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A HAND-HELD SENSOR FOR LOCAL MEASUREMENT OF MAGNETIC FIELD, INDUCTION AND ENERGY LOSSES

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*Abstract: The present work concerns magnetic circuits which are built of laminated soft magnetic materials, e.g. cores of transformers or of rotating machines. Such systems tend to show very complex local distributions of the magnetic field vector **H**, the induction vector **B** and the energy loss P. For simultaneous measurements of all these local quantities, we designed a hand-held sensor which can be arranged on the surface and - taking advantage from small sensor thickness - also between the core sheets. All data are displayed instantaneously on the computer screen. The measuring method is based on search coils for the planar components of **H**, and on the needle method for the components of **B** out of the electric field vector **E**. The losses P are derived from the Poynting vector **S** = **E** ´ **H**. The sensor proves to be an effective tool, e.g. for rapid investigations of T-joint regions in transformer cores which tend to show rotational magnetization. Apart from such practical applications, the present paper is focused also on fundamental problems of the novel sensor design.*

Keywords: sensors, magnetic field measurement, induction measurement, transformer cores, magnetic losses

1 INTRODUCTION

For the investigation of laminated, soft magnetic cores of electric machines, the local distributions of the following three quantities are of interest: the magnetic flux density vector ***B***, the magnetic field vector ***H*** and the power loss *P*. Conventional methods for the measurement of these quantities tend to be time consuming and destructive in most cases. For example, holes have to be drilled for the induction coil method for the measurement of ***B***. As well, the rise-of temperature method for the determination of *P* is tricky, sensitive with respect to artefacts and time consuming.

The aim of this work was to develop a sensor system which does not show the mentioned disadvantages. Further, it should be applicable also for inner regions of magnetic cores. To meet these demands, a hand held sensor was designed which can be placed on core surfaces but also in inner core regions as demonstrated by Figure 1. Local results of all three the magnetic flux density ***B***, the magnetic field ***H*** and the power loss P are displayed on a computer screen in an instantaneous way as already has been reported earlier in [1]. The present paper gives a closer description of the test System.

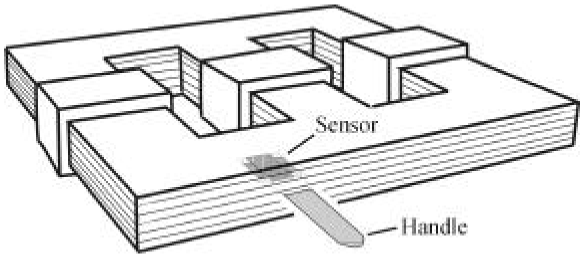

Figure 1. Practical application of the hand-held sensor for the interior of a transformer model core.

2 SENSOR DESIGN

The sensor consists of a 2 mm thick handle which carries a square active sensor region at its end. This 50 mm × 50 mm end region carries two crossed field coils for the determination of the two components H_x and H_y of the vector $\boldsymbol{H}$. Further it carries four extremely sharp needle contacts for the determination of the two components B_{xy} and B_{yx} of the vector $\boldsymbol{B}$ through two components of the electric field vector $\boldsymbol{E}$ [2]. The effective area size of about 25 cm² was chosen as a compromise between local resolution and averaging over inhomogeneities of the core material. Especially this is essential in the case of highly grain oriented SiFe sheets the grain size of which tends to be as large as 10 mm.

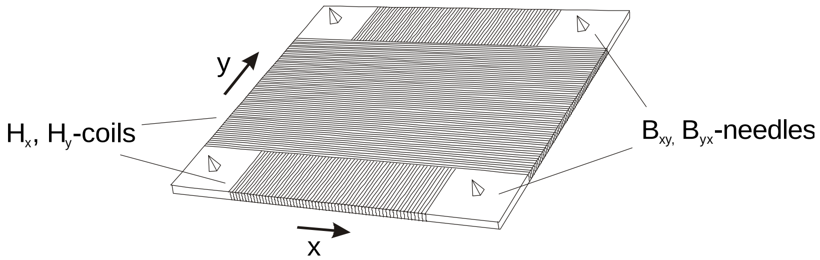

Figure 2. The active sensor region with B-needles and H-coils.

