SPATIAL DISTRIBUTIONS OF MAGNETOSTRICTION, DISPLACEMENTS AND NOISE GENERATION OF MODEL TRANSFORMER CORES

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Abstract. *Recently, the relevance of audible noise of power transformers tends to increase due to the growing environmental awareness. For sound assessment, two standardised methods reveal the global noise of the whole system, as resulting from the interaction of core, windings, oil and tank. But for a deeper understanding of noise generation, it would be advantageous to investigate also the individual roles of the single above components in closer ways. This paper summarizes attempts to study the first component, i.e. the soft magnetic core, by means of model cores. For the first time, we analysed local distributions of all three strain, displacement and audible noise, keeping in mind that these quantities depend on many parameters like material, stacking, clamping, induction, rotational magnetization, or additional DC-bias, in complex ways. In-plane strain proved to be dominated by magnetostriction, with maximum intensities in corners and T-joints. The interpretation of in-plane displacements proves to be complicated by the unknown resting point of the whole system. However, the results reflect contributions of both magnetostriction and magneto-static forces. Out-of plane displacements proved to be dominated by effects of magneto-static forces, in particular at overlaps of corners and T-joints, due to imperfect clamping. Regional measurements of audible noise were performed in the near-field mode by means of automatic scanning by microphone over free core regions within a noise-isolating scanning chamber. As to be expected, the results showed strongly inhomogeneous distributions with maxima at T-joints and corners. As a conclusion, model core results have very restricted relevance for full sized cores in quantitative ways. But they favour an understanding for crucial mechanisms and for core regions that play dominating roles.*

1 INTRODUCTION

Recently, the relevance of audible noise of power transformers tends to increase due to growing environmental awareness. Nowadays, transformers are located closer to the urban areas. Thus, noise reduction may be more relevant than loss reduction. For the assessment of audible noise of industrial transformers, two standardized methods are generally used, i.e. Sound Pressure Measurement and Sound Intensity Measurement [1, 2]. Both reveal the *global* noise of the whole system as resulting from the interaction of core, windings, oil and tank. However, it is evident that a deeper understanding of noise generation needs separate investigations of the roles of the single above components in closer ways.

This paper summarizes studies on the first component, i.e. the core. Apart from the windings, the core can be assumed as a primary source of audible noise [3]. It is well known, that the latter originates from both magnetostriction and magneto-static forces. However, a clear distinction between them is an almost impossible task, since both interact, apart from exhibiting the same spectral components. We assume that a split would need very specific experimental and/or analytical modelling.

As it is well known, the core's audible noise generation is a complex process depending on many parameters like material, stacking, clamping, induction, rotational magnetization, additional DC-bias, etc. Concerning the material, it is known, that compared to non-oriented SiFe, that of grain-oriented (GO[1]) SiFe is lower, due to weaker magnetostriction (MS[2]) as a result of a highly ordered texture. Even better performance can be expected from laser scribed materials (e.g. [4]). The core clamping influences local strains of both MS and magneto-static forces, as closer discussed in [3, 5]. Also rotational magnetization has a very significant impact on MS, causing increases up to a factor of 10, compared to mere alternating magnetization (see [6]). Finally, additional DC-bias, caused e.g. by geomagnetically induced currents, leads to general increases of local strains, especially in regions of mere alternating magnetization, audible noise being distinctly enhanced (e.g. [7]).

As already mentioned, most authors consider audible noise for the entirety of a transformer [1, 2, 8]. Only few ones concentrate on the magnetic core by numerical calculations, in particular of local distributions of core surface displacements, e.g. using FEM techniques [9, 10] and by measurements of audible noise in single-phase cores [11] and in three-phase cores [12, 13, 14]. Most commonly, the numerical models are restricted to 2D calculations of core packages without considering the impact of the overlaps [10, 15]. In [15], a coupled 2D magnetic and mechanical FEM-model for the investigations of the influence of magnetostriction and Maxwell

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[1] grain-oriented

[2] magnetostriction

(magneto-static) forces to the dynamic displacement of the inductor is presented. As an important result, the authors found that magnetostriction and Maxwell forces might even interfere destructively for a certain frequency range. In [16], the authors present a model for the prediction of the magnetostriction in several direction. However, the model is validated only for the case of non-oriented silicon steel, having a low relevance for modern transformer cores, stacked from grain oriented materials. In [17], a 3D model is used to calculate the magnetic field distribution and vibrations of a 3-phase transformer core and windings. Subsequently, the noise distribution is calculated based on achieved vibration data. The authors tried to verify the achieved distribution by standardized measurements of the noise at four local positions, 1m away from the transformer tank.

The acoustic measurements show the high impact of the clamping [11], of the compressive stress [12] as well as of the design of the overlaps on the noise generation [13]. In a rather surprising way, in [12], the authors show that increase of the local noise does not necessary mean increase of the peak-to-peak magnetostriction.

In our own studies, we performed various experimental analyses on different 1-phase and 3-phase model cores. The latter prove to be very effective for basic studies on mechanisms of loss generation. On the other hand, studies on vibrations or even noise are problematical a priori, in particular due to the well known relevance of eigen-values [9, 16]. However, keeping the latter in mind, experiences show that experimental modelling may yield basic conclusions, in particular if local investigations are performed in comparative ways.

