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COMMUNICATIONS

Printed detector bands for measurements of strain in core interior of transformers

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In the recent years, the reducing of audible noise of laminated machine cores has become great importance, due to high relevance given to environmental awareness. The strain caused by magnetostriction and magnetostatic forces is recognized as one of the main sources of noise. Especially for transformers, strain in the core interior tends to be different from that on the surface, due to differences of clamping, variation of in-plane fluxes and pronounced off-plane (normal) fluxes. For the first time, local measurements of strain in the core interior are presented by means of a novel printed detector band. First results tend to be very promising, exhibiting very high sensitivity and resolution. So far, the relevance of measurements is restricted to comparisons of different core regions.

Keywords: magnetostriction, transformer cores, magnetic sensors

1 Introduction

In the recent years, the reduction of audible noise of laminated machine cores has become great importance, mainly due to high relevance given to environmental awareness. In particular, transformers tend to be situated closer to the population, due to steadily increasing energy demands. It means that decreases of the audible noise generated by them is of highest priority. As it is well known, the noise of a transformer is caused by the current that flows through windings, by the cooling system (fans and pumps of big power transformers) and by magnetization of the core. The latter is the focus of the current work. Core noise is generated by strain caused by magnetostriction and magnetostatic forces. A clear distinction between both of them is only possible by analytical interpretations, since both yield similar spectral components.

Several methods exist for strain measurements. Highest resolution may be achieved by interferometry methods, making the latter very attractive for cores of low nominal magnetizations. In [1], the corresponding advantages of laser interferometry are presented. Measurement of magnetostriction by both, laser displacement meter and laser Doppler vibrometer are presented in [2]. For high magnetizations, due to strong core vibrations, direct measurements by laser interferometers are critical, error prone and not reproducible [1]. As an alternative, measurements by strain gauges directly stuck on the surface [3], provide much better results for $B_{\mathrm{nom}} > 1$ T. Recently, measurements with acceleration sensors were presented in [4]. As an advantage, by means of the latter, strain not only in the plane, but also in off-plane, normal direction can be measured. However, for this method, a complex post-processing as well as complex analyses of the obtained signals are needed, as outlined in [4]. Typically, the acceleration sensors are of small size, thus preventing effective averaging over several grains of grain oriented material. An overview of several not-typical and rarely used direct and in-direct measurements methods like dilatometry are presented in [5]. Magnetostriction can also be estimated by observation of magnetic domains [6], however the latter is extremely laborious and requires a removing of coating.

A significant drawback of all existing methods is the fact that they can be used only for measurements on core surfaces. However, in particular, transformer cores are stacked from several packages of different width. Furthermore, circular limbs tend to be combined with semicircular yokes. It means that transformer cores represent 3D magnetization objects with very complex flux distribution, as recently found in [7]. The strain depends strongly on the induction and the clamping, as described in details in [8, 9]. However, on one hand side, the induction within a transformer core tends to show variations of more than 10% [10], and on the other hand the clamping is not uniform [8]. Furthermore, distinct off-plane fluxes exist, especially in the overlaps of corners and T-joints, as measured recently by an ultra-thin sensor [11]. The off-plane induction shows strong variations in the individual packages, and they tend to cause strong increases of magnetostriction [12]. The arguments mentioned above indicate in clear ways that the strain in the core interior differs from the strain on the surface.

In a previous work [3], for the first time, we performed local magnetostriction measurements by means of strain gauges in 20 locations on the surface of a 3-phase transformer core. However, measurements in the core interior were ineffective. Apart from laborious preparations of

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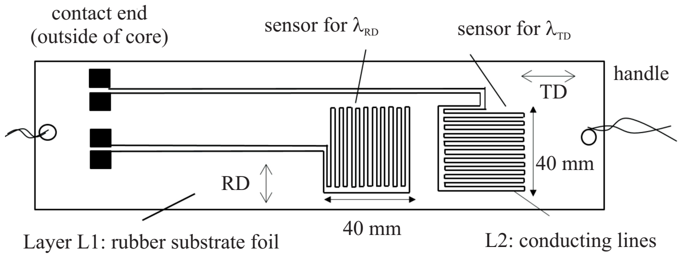