According to Figure 3, the voltage data of the four sensor components are acquired by a multi-channel ADC computer board with differential input and a high resistance input (10MΩ). The board has a built-in amplifier with an amplification of 1000. Because of the different orders of magnitude of the sensor signal and the operation voltage of the machine (e.g., a transformer), the individual contacted lamination has to be grounded with the ADC board. The resolution of the ADC is 12 bit, which is the limit with respect to sensor noise.

The measurement is started as soon as the computer registers full contact of the four needle contacts. The calculation of the local time values of $\boldsymbol{B}$, $\boldsymbol{H}$ and $\boldsymbol{E}$ is made instantaneously, and the loss P is evaluated from the Poynting vector $\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H}$. All data are instantaneously displayed on the screen.

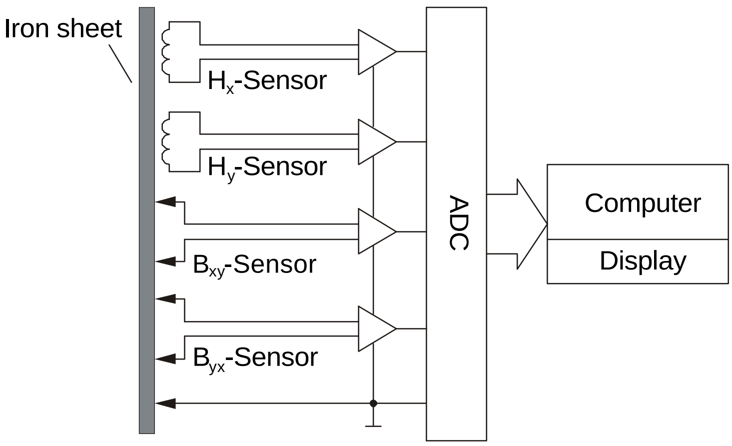

Figure 3. Block diagram of signal processing.

3 THEORETICAL CONSIDERATION

The present sensor comprises two field coils and two pairs of needle contacts. In principle, these components are well known as being used for other purposes since many years (actually, the needle method originates from 1955 [3]). The best known application is given for so-called rotational single sheet testers. They are used to investigate the behaviour of a defined sample of material subject to defined time patterns $\boldsymbol{B}(t)$ of the induction vector. Contrary to the here discussed application, the investigated sample region shows homogeneous magnetization by definition. The corresponding basic principles of measurement have been described, e.g., in [2]. As illustrated by
Figure 4a, the magnetic state of the sample is characterized by a magnetic field configuration which shows symmetry with respect to the sample's central area, that is $\boldsymbol{B}(z,t) = \boldsymbol{B}(-z,t)$ and $\boldsymbol{H}(z,t) = \boldsymbol{H}(-z,t)$. Also the modulus of the electric field vector $\boldsymbol{E}$ shows symmetry, i.e. $\boldsymbol{E}(z,t) = -\boldsymbol{E}(-z,t)$, but the direction is

antiparallel in the lower sheet half. Thus the voltage *U*y (= *U*y´) between a pair of needles of distance Δy yields the mean value of the corresponding induction component in an exact way. As well, the Poynting vector ***S*** is perpendicular to the sheet surface and yields total losses in an exact way (for details see [2]).

