Magnetostriction of Transformer Core Steel
Considering Rotational Magnetization

G. Shilyashki¹, H. Pfützner¹, Member, IEEE, J. Anger², K. Gramm², F. Hofbauer¹, V. Galabov¹, E. Mulasalihovic¹

¹Vienna University of Technology,
Institute of Electrodynamics, Microwave and Circuit Engineering (EMCE), Vienna, Austria
²ABB Transformers, Ludvika, Sweden

As well known, the power loss of transformer core steel depends on a series of parameters which vary in the final core in complex ways. The aim of the present study was to investigate the corresponding dependencies for the second key characteristic, i.e. magnetostriction (MS), as the most significant source of no-load noise. The MS-performance of core material was investigated by means of a rotational single sheet tester (RSST). Compared to loss, the peak-to-peak MS in rolling direction (RD; as the direction of strongest strain) shows similar increases with increases of both induction and axis ratio \( a \). On the other hand, the shape of induction pattern \( B(t) \) proves to be rather insignificant, MS being similar for elliptic and rhombic magnetization. While increased dynamics of the pattern yields rising eddy current loss, MS remains unaffected. However, the harmonics show increases as being of relevance for audible noise. While mechanical tension in RD yields slight decreases of MS for alternating magnetization, MS for rotational magnetization increases for both tension and compression. As in the case of loss, MS shows significant increases for DC-bias which correlates with reports of increased noise. The study also included local measurements on a 2-limb, 1-phase model core and on a 3-limb, 3-phase core. MS remains in the order of 0.5 ppm for the 1-phase core, except from its corners. On the other hand, T-joint regions of the 3-phase core show values up to the order of 6 ppm, in accordance to RSST-results. Moderate DC magnetization, as being possible in practice as a long term phenomenon, yields distinct increase of MS intensity and MS harmonics with strong regional differences.

Index Terms — magnetostriction, losses, DC-bias, rotational magnetization, silicon steel, strain, stress, transformer cores.

NOMENCLATURE

- AM — alternating magnetization
- CGO — conventionally grain oriented
- DC — direct current
- GO — grain-oriented
- HGO — highly grain-oriented
- HD — hard direction
- MS — magnetostriction
- NO — non-oriented
- RD — rolling direction
- RM — rotational magnetization
- RSST — rotational single sheet tester
- TD — transverse direction
I. INTRODUCTION

As well known, the power loss of transformer core steel depends on a series of parameters which vary in the final core in complex ways. The aim of the present study was to investigate the corresponding dependencies for the second key characteristic, i.e. magnetostriction (MS), as the most significant source of no-load noise. In this first chapter, we discuss the corresponding preconditions as well as the state of the art.

A. Preconditions

Magnetostriction (MS) and power loss of grain-oriented (GO) electrical steel have been considerably reduced in recent times. However, for transformers, there is a tendency of rapidly increasing specific demands which result from both restricted resources and rising environmental concerns. Considering the core, both industrial producers and academic researchers try to improve the material properties even further. In addition, attempts are made to decrease losses with respect to energy efficiency. Audible noise is capitalized in a strongly increasing way [1,2,3], due to the fact that rising energy demand tends to bring transformers closer to the residential centers. This means that increased relevance is given for magnetostriction which can be assumed as the main source of audible noise, apart from magneto-static forces [4].

![Fig. 1. Quasi-DC MS $\lambda_{RD}$ in RD as a function of induction $B_{RD}$ for CGO SiFe and HGO SiFe, measured on single sheet tester for alternating magnetization with 60 Hz (after NSC data catalogue [5]). In addition, the corresponding DC peak-to-peak values $\lambda_{RD,PP}$ are given by dashed lines, in approximation.](image)

During the last 30 years, the gradually improved development of highly grain-oriented (HGO) materials yielded strongly reduced losses for magnetization in the rolling direction (RD). Linked with that, the ordered texture yielded also strongly reduced magnetostriction. The situation is well illustrated by Fig.1 which shows typical values for the MS-caused strain $\lambda_{RD}$ in RD. For the most relevant range of...
induction, i.e. 1.4 T to 1.75 T, the order of \( \lambda_{RD} \) was reduced from about 1 ppm for the conventional grain-oriented (CGO) case down to less than 0.5 ppm for the HGO-case (based on data taken from [5]). For these improvements, an almost full understanding has been attained, in special through domain analyses, as reported in several papers (see section B).

Transformer cores take advantage from the above improvements in regions which show alternating magnetization (AM) in RD, i.e. limbs and yokes. On the other hand, T-joint regions and partly also yokes tend to show rotational magnetization (RM) with considerably high components of induction \( B_{TD} \) in the transverse direction (TD) of material (Fig.2) [6]. This results in strong regional increases of losses. As well, in distinct analogies, RM yields strong increases of magnetostriction, as reported in several papers (see section B).