Fig. 1. Basic design for a printed detector band for strain measurement

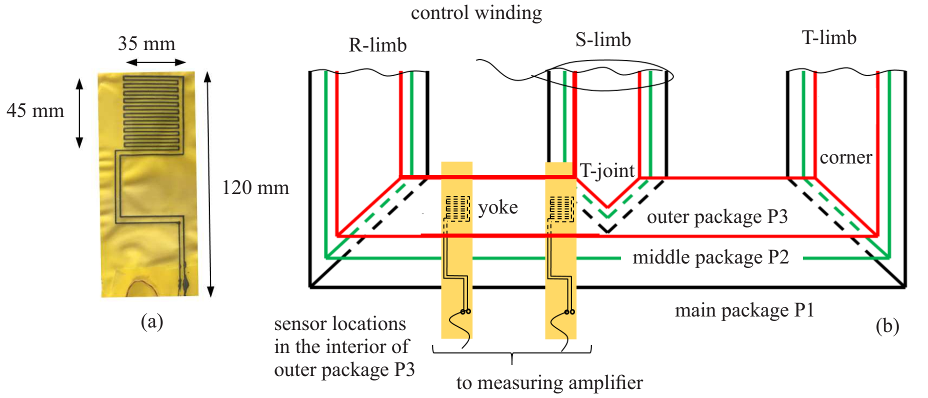

Fig. 2. Experimental: (a) – manufactured sensor, (b) – a schematic illustration of the investigated 3-phase, 3-limb model transformer core with the manufactured sensor inserted in the yoke and in the T-joint, respectively

laminations, including opening the core, taking out of individual sheets, sticking strain gauges and finally restacking the core, the mechanical stress through core clamping proved to influence and even destroy the junction between the electrical contacts of gauges and lead wires. The latter was the motivation to manufacture novel types of sensors. With these so called detector bands, for the first time, measurements of the strain in the interior of laminated machine cores, in particular in a transformer core are presented.

2 Sensor design and manufacturing

A schematic concept of a novel detector band for measurements of strain RD in rolling (RD) and in transverse direction (TD) is illustrated in Fig.1. The idea was to manufacture the senor by a printing procedure. Similar to the principle of conventional strain gauges, the detector band should detect the strain as a change of its electrical resistance. The here presented detector band is specially designed for measurements in the interior of laminated machine cores. As a carrier (compare Fig.1), a rubber-like substrate is used. The latter shows high elasticity and surface friction. Put in the interior of a core, it is expected that after clamping the rubber will follow the dynamic strain of the laminations. Furthermore, in compressed state, the rubber exhibits a minimum thickness of the small order of several tens of micrometers that can be assumed to be without after-effects on flux distributions. As a significant advantage compared to conventional strain gauges, the contact ends are placed outside the core, not to be damaged by weight of laminations as well as not to cause any additional inter-laminar air gaps. Compared to the conventional strain gauges, typically used for detection of strain in transformers [3, 8], the novel sensors are planned to be of larger width, well averaging over course grain structures, and promising higher signal intensity and better sensitivity.

The detector band is manufactured by in-house developed 3D/2D printing assembler for manufacturing of variety of magnetic foils sensors for analyses in transformer cores, as presented in [13]. The assembler consists of an extruder for plastic material and two nozzles for conductive ink as well as of a large thermo-controlled platform of 1000 mm length and 400 mm width. Figure 2 (a) shows the here applied sensor. The choice of a suitable ink represented a significant challenge of the current work. First attempts were performed with a carbon-based ink (bare conductive), mixed with water. The benefits of the latter are the low cost as well as good compatibility with the used dispenser system, driven by linear motors. However, a significant disadvantage is the high electrical resistance ($R > 15\,\mathrm{k\Omega}$) of the manufactured sensor and its variations in dependence of clamped state. Significant improvements were achieved by using of nickel-based ink. The electrical resistance was significantly reduced. However, the nickel ink printed on the rubber substrate proved to be very brittle, even by smallest kinks, which are unavoidable in the clamped state of a core. Finally, a silver ink from Henkel (Electrodag 6028 SS) was used. The manufactured sensor proved to be very suitable for our application due to its low resistivity (R between $15\,\Omega$ and $40\,\Omega$, dependent on the path width), and at the same time high mechanical stability.