The main target of the current paper is to summarize our experiences from regional measurements on magnetostriction, displacements and audible noise. A second aim is to discuss basic problems of such measurements, as well as restrictions of practical relevance. All in the work investigated cores were magnetized with sinusoidal excitation with 50 Hz for the practically relevant case of B_{NOM} = 1.7 T, measured and controlled in the middle limb.

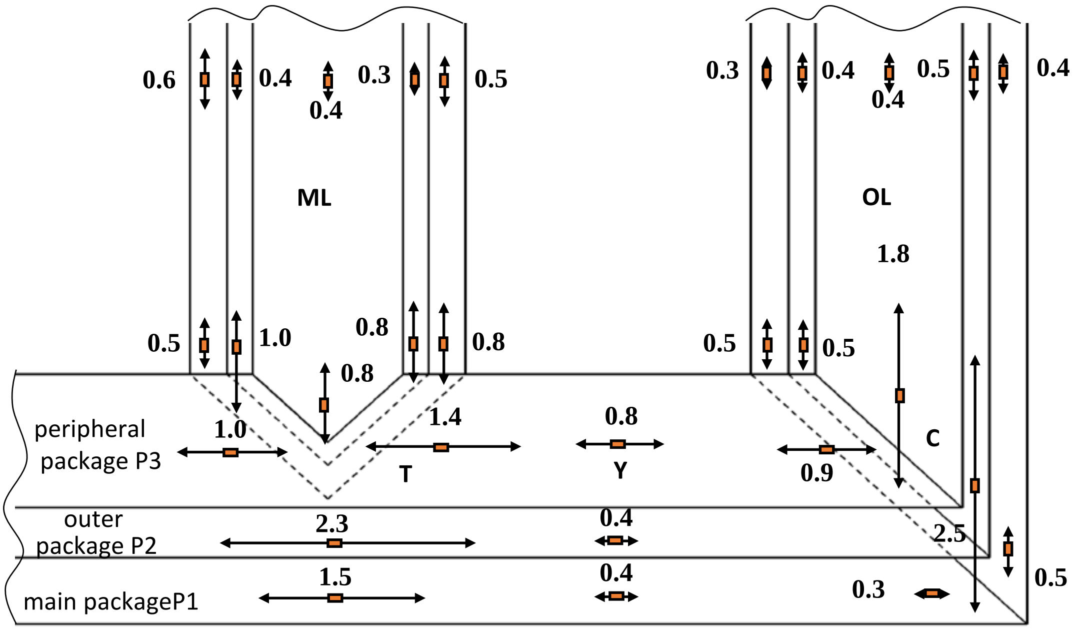
2 LOCAL DISTRIBUTIONS OF STRAIN

As it is well known, measurements of magnetostriction (MS) are being performed in routine ways for all types of laminated soft magnetic materials as being applied for transformer cores. A material sample is magnetized in a so-called single sheet tester or rotational single sheet tester, and MS-caused strains are detected by means of strain gauges (e.g. [6, 19]), or also by interferometers (e.g. [20, 21]). The results proved to be affected by many impact factors, as summarized in [6].

In a rather surprising way, literature does not report any study of regional in-situ measurements, as performed directly on transformer cores, neither on core surfaces nor in the core interior. A possible reason may be that such measurements are highly problematical, as revealed by our own attempts of investigations. First, let us report results, then discuss the problems of measurement.

In a series of studies, we arranged strain gauges on the surface – and partly also within the stack – of model transformer cores. Considering the large grain size of modern core steel, we use about 50 mm long sensors for averaging. For temperature compensation, each gauge was placed in a quarter bridge circuit together with a top-on dummy gauge. It is well known, that the sensitivity of the strain gauges is worse than that of interferometers. However, both method prove to yield quite similar results for transformer core materials and magnetization values above 1.3 T, as demonstrated in [20]. From our experience with measurements of magnetostriction of transformer cores, we found that the sensitivity of the strain gauges is roughly about 0.1 ppm. The main factor, influencing the sensitivity of the gauge is the complex process of fixing it to the core surface.

Figure 1 shows typical results for a square 3-phase model transformer core with outer dimensions of 750 mm and a stacking height of 57 mm. The core was stacked from three packages of different width and height: main package P1 (width 150 mm, height 30 mm), outer package P2 (110 mm, 11 mm) and peripheral package P3 (100 mm, 8 mm). It was built up from highly grain oriented (HGO)[3] material of type 0.85-23DR.



all values in **ppm**

Figure 1: Local distribution of peak-to-peak strain $\varepsilon_{\mathrm{RD}}$ in RD in a 3-phase, 3-package model transformer core, stacked from highly grain oriented material, for B_{NOM} = 1.7 T. All values are given in ppm.

