do not agree well

in GO because of the influence of the outer corner joints which affects the flux distribution through changing the magnetic reluctance path in each layer of strips.

(2) Magnetic measurements of jointed assemblies in the Epstein frames are only independent of the outer corner joints when magnetized in the immediate vicinity after the knee point of the B-H curve. At lower inductions, the impact of the outer corner geometry on the flux distribution would be greater than the permeability of the test specimen.

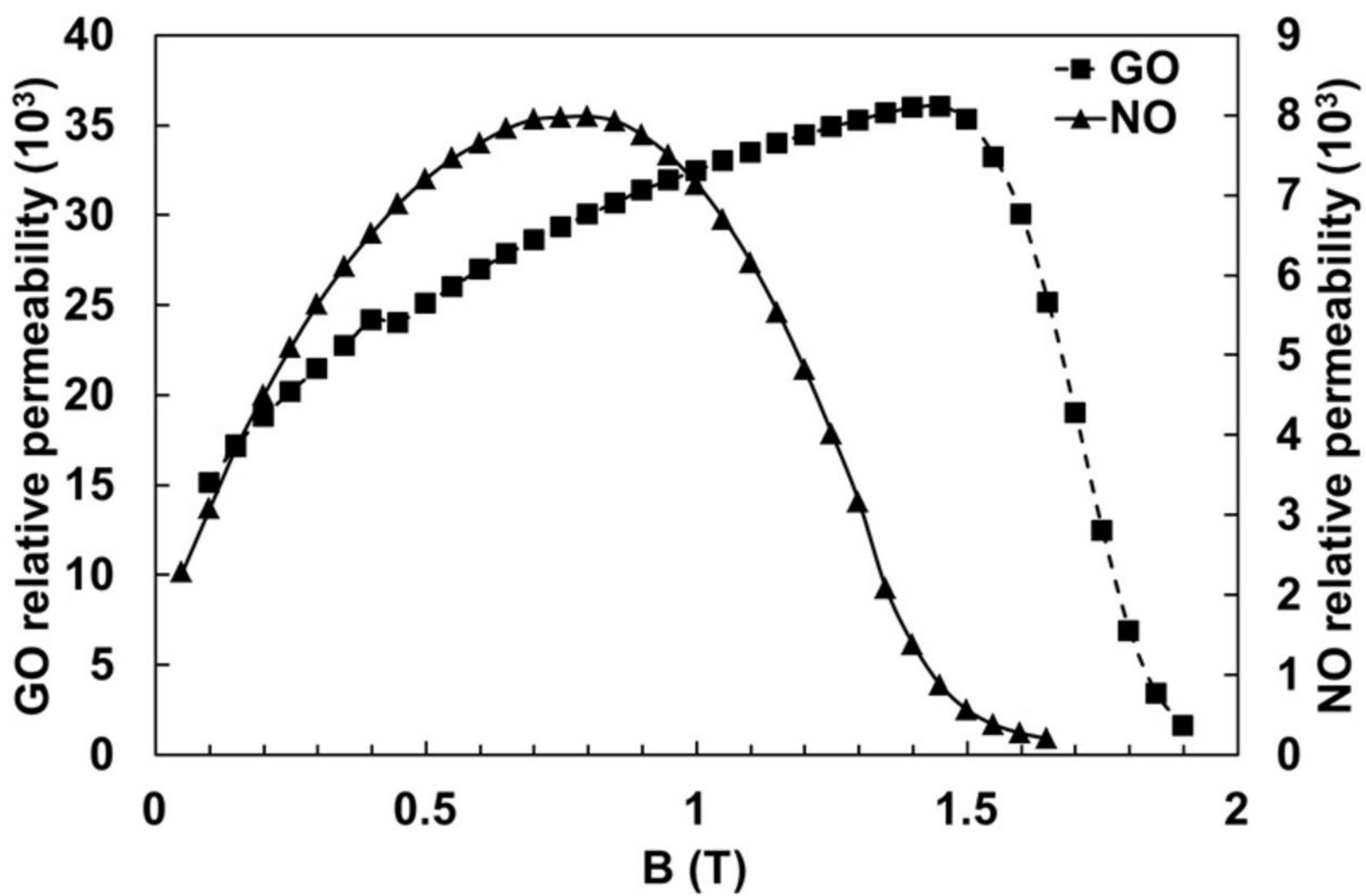
(3) The Epstein frame limb is too short to accurately study the flux distribution in artificial joints when it is assembled with high permeability materials. The minimum length of the test zone to have a uniform flux distribution depends on the relative permeability of the test specimen hence the nominal flux density.

ACKNOWLEDGMENTS

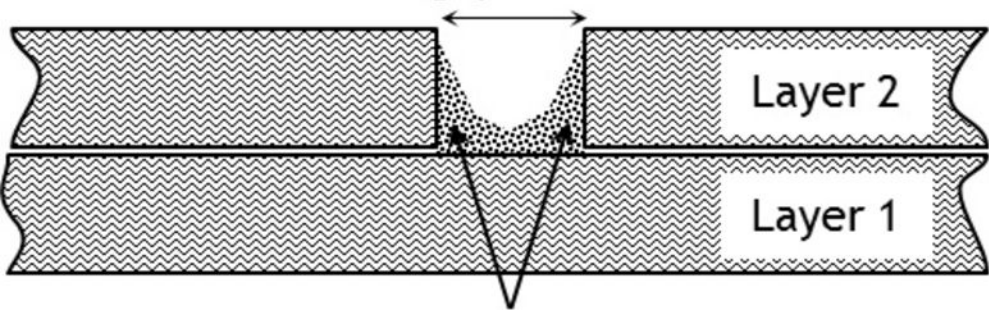
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Air gap = 1 mm



Layer 2

Layer 1

Glue