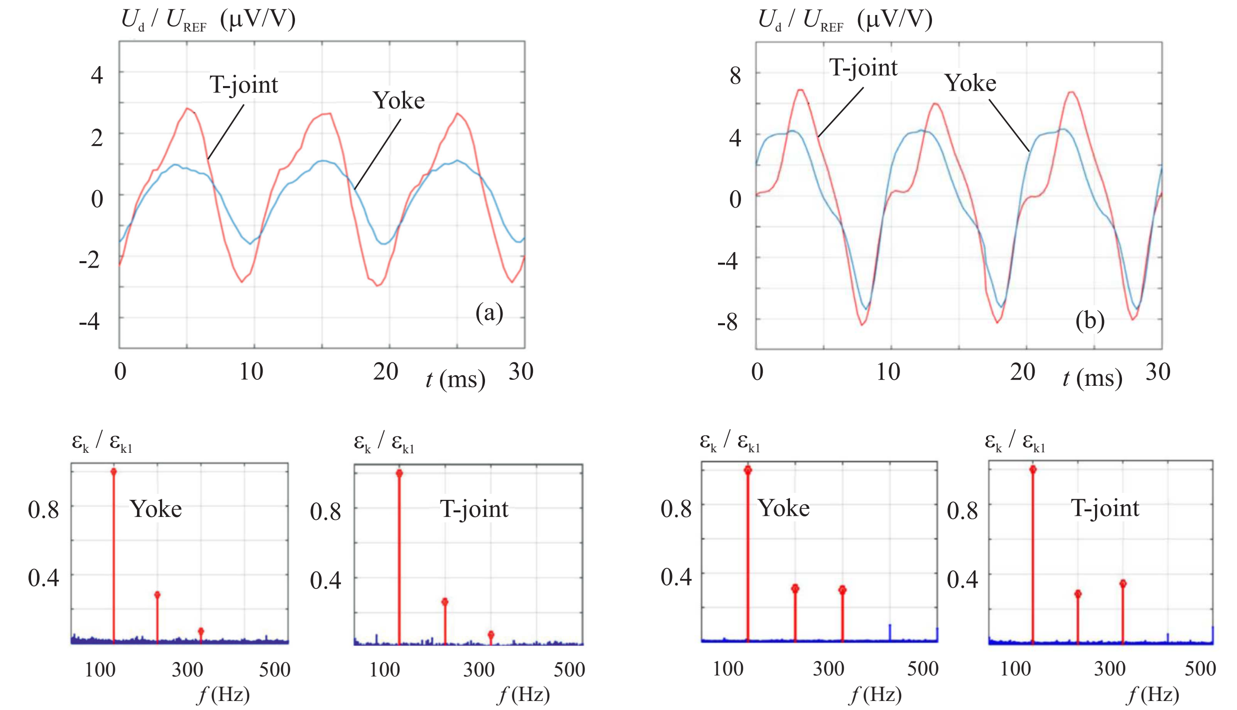

Fig. 3. Examples of results courses of time and corresponding amplitude spectra for yoke and T-joint, respectively, the higher harmonics are related to the fundamental components: (a) – $B_{NOM} = 1.2$ T, (b) – $B_{NOM} = 1.6$ T

3 Experimental

The manufactured sensor can be used in the core interior of any type of laminated machines like motors, generators, transformers *etc*. In the current paper, we tested the manufactured detector band, Fig. 2(a), in the interior of a 3-phase, 3-limb model transformer core, stacked from highly grain-oriented material, as shown in Fig. 2(b). In order to simulate a typical construction of a real transformer core, the investigated model core was stacked from three packages of different width:

- main package P1, width 150 mm, height 25 mm,
- middle package P2, width 110 mm, height 15 mm,
- outer package P3, width 80 mm, height 11 mm.