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[3] highly grain oriented

Figure 1 includes results of measured strain values $\varepsilon_{\mathrm{RD}}$ (in ppm) in rolling direction (RD)[4] for the state of locally balanced clamping in all core regions (see below). The values are length-coded by double arrows in logarithmic scale. Local values show strong variations as resulting from errors of measurement, but also from many impact sources like inhomogeneous induction, interactions of the three core packages, and others. However, the regional *mean* values in Table 1 reflect almost even strain distribution in the outer limb, the middle limb and the yoke with an order of $\varepsilon_{\mathrm{RD}} = 0.5$ ppm. This value is in the range of catalogue values of magnetostriction for HGO materials. Higher values (approaching 1 ppm) at the end of the middle limb can be interpreted by regionally increased flux distortions. The latter cause increased harmonics of MS, leading to increases of the corresponding peak-to-peak values. But – much more important – they also cause higher harmonics that have high impact on audible noise, the human ear being highly sensitive to them.

region	OL[5] outer limb	ML[6] middle limb	Y[7] yoke	C[8] corner	T[9] T-joint
averaged strain	0.4 ppm	0.6 ppm	0.5 ppm	1.2 ppm	1.4 ppm

Table 1: Regional mean values of measured peak-to-peak strain $\varepsilon_{\mathrm{RD}}$.

Even higher values, above 1 ppm, were detected in the corner regions, indicating effects of partly saturated overlaps of laminations. Highest values arise in T-joint regions as a result of rotational magnetization, as discussed in detail in [5]. The highest MS-value of 2.3 ppm is detected straight below the V-element of the T-joint area. This coincides with maximum values of power losses. The area of V-element represents a kind of “worst spot”, strongest rotational magnetization being linked with local saturations of overlaps, as well as with strong magneto-static forces between the individual laminations [3]. Here, it should be noted that model cores built up from lower grade material showed distinctly higher strain values as reported in [6].

In order to interpret the achieved results, we developed a novel 2D numerical model [22] for the estimation of the local distribution of magnetostriction, based on the novel multi-directional non-linear equivalence circuit calculation (MACC) procedure [23]. The model considers two main flux paths a window path and a peripheral path. Each path is simulated by a series of reluctances in rolling direction. The interaction between the two paths

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[4] rolling direction
[5] outer limb
[6] middle limb
[7] yoke
[8] corner
[9] T-joint

is realized by reluctances in transverse direction. For the calculation of the reluctances the non-linear permeability function μ_{RD} in rolling direction and μ_{TD} in transverse direction, obtained from catalogue [24], are taken into account, compare [25, (Figure 2)]. The basic idea of MACC is to vary all local induction values in RD and in TD, until they agree to the corresponding permeability values according to the non-linear permeability functions, compare [25, (Figure 2)]. Furthermore, the model considers the reluctances of the overlaps of the corners and T-joint. The latter show strong non-linear dependence on the induction, due to partly saturation for values $B_{\mathrm{NOM}} > 1$ T.

The model calculates all local induction values in rolling direction (RD) and in transverse direction (TD) in order to simulate rotational magnetization. A priori measured values of the peak-to-peak magnetostriction λ_{RD} are assigned to each local calculated induction value, taking into account the peak induction in RD and in TD. The so far performed modelling was restricted to a single package of a 3-phase, 3-limb core stacked from conventional grain oriented (CGO) materials.

Figure 2 shows the results of the performed simulation. Due to symmetry, the corresponding values in the T-limb are not illustrated. The increases of λ_{RD}, related to the lowest value ($\lambda_{\mathrm{RD}} = 0.22$ ppm) are given through the lengths of the double arrows in logarithmical scale. The results show a quite even distribution of λ_{RD} for all regions of the core with values between 0.77 ppm and 0.92 ppm (compare Figure 2). The only exception is the T-joint region, where the measured values of λ_{RD} even exceed 9 ppm (Figure 2). The calculated values are clearly higher than the measured ones (Figure 1), mainly due to different types of the investigated materials. It is well known, that the CGO-materials exhibit much higher MS-values than the HGO-materials, used for the measurements. Both measurements and simulations show that the rotational magnetization is the main source of increased magnetostriction. While the simulations do not show any increased magnetostriction values in the corners, the measurements show very high strain $\varepsilon_{\mathrm{RD}}$ with values up to 2.5 ppm. The interpretation can be definitely given by the magneto-static forces, that were not considered in the simulations.

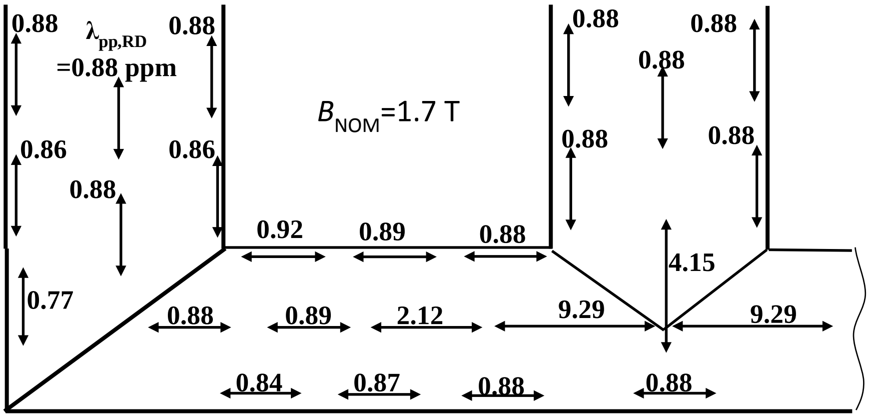


Figure 2: Regional distribution of peak-to-peak magnetostriction λ_{RD} in ppm for the rolling direction for B_{NOM} = 1.7 T from [22].