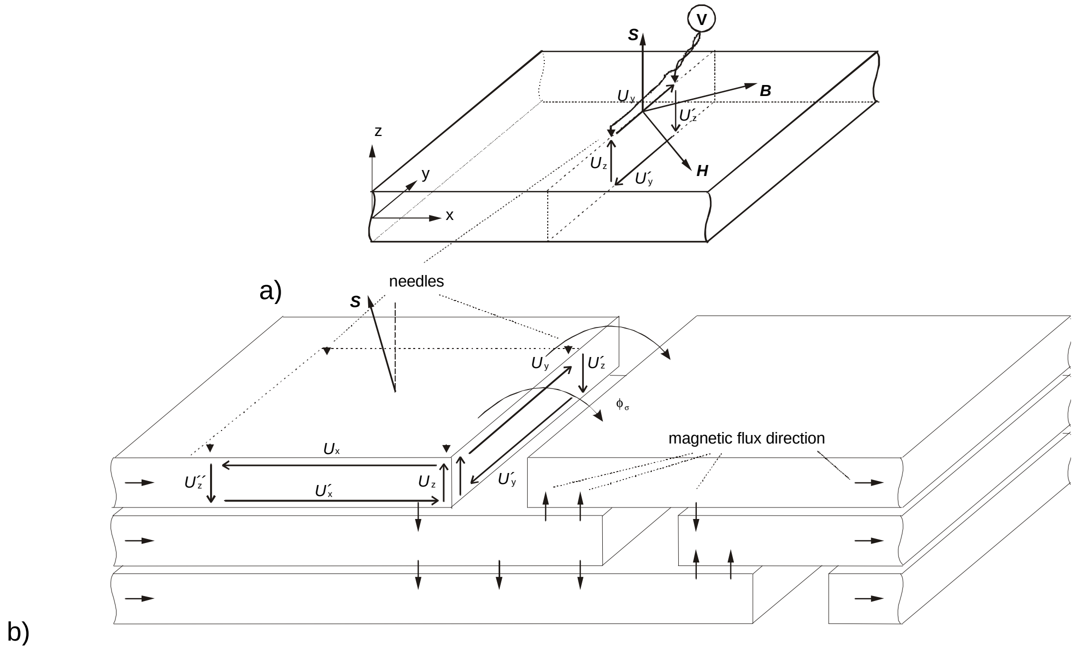

Figure 4: Schematic outline of signal establishment (compare the text). (a) For the homogeneously magnetized sample of a single sheet tester. (b) For a inhomogeneously magnetized laminated soft magnetic core, e.g., a transformer core (joint region).

On the other hand, the here discussed application is characterized by several possible sources of errors of measurement. For a schematic illustration,
Figure 4b shows the arrangement of needle contacts close to the overlap region of a transformer core. Inevitably, such joints include air gaps between neighbouring laminations. There results interlaminar flux in z-direction within the core, and the surface may show stray flux ϕ_σ through air. Both mechanisms mean that the symmetry condition ***B***(z,t) = ***B***(-z,t) may be infringed. As a consequence, *U*y may deviate from *U*y´ and thus does not represent the mean induction of the considered surface region any longer, apart from the fact that possible deviations of the mean vector ***B*** out of the sheet plane are not detected. As well, ***H***(z,t) = ***H***(-z,t) is not guaranteed any longer. Rather a tangential field coil will detect only the in-plane component of the upper surface's field vector ***H***. As a further consequence, the direction of the Poynting vector ***S*** may deviate from the normal direction. Finally, pronounced errors have to be expected if the measurement is performed in close vicinity of sheet edges as sketched in
Figure 4b, due to the fact that the voltages U_z cannot be assumed to be zero here. Closer discussions of consequences cannot be given here. However, we should keep in mind that all results of measurement show approximate character a priori. Of course this is valid also for the results as given in the following.

In addition it should be mentioned that another accuracy problem results from the fact that the here discussed sensor signals concern a single lamination the magnetic state of which may not be representative for the laminations further up or down. According to standards, the laminations may show thickness tolerances up to 10% which may yield strong variations especially of the local intensity of field.

4 RESULTS AND DISCUSSION

Figure 5 shows a comparison of results of the needle method with results of the induction coil method. The time courses of both the electric field *E*(t) and the mean flux density *B*(t) (averaged over the cross section of the investigated sub region of a lamination) show very small deviations. This demonstrates that the above mentioned sources of errors are not predominant here and it supports the effectiveness of the simple-to-handle needle method.