The core was magnetized by an adjustable transformer of type Ruhstrat, using in-house developed software. The magnetization was controlled in the middle S-limb. Measurements were performed for two nominal magnetization, $B_{NOM} = 1.2$ T, as important for "silent" transformers, and $B_{NOM} = 1.6$ T, as in general typical. The signals from control winding were detected by a DAQ-device (NI-USB6216).

The manufactured detector was inserted between adjacent laminations, into the interior of the outer package P3 of the core, Fig. 2(b), by means of handle ends of the foil (not illustrated in Fig. 2). For direct comparison, measurements were performed in two positions, yoke and T-joint, respectively. The detector band was put into a bridge circuit together with a potentiometer as well as two (integrated into the measuring amplifier Spider 8, company HBM) constant electrical resistances. Evaluations including Fourier analysis of detected signals as well as illustrations of results were performed in Matlab.

4 Examples of results

Figure 3 shows examples of results for both locations, yoke and T-joint (Fig. 2), for $f = 50$ Hz, and for $B_{NOM} = 1.2$ T, Fig. 3(a), and $B_{NOM} = 1.6$ T, Fig. 3 (b) respectively. Courses of time of the from the amplifier detected difference voltage U_d, related to its reference voltage $U_{REF} = 5$ V, are presented for three magnetization periods as average values from five measurements. In the lower figures, the corresponding mean amplitude spectra are illustrated, where the higher harmonics are related to the fundamental component of 100 Hz. The spectra show high signal intensity and low noise, compared to the conventional strain gauges (compare Fig. 3 from [3]), even for low magnetization of core. As mentioned, the high width of the manufactured detector band tends to improve its sensitivity significantly.

Figure 3(a) shows that T-joint exhibits considerably higher strain intensities than the yoke, especially for $B_{NOM} = 1.2$ T. The latter corresponds to tendencies, as observed on the surface of transformer cores, as presented in [3]. The higher intensities can be explained by the strong rotational magnetization that appears within the T-joint region. As shown in [6], the periodic annihilation and generation of oblique domains under rotational magnetization causes a distinct increase of magnetostriction, hence also of the measured strain.

With increasing the nominal magnetization, an increase of the higher harmonics is observed for both investigated regions. It should be stressed that the higher harmonics have a great impact on the audible noise, considering the sensitivity of the human hearing. An unexpected strong increase of the strain with increasing nominal magnetization is observed, especially for the yoke region. The latter can be explained by non-linear effects, due to missing calibration of the sensor, as discussed in the following chapter.

5 Problems of calibration

As already mentioned, the vertical axis of Fig. 3 does not represent the strain, but variations of the difference voltage U_{d}, as provided by the measuring amplifier, related to U_{REF} . As is well known, by conventional strain gauges, the strain is proportional to the measured value U_{d}, according to a linear dependence. However, for our sensor, indications exist that the effective strain may suffer from the to-be-detected strain, depending on parameters of the plastic substrate foil. It means that a calibration of the sensor is needed.

As a crucial problem, a calibration of sensors could not be performed so far. Attempts were made to apply conventional strain gauges for comparisons. But for interlaminar measurements with clamping, they proved to be ineffective. The electrical junctions of many of the used strain gauges were damaged. The few obtained results of signals were not reproducible, with extremely high scatter. Obviously, clamping yields chaotic distributions of 3D local strains within a strain gauge, without correlation to the strain of lamination.

In principle, ordinary strain gauges can be calibrated on a plain surface of defined strain. On the other hand, the manufactured detector band is not fixed but it is clamped between two surfaces, a minimum value of pressure being necessary for effective coupling between sensor band and material surfaces. Further work is needed to establish a numerical model for an understanding, and for corresponding interpretations of results. So far, their relevance is restricted to comparisons for different locations of measurement. However, this strong restriction is in contrast to the fact that not any alternative is given for the novel sensor type, so far.