Above, it was mentioned that the results of Figure 1 represent a case of balanced mechanical clamping. The latter proves to be a crucial problem of model cores where some access to the core surface is demanded. Experience shows that too weak clamping favours magneto-static forces as a reason of chaotic nature of both vibrations and local strain values. On the other hand, very strong clamping yields torsion of laminations with extreme strain values in locations of high mechanical compression. To attain "balanced" conditions, a medium state of clamping was adjusted that promises representative results. According to the mentioned above, it is obvious that a good reproducibility of the measured strains is not good, since even small changes in the clamping state cause significant differences in the measured strains. However, for the "balanced" conditions the tendencies were very well reproducible. Anyhow, the tendencies according to Table 1 are compatible with physical expectations. This indicates that model core studies on magnetostriction have practical relevance, if interpreted in careful ways.

3 LOCAL DISTRIBUTION OF DISPLACEMENT

For straight-forward procedures, it offers itself to integrate over locally determined strain values ε (caused by MS and/or magneto-static forces) in order to estimate the corresponding displacements δ of core surface positions. In literature, studies of local distributions tend to be restricted to singular points. For example [26] discusses one point on the middle limb and one at the yoke of a 3-phase transformer package modelled by FEM, finding maximum displacement values of about 5 µm. As well, [27, 28] report FEM results in comparison with measurements at three positions, detecting values up to about 0.2 µm and 0.4 µm, respectively, however for extremely small 1-phase cores. In [10], displacement measurements were performed at 5 different locations on the surface of a three phase model transformer core by means of accelerometers. The results show distinct asymmetries as a result of resonance phenomenon [10]. In own experiments [3], we found for similar 1-phase arrangements, off-plane displacements δ_{ND} in normal direction (ND; perpendicular to the plane of magnetization) up to about 0.3 µm and in-plane values δ_{RD} in rolling direction of similar order.

In order to get closer to practical conditions, we focussed our more recent work on 3-phase model cores that are built up from three packages, as also described further up for strain. For displacement measurements, we applied acceleration piezo-electric sensors (B&K 4326) connected to a charge amplifier (B&K 2635). The signal acquisition and processing was performed in Labview. The displacement is calculated as a double integral of the obtained acceleration signal. For the evaluation of the off-plane vibrations, the rms values δ_{ND} are calculated, whereby only the even harmonics (100 Hz, 200 Hz …1000 Hz) were considered.

Figure 3 shows results for a square 3-package core of 500 mm size assembled from GO material C130-30. Contrary to the case of MS-measurements, where additional balancing clamping in all core regions was performed, here the clamping was restricted to existing manufacture clamping, for access to surface positions. The squares with dot mark positions of off-plane measurements. For the location T in T-joint and M in the middle limb, a frequency analysis is presented in Figure 4. The blank squares mark four selected positions of in-plane measurement direction (lateral), in positions A and B at the edges of the package P1, positions C and D of P2.

Off-plane displacements δ_{ND} were measured at about 40 local positions. The corresponding results in Figure 3 show strongly inhomogeneous distributions. However, clear tendencies are indicated by regional values of Table 2. Lowest rms-values round 1 µm were measured in the yoke, followed by about doubled ones in the limbs, the middle limb showing higher values than the outer one. As expected, the highest values were detected in the corners with about 4 µm, and in the T-joint region with about 6 µm. Close from the V-element of the T-joint we found a maximum value as high as 13.7 µm.