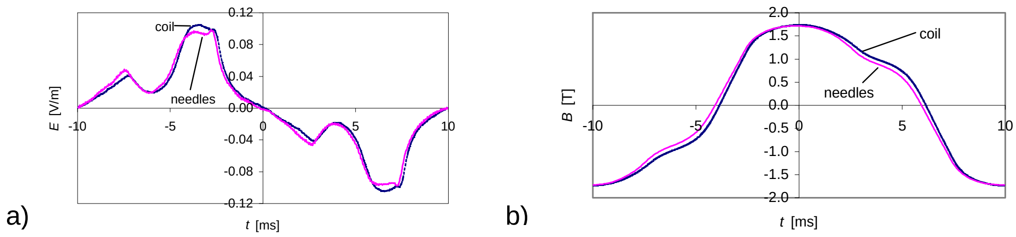

Figure 5. Comparison of results of the needle method with results of the induction coil method (coil through 0.8 mm holes in the top lamination of an outer limb, close to the corner). (a) Typical time courses *E*(*t*) of the electric field (coil data calculated). (b) Corresponding time courses *B*(*t*) of the mean flux density (needle data calculated).

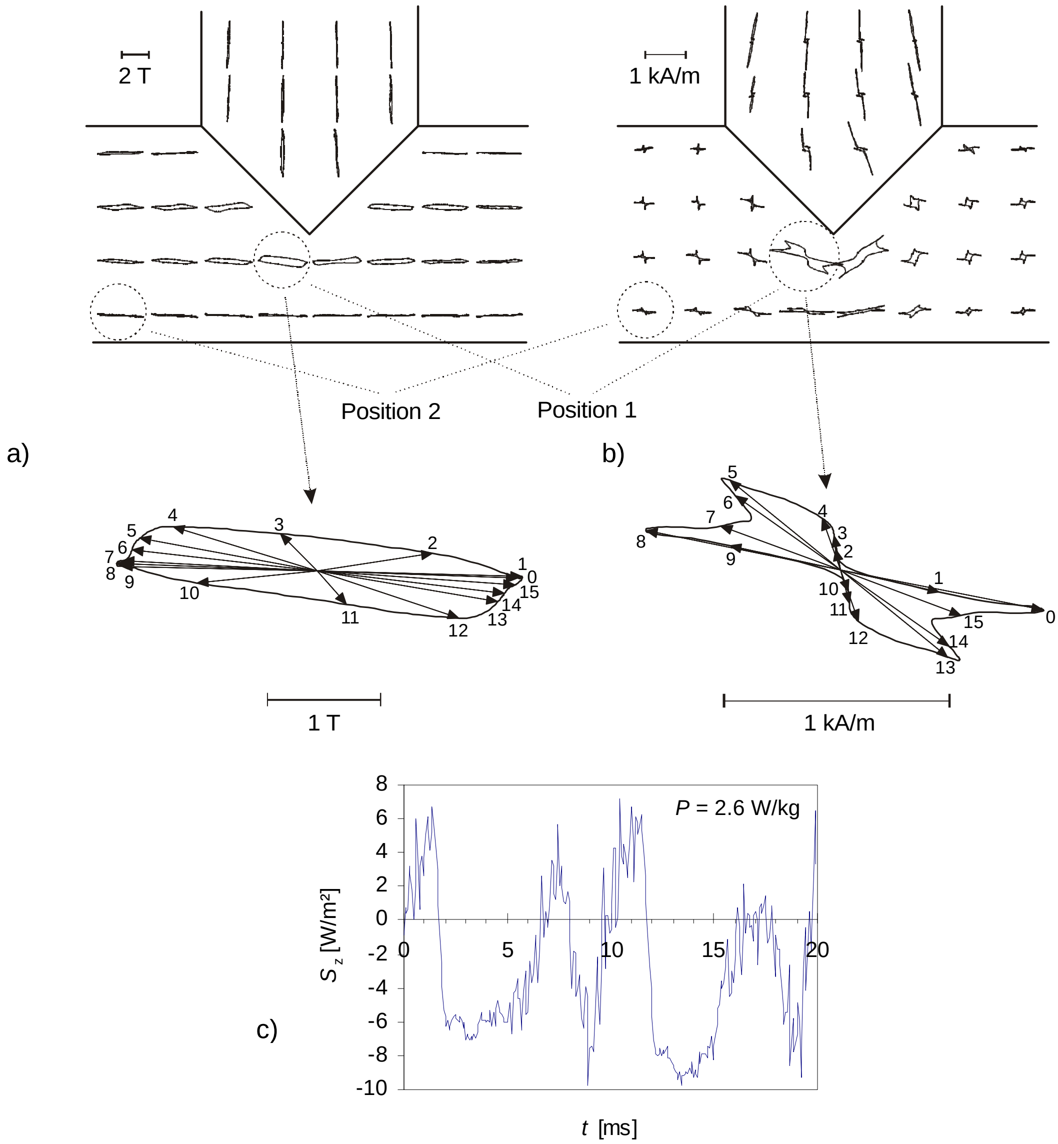

Figure 6. Typical results of measurement for 36 sub-regions of a transformer core. (a) Time patterns ***B***(*t*) of the induction vector (with detail for position 1). (b) Time patterns ***H***(*t*) of the field vector with detail for position 1. (c) Poynting vector ***S*** as a function of time *t* for one cycle for position 1, and the resulting local loss value *P*.

For a 3-phase transformer core assembled from highly grain oriented SiFe, Figure 6 shows results for 36 sub-regions (positions) close to the T-joint. The measurement was taken in a cooling duct arranged in the center of the core. Figure 6a shows the time patterns ***B***(t) of the induction vector. While the central limb exhibits almost pure alternating magnetization, the yoke shows distinct rotational magnetization of lozenge type. For position 1, the additionally given detail figure shows the loci of ***B*** for 16 equidistant instants of time, the period length being 20 ms. We see that ***B*** tends to pause in a small angle to the rolling direction (points 7,8,9 and points 15,0,1) while it “swaps” rapidly through the transverse direction within some few ms. The field vector ***H*** (Figure 6b) shows a complex