Losses of transformer core steel depend on a series of parameters which vary in a final core in complex ways. For AM, power loss depends on the type of material, and it can be classified in descending order from CGO over HGO down to scribed HGO. For RM, losses show strong increases with increasing axis ratio \( a = B_{TD}/B_{RD} \) (\( B_{TD} \) peak induction in TD, \( B_{RD} \) peak induction in RD). Recent investigations on RM have shown that losses are also influenced by the shape of the magnetization pattern; for a given value \( a \), it rises with increasing induction \( B_{HD} \) in hard directions [6]. This is significant, since transformer cores tend to show rhombic patterns corresponding to restricted \( B_{HD} \). Finally, power loss also increases with increasing peak angular velocity \( \omega_{MAX} \) of the induction vector [6].

![Fig. 2. Definitions at the example of an elliptic rotational magnetization pattern with \( a = 0.5 \) after [6]. The magnetization vector \( B \) rotates with the instantaneous angular velocity \( \omega(t) \). The induction peak values in transverse direction (TD) and rolling direction (RD) determine the axis ratio according to \( a = B_{TD}/B_{RD} \). The hard directions (HDs) show an angle of about 55° to the RD.](image)

A further impact factor for core losses is given by mechanical stress, e.g., caused by clamping and by weight of core and coils. For example, tension in RD reduces losses, but for most constellations, stress sums up to a disadvantageous increase, depending on many parameters. Finally, a significant impact factor for the magnetic performance of transformers is additional direct current (DC) magnetization. Very strong DC-bias may arise due to geomagnetically induced currents (GICs) caused by increased solar activity [7]. It is a short-time phenomenon with little energetic relevance, however, due to heat-up, it even can destroy a transformer [7]. Weak or
moderate DC-bias may arise due to non-compensated thyristor switches or imperfect transistor sets. If remaining unnoticed or tolerated by grid operation, it may represent a long-term factor that deteriorates the performance of the core. Loss increases were observed in special for the surfaces of transformer cores [8,9].

The above effects on losses have been subject of intensive academic and industrial research. On the other hand, rather small attention has been made on the corresponding effects on magnetostriction (MS). One reason may be that studies on MS tend to be more complex, a second may be that losses tend to be stronger capitalized than audible noise. However, as already mentioned, this situation has changed during the last years, especially in the industrially leading regions of the world.

B. Aims of study

With respect to the above, it was the aim of the present study to perform a consequent investigation whether the above discussed impact factors of losses are valid also for magnetostriction (MS) in comparable ways. A basic question was whether a loss increase would be linked with an increase also of MS, as a general rule - if yes, this would favor attempts of industry to reduce losses and noise in a simultaneous way. The second question was to estimate effects in a quantitative way.

In the present paper, results of MS-measurement as a function of impact parameters are compared with the corresponding tendencies of loss behavior. Cases of different performance are discussed with emphasis. To guarantee industrial relevance, it was tried to perform all experiments under conditions that are similar to practice. As an example, induction peak values are varied between about 1.3 T up to 1.8 T, values of axis ratio exceeding 0.5 are not considered at all, since being irrelevant for industrial practice.

Chapter II of this paper presents a survey of the main results of a quite extensive study performed by means of a rotational single sheet tester (RSST) applying rather large hexagonal samples of material. Chapter III concerns model core experiments which were performed in order to check the practical relevance of RSST-simulations. Local distributions of MS are reported for surfaces of both a 2-limb, 1-phase core and a 3-limb, 3-phase core, considering also effects of weak DC-bias. Finally, chapter IV includes a summary of major results as well as an industrial assessment of the observed phenomena.

C. State of the Art

During the last years, world-wide attempts have been made in order to design improved methods for the experimental measurement of magnetostriction (MS). As well, these methods have been applied to various kinds of materials which were magnetized under AC or DC. And finally, attempts were made to study the relevance of the most important factors of
impact. The following gives a short summary about the corresponding state of the art.

Traditionally, MS measurements are performed by means of strain gauges. Recent improvements of the technique concern rotational magnetization (RM) which yielded the need of multi-directional measurements. As well known, for a full assessment of data, a set of three strain gauges is necessary. Techniques were developed for two individual sensors [10], three individual ones [11,12], but also for combined sensor sets [13,14]. In order to average over large grains of modern transformer core steel, extra-long sensors of about 50 mm length were introduced [11,15]. Extrapolations of MS in the off-plane direction were reported for RM in [16,17]. Time analyses of MS for RM were reported in [11,17,18].

Alternatives to strain gauges were summarized in [19], including exceptional methods like dilatometry. However, the focus is put on optical methods. They comprise laser doppler vibrometer [20-24], optical fiber displacement detector [25] and laser interferometry [26-28]. As advantages, higher resolution and no need of permanent sensor attachment are reported, as disadvantages high expenditure and reduced stability. As further alternatives, MS was determined by accelerometer technique [29,30] and by atomic force microscopy [31].