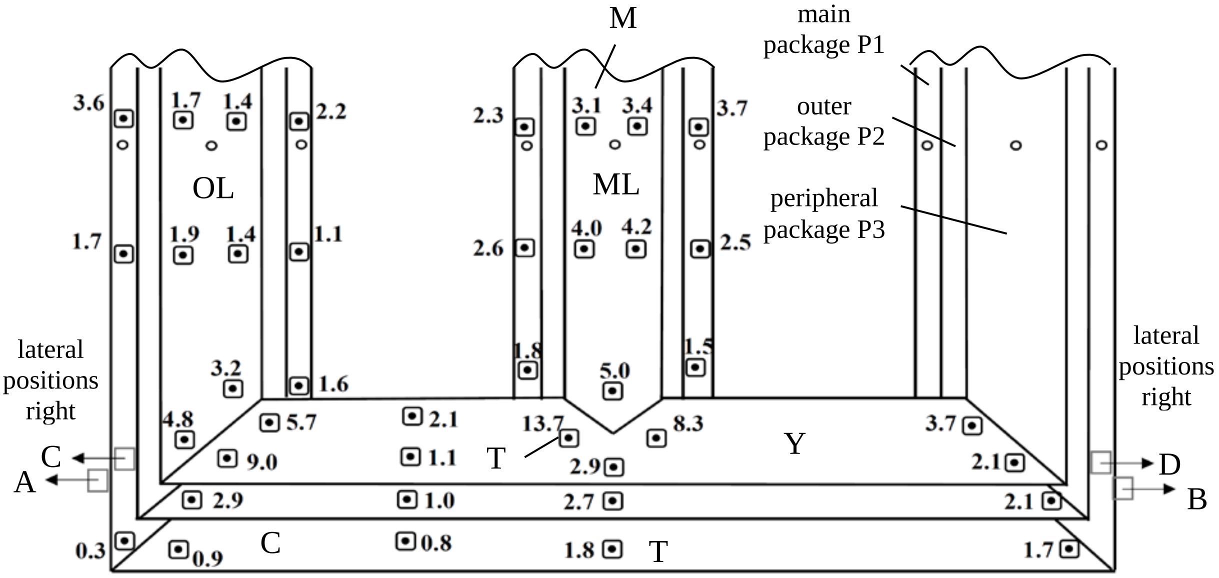


Figure 3: Regional displacement distributions in a 3-phase, 3-package model transformer core, stacked from GO material C130-30 for B_{NOM} = 1.7 T. All rms values of the displacement are given in µm.

Concerning the individual packages, lowest values were registered in the main package P1, higher ones in P2 and highest in the peripheral package P3. One of the several possible reasons is the fact that the main package exhibits best clamping, also through the mass of the packages P2 and P3, the core being studied not in upright but in horizontal position.

region	OL outer limb	ML middle limb	Y yoke	C corner	T T-joint
averaged displacement in ND	2 µm	2.9 µm	1.3 µm	3.9 µm	5.7 µm

Table 2: Regional mean values of measured rms displacement values δ_{ND} in the off-plane normal direction.

Figures 4a and 4b show examples of the amplitude spectrum of the displacement for the location T in T-joint and location M in the middle limb, respectively for the peripheral package. As expected, the 100 Hz component tends to be very pronounced due to magnetostriction and magnetostatic forces, since the core was excited with 50 Hz. Both spectra for T-joint and middle limb indicate significant intensities of the 2nd and 3rd harmonic. The higher harmonics have much greater impact on the audible noise, considering the sensitivity of the human ear. The higher harmonics than the 3rd show very low intensities and may be neglected. However, in the current work, for the calculation of rms values of the off-plane displacement all even harmonics (100 Hz, 200 Hz …1000 Hz) were considered.

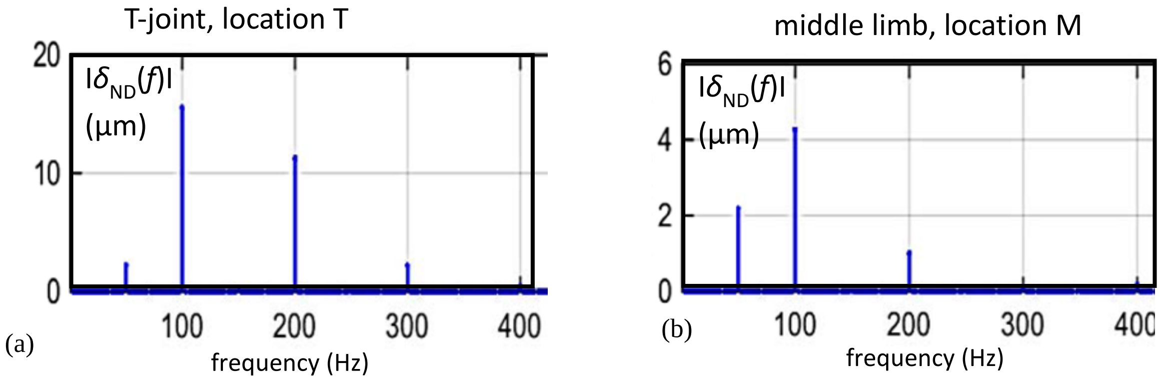


Figure 4: Examples of the amplitude spectrum of off-plane displacement. (a) Location in T-joint of the peripheral package. (b) Location in the central part of the middle limb of the peripheral packages.

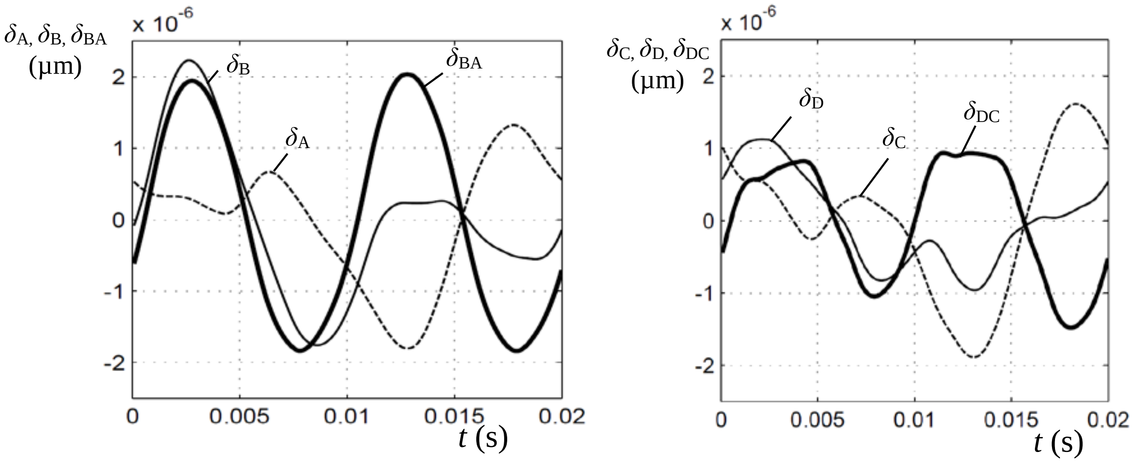
As an interpretation, the detected very high orders of off-plane displacement cannot be explained by mere magnetostriction, due to the low height of stacking. It is evident, that the dominant mechanism is given by magneto-static forces, apart from possible impact from eigen-frequencies. In particular, in overlap regions of the corners and T-joints, strong forces arise between lamination ends, as a simple interpretation. We assume that the results do not have quantitative relevance for well-clamped transformers. However, qualitative relevance is given with respect to differences for the individual regions, in particular for cases of deteriorated mechanical stabilization of a core, in connection to damaging or aging.