6 Conclusions

A novel detector band for measurements of strain in the interior of laminated cores was manufactured by a printing procedure. The detector band is handicapped by the fact that calibration could not be performed so far, and is restricted to comparative measurements of different core regions. Further studies are needed, in order to clarify non-linear effects. However, with the manufactured detector band, for the first time, strain measurement in the interior of a core are presented. The first results are very promising corresponding to expectation based on theoretical considerations. In contrast to conventional strain gauges, the manufactured detector can be used even for low nominal magnetization, due to its high sensitivity and resolution.

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References

[1] S. G. Ghalamestani, T. G. D. Hilgert, L. Vandevelde and J. J. Dirckx and J. A. A. Melkebeek, "Magnetostriction measurement by using dual heterodyne laser interferometers", *IEEE Trans. Magn.* , vol. 46, no. 2, pp. 505-508, (2010).

[2] M. Hirano, Y. Ishihara, K. Harada and T. Todaka, "A study on measurement of magnetostriction of silicon steel sheet by laser displacement meter", *J. Magn. Magn. Mater. 254-255*, pp. 43-46, (2003).

[3] G. Shilyashki, H. Pfützner, F. Hofbauer, D. Sabic and V. Galabov, "Magnetostriction distribution a model transformer core", *J. Electr. Eng. 61-7*, pp. 130-132, (2010).

[4] G. Shilyashki, H. Pfützner, P. Hamberger, M. Aigner, A. Kenov and I. Matkovic, "Spatial distribution of magnetostriction, strain, displacements and noise generation of model transformer cores", *Int. J. Mech. Sci. 118*, pp. 188-194, (2016).

[5] N. B. Ekreem, A. G. Olabi, T. Prescott, A. Rafferty and M. S. J. Hashmi, "An overview of magnetostriction, its use and methods to measure these properties", *J. Mater. Proc. Tech. 191*, pp. 96-101, (2007).

[6] V. Galabov, H. Pfützner, G. Shilyashki, H. Yamaguchi, Y. Okazaki and S. Arrai, "Domain reconstructions of g. o. SiFe during rotational magnetization considering also 3-D flux components", *J. Appl. Electrom. Mech. 44*, pp. 417-428, (2014).

[7] H. Pfützner, G. Shilyashki, P. Hamberger, M. Aigner, F. Hofbauer, M. Palkovits, E. Gerstbauer, I. Matkovic and V. Galabov, "Automatic 3-D building factor analysis of a grain oriented model transformer core", *IEEE Trans. Magn. 50-4*, 8400604, (2014).

[8] G. Shilyashki, H. Pfützner, J. Anger, K. Gramm, F. Hofbauer, V. Galabov and E. Mulasalihovic, "Magnetostriction of transformer core steel considering rotational magnetization", *IEEE Trans. Magn. 50-1*, 8400115 pp. 1-10, (2014).

[9] R. Penin, G. Parent, J. P. Lecointe and J. F. Brundy and T. Belgrand, "Impact of mechanical deformations of transformer corners on core losses", *IEEE Trans. Magn. 51-4*, 8400605, (2015).

[10] G. Shilyashki, H. Pfützner, P. Hamberger, M. Aigner, E. Gerstbauer, M. Palkovits and G. Trenner, "Pin sensor for induction measurements in transformer cores", *IEEE Trans. Magn. 51-1*, 4001904 (2015).

[11] G. Shilyashki, H. Pfützner and C. Huber, "Interlaminar Magnetic Flux Assessment of a Transformer Core Measured by an Extra-thin Printed Foil Detector", *IEEE Trans. Magn.* , 53-9, 8400706, (2017).

[12] G. Shilyashki, H. Pfützner, P. Hamberger, M. Aigner, F. Hofbauer, I. Matkovic and A. Kenov, "The impact of off-plane flux on losses and magnetostriction of transformer core steel", *IEEE Trans. Magn. 50-11*, 8401604, (2014).

[13] H. Pfützner, G. Shilyashki andA. Windischhofer "Magnetic Detector Bands for Interior 3D-Analyses of laminated machine cores", *J. Appl. Electrom. Mech*, vol. 65-4, pp.585–594, (2018).

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