behavior which can be explained by an interaction of all three anisotropy, eddy currents and hysteresis. Finally, Figure 6c shows the course of time of the Poynting vector ***S***. Its integral yields the mean power loss *P*. For position 1 we find the very high value *P* = 2.6 W/kg, while position 2 (Figure 7) yields only 2.0 W/kg due to much less pronounced magnetization in transverse direction.

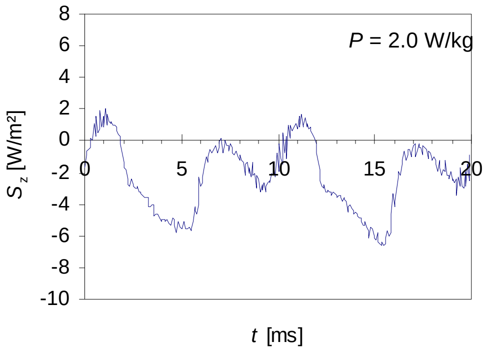

Figure 7. Poynting vector ***S*** as a function of time *t* for one cycle for position 2, and the resulting local loss value *P*.

5 CONCLUSIONS

The results of the present study yield the following main conclusions:

a) The used sensor design - i.e. a square active sensor region mounted on a handle – allows rapid access to individually chosen surface positions of laminated soft magnetic cores. Inner arrangements are possible in cooling ducts or also between individual layers which however may cause artifacts due to local bending and thus changed magnetic behavior of the material.
b) The sensor yields instantaneous results on the local time pattern ***B***(t) of the induction vector, on the local time pattern ***H***(t) of the field vector, and on local losses *P*.
c) The applied principle of measurement is based on the assumption that the contacted lamination shows symmetric magnetization with respect to its central area. Thus the results are of approximate nature if asymmetric flux arises normal to the lamination, e.g., due to stray flux or due to interlaminar flux as arising in joint regions of transformer cores.

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