Besides the off-plane displacements, in-plane values δ_{RD} in rolling direction (RD) were measured at about 30 positions. Typically, they showed intensities of the order of 1 µm with irregular variations. Effective interpretations prove to be complicated through the problematic of lacking resting point. A priori, one could expect that a transformer core exhibits a permanent, centrally located point which can serve as a reference REF for displacements as registered at other locations. But this is not the case. Attempts of localisation indicate that REF may arise in any core region and change as a result of minor modifications of the system. This disfavours analyses of displacement. The alternative would be to put the focus on vibrations, however, with the disadvantage that physical interpretations become even more difficult. That is, the relationship to basic mechanisms like magnetostriction or forces is mantled even more.

To meet the problem of unknown point REF, we evaluated over-all displacement *differences* for core main axes, based on paired detection points, as illustrated in Figure 3 for the entirety of the yoke. For the main package P1, we evaluated displacements at the lateral positions A and B. The signals from the left side A and from the right side B were triggered at the flux of the middle limb. The effective over-all change of yoke length was calculated as the difference between the measured displacements according to

$$\delta_{\mathrm{BA}}(t) = \delta_{\mathrm{B}}(t) - \delta_{\mathrm{A}}(t)\ . \tag{1}$$

Figure 5a shows corresponding time-traces for P1. Both packages show well pronounced 100 Hz components of dynamic displacements. The two individual signals $\delta_{\mathrm{B}}(t)$ and $\delta_{\mathrm{A}}(t)$ exhibit strongly non-sinusoidal responses. $\delta_{\mathrm{B}}(t)$ exhibits much stronger amplitude which yields the conclusion that REF is located in the left core half. In a rather surprising way, $\delta_{\mathrm{BA}}(t)$ proves to be almost sinusoidal. This would mean that the periodical shrinking of the yoke – as resulting from magnetostriction and forces – has sinusoidal character, in approximation. The peak-to-peak intensity results close to 4 µm, a quite high value, even if we consider a strong contribution of rotational magnetization in the T-joint. On the other hand, the investigated core is not built up from HGO steel which means that magnetostriction tends to be high.



(a) (b)

Figure 5: In plane displacements measured by acceleration sensors in lateral positions of the left and the right side of the yoke for B_{NOM} = 1.7 T. The difference signals between right side and left side are given in bold.
(a) Main package P1 (positions A and B). (b) Outer package P2 (positions C and D).

Figure 5b shows corresponding signals for the yokes outer package P2. Here, the amplitudes of the strongly distorted displacements $\delta_{\mathrm{D}}(t)$ and $\delta_{\mathrm{C}}(t)$ are more balanced. This would indicate a more central position of the packages individual point REF – a vague way of interpretation that should be put for discussion. The difference $\delta_{\mathrm{DC}}(t)$ deviates from a sinus, showing indication of positive saturation. The intensity results as being close to 2 µm.

As a major conclusion, it seems to be rather impossible to apply model cores for a quantitative assessment of displacements as to be expected for full sized transformers. Main reasons are the restricted stacking height in combination with imperfect clamping. Off-plane displacements tend to reflect mere effects of magneto-static forces. On the other hand, laterally detected in-plane displacements can be assumed to reflect the total of contributions from magnetostriction and magneto-static forces (at overlaps). While quantitative conclusions are most problematic, qualitatively, the results of displacement show similar tendencies with regional differences of measured strain values. That is, the relevance of different core regions is indicated in approximate ways. Further experiments should be performed with larger stacking height and more effective clamping, specifically designed for access of sensors to selected core surface positions.

4 LOCAL DISTRIBUTIONS OF NOISE GENERATION

Attempts to detect local distributions of noise generation were performed in a specifically adapted scanning chamber. As sketched in Figure 6, it shows cubic geometry of about 1.5 m inner dimensions and is equipped with a 3D computer-controlled scanning head with 10 µm spatial resolution. An extra insulation was provided for reducing contributions of noise coming from the windings. The local sound intensity (in undefined near-field mode) was measured, using a microphone B&K 4165 and a measuring amplifier B&K 2606. The output signal of the measuring amplifier is connected to 16 bit data acquisition device from national instrument (NI USB-62-16, 16 bit). The used sampling frequency for the sound measurements was 12.8 kS/s. The evaluation of the results were performed in Labview, while the frequency analyses and illustration were performed in Matlab.

The microphone was mechanically attached to the scanning head. Partly, it was equipped with a shell for improved directional response. According to Figure 7a, the measurements were performed at nine equidistant locations 1...9 along the entire middle part of the whole yoke, at two different heights to the surface, d = 20 mm and d = 50 mm. The test procedure was controlled in a fully automatic way, by specific Labview software. At each single location, the acoustic signal was captured for about 3s, for nominal magnetization of B_{NOM} = 1.7 T. The signal evaluation and the calculation of the corresponding local power levels were performed in Matlab.

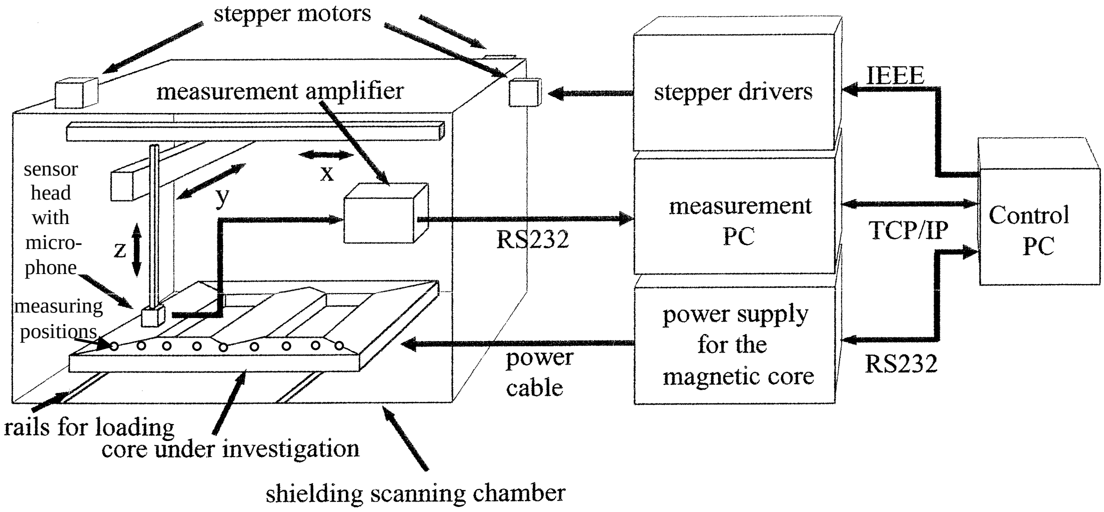


Figure 6: Test chamber for acoustic near-field analyses by automatic scanning by a microphone.

Figure 7b shows test results for a 3-phase 1 m x 1 m model transformer core package, stacked from HGO material with a stacking height of 16 mm. The data of the graph of results indicates a quite vague tendency of maximum noise intensities at the T-joint region and at the corners, the differences to the yoke regions being approximately 10 dB. However, local differences of the same order proved to result from smallest modifications of clamping, depending also from the arrangement of shell and changes of detection distance. Distinct effects resulted from smallest modifications of the position of the magnetic core, as to be expected from changed eigenfrequencies.

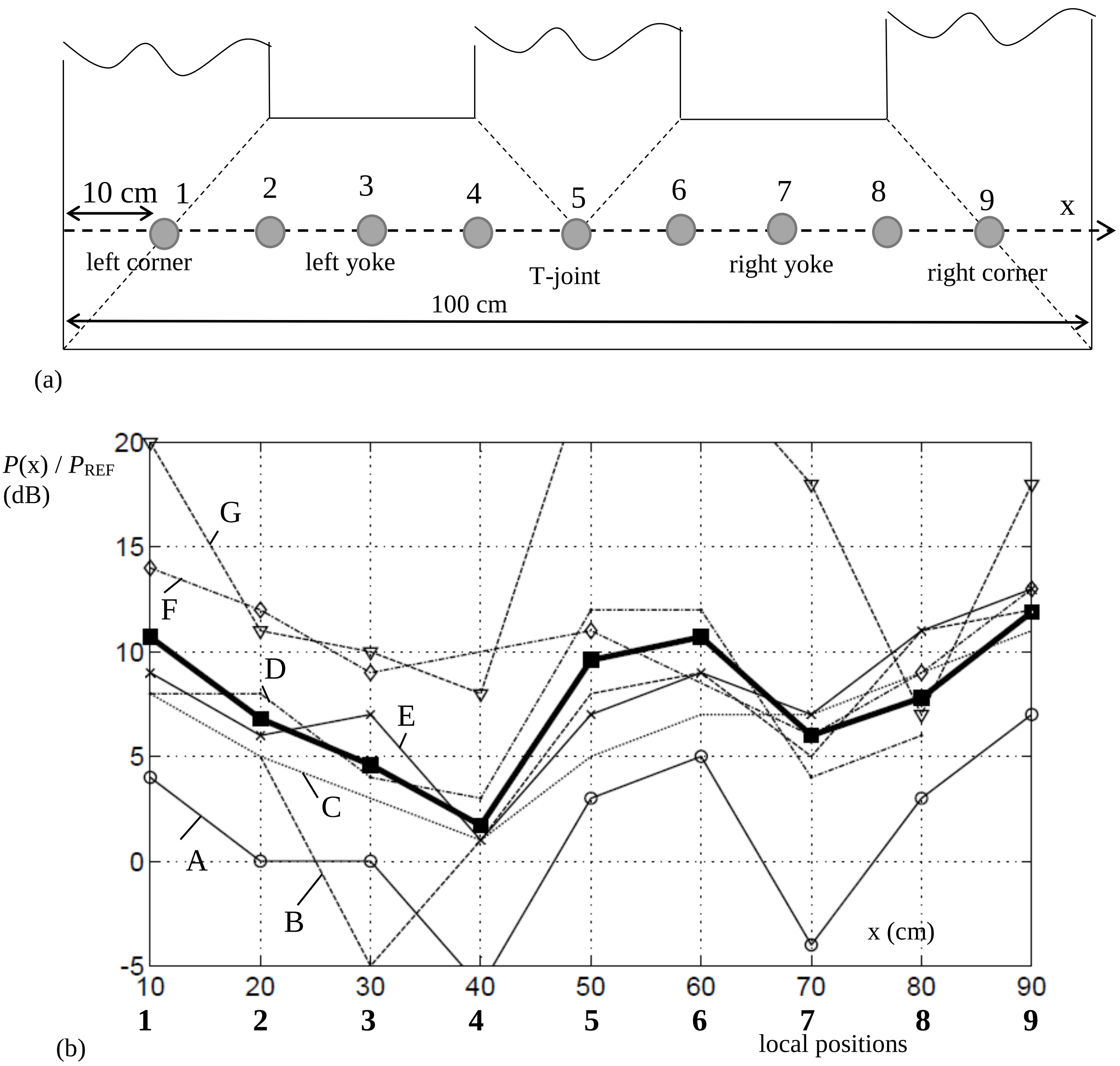


Figure 7: Acoustic measurements, performed at the surface of a transformer core package, stacked from highly grain oriented material for B_{NOM} = 1.7 T. All measured sound pressure levels are related to the sound pressure, measured in the left yoke (location 3) for case A. The eight individual curves concern the following conditions of measurement (*d* the distnce between sensor and lamination surface):

A – no clamping, with shell, *d* = 2 cm	E – no clamping, with shell, *d* = 5 cm
B – no clamping, no shell, *d* = 2 cm	F – with clamping, with shell, *d* = 5 cm
C – no clamping, no shell, *d* = 5 cm	G – with clamping, with shell, *d* = 2 cm
D – with clamping, no shell, *d* = 2 cm	H – over-all average (thick curve)

As to be expected a priori, a model core will never reflect the noise generation of a full size core. However, the so far results indicate that carefully performed, regional near field measurements may give information on consequences of modified core designs. For example, we expect qualitative information on tendencies of different joint designs in dependence from the nominal induction. At present, we start measurements at model core of normal stacking height, aiming for more defined conditions of emission. Possibly, the near field measurements may also prove effective as a diagnostic tool with respect of defects of stacking.

4 CONCLUSIONS

The current paper presents experiences from the application of transformer model cores in the context of audible noise. Many studies demonstrated that models are a helpful tool for the assessment of phenomena of energy loss, provided that specific model core effects are kept in mind. In particular, the latter concern the problem of scaling down, and up, respectively. As well, low stacking height, poor clamping, enhanced stray fields are further characteristics that restrict the validity of model cores. An alternative would be the application of numerical modelling like FEM. However, it has several drawbacks as well. For example, they concern difficulties to consider interactions of non-linearity, anisotropy, hysteresis and eddy currents, as well as the strong impact of joint designs.

Starting out from high experience with model cores for loss assessment, it was clear a priori that the field of audible noise would be much more complex and problematical. And indeed, the relevance of model core studies proves to be strongly restricted for three investigated quantities. The tests concerned regional distributions of magnetostiction, displacements and acoustic noise generation for different 3-phase transformer core geometries and different types of materials. As a whole, all cores show strongly inhomogeneous distributions of all three investigated characteristics. However, some spatial tendencies could be outlined in a general way: The T-joints exhibited maximum intensities of all three quantities, which confirms a significant role of rotational magnetization. Both 1-phase cores and 3-phase cores showed maxima at corners. It indicates an impact of saturated joint regions, but has also to be related to vibrations that are caused by magneto-static forces, due to imperfect clamping.

In more detail, regional strain measurements prove to be effective on model cores. It is likely that conclusions on full size cores are possible. The results confirm strong effects of rotational magnetization on magnetostriction. They also reveal the important role of clamping which should be balanced, keeping the total of core areas in a “relaxed” state to avoid local hyper-maxima of strain in mechanically compressed sub-regions.

Measurements of displacement in off-plane direction would need full stacking height in order to be of practical relevance. This should be considered in future experiments. The interpretation of in-plane displacement measurements is complicated by the fact that an investigated core lacks a symmetrically localised resting point. However, conclusions on integral-effects of magnetostrictive strains seem to be feasible.

Finally, regional tests on the generation of audible noise prove to be the most difficult task, the results of measurement being affected by smallest modifications of the involved system. However, the here reported near field measurements may offer a diagnostic tool for the identification of core defaults in comparative ways. It proved to be advantageous to use computerized scanning due to the fact that defined test procedures are repeatable under constant environmental conditions.

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