Very restricted work was done on in-site MS-measurements on transformer cores. First tests on different locations of model cores were reported in [32]. In a wider way, the consequences of RM on vibration or acceleration were studied by accelerometers [4,33] or scanning laser doppler vibrometer [2,34], that on noise by microphone techniques [29,35-38]. Displacements were also modeled through MS-data [39,40], also considering RM [41]. Finally, some attempts were made to complement experimental measurement through analytical or numerical modeling [42,43] and also through neural network modelling [44].

As a very important aspect, attempts were made to interpret MS of transformer steel samples by means of domain investigations ([45] for AM, [16,46] for RM). Most studies concern the Kerr effect technique [21,47]. Also the electron microscope method was applied [48], with the very significant advantage that samples with stress coating can be investigated.

Concerning impact factors, the very significant role of mechanical stress was reported in [14,15,29,42,49-55] for AC and in [15] for RM. Harmonics were discussed in [30,56], influences of RM patterns in [6,57]. Further the impact of DC-bias is described in [58, 59] for AM and in [60] for RM.
II. RSST - SIMULATIONS

A. Experimental Set-up

In order to study elaborately the individual parameters of rotational magnetization (RM) and their impact on magnetostriction (MS) for different types of materials, simulations of exactly defined induction patterns $B(t)$ are essential. Simulation of elliptic and rhombic shape with different axis ratios and varying dynamics were performed by means of a specific rotational single sheet tester ([26]; Fig.1). As a specific advantage, it uses a 3-phase excited, 6-pole-piece yoke system instead of the usual 4-pole-piece system. Thus the hard directions of highly textured samples are supported in specific ways. Measurements are performed on hexagonal samples of about 160 mm diameter. The large size offers sufficient averaging even for modern materials which tend to show extra-large grain sizes close to 10 mm.

![Fig. 3. 3-phase excited rotational single sheet tester with large hexagonal sample of material. Two extra-long strain gauges are arranged on the top of the sample, one applied in RD and the second one in TD. For multidirectional tests, a third sensor is added preferable in 30° to the RD.](image)

As a specific feature of apparatus, a software controlled algorithm approximates 4000 instants of time with 0.2% mean square deviation. This enables the simulation of arbitrary magnetization patterns of different axis ratios $a$ and different angular velocity of the induction vector $B(t)$. Simultaneously, the corresponding field pattern $H(t)$ is detected, which enables the calculation of power loss in a direct way.

As already discussed further above, for MS measurements, several options are given. With respect to the above mentioned large crystallites of the given materials, the sensor should average over several centimeters, as a specific demand. In the present work, we used extra-long strain gauges, effective results being attained by 50 mm long gauges of type LY42-50/120. From the experiences gained from the performed measurements, we conclude that the following demands are given for the needed number of sensors:
(a) for industrially relevant data for AM in rolling direction (RD) - one sensor in RD,
(b) for industrially relevant data for RM - two sensors, one in RD and one in transverse direction (TD) respectively (Fig.3),
(c) for fundamental physical studies - three sensors in RD, TD and in a third direction like 30° to the RD. It should not coincide with one of the two hard directions (close to 55° to the RD) since the latter tend to show extremely weak strain.
Each gauge is placed in a quarter bridge circuit together with a top-on dummy gauge for temperature compensation.

As an option, the three gauges were replaced by three interferometers as described in [26]. Laser sets in connection with mirrors rest on six needles arranged on the sample surface in 50 mm distance from each other. As demonstrated by [26], the two methods prove to yield quite similar results. On the other hand, interferometry showed high susceptibility with respect to thermal and mechanical problems, and in special to out-of-plane vibrations. Thus, more recent experiments were performed with the more robust strain gauge method.

Most measurements were made for both conventional grain-oriented material of type 30M5 and laser scribed highly grain-oriented material of type 23ZDKH90.
B. Magnetostriction for Alternating Magnetization (AM) in Rolling Direction

For most types of transformer core materials, catalogue data on magnetostriction (MS) is restricted to the case of AM in rolling direction (RD). The most common way of data presentation is to give the quasi-DC "virgin curve" $\lambda_{RD}(B_{RD})$, where $\lambda_{RD}$ is the strain as arising if the sample is magnetized with induction $B_{RD}$ in RD starting out from the demagnetized state. As demonstrated by Fig.1, rising $B_{RD}$ yields increasing negative strain which approaches its extreme close to about 1.6 T for CGO-material and 1.7 T for HGO-material. For approaching saturation, the strain becomes positive.

The above behavior can be interpreted by means of results of domain studies. It is well known that the motion of bar domain walls does not contribute to MS, but oblique domains like lancet slopes have great impact on it. In demagnetized state $B_{RD} = 0$, the bar domains have balanced width. Increasing the magnetization yields a widening of each second domain and thus an increase of the concentration of lancets in order to decrease the stray field energy. Assuming that the atoms are slightly elongated in the direction of their magnetic moment $m$ allows interpreting the tendency of negative strain $\lambda_{RD}$. The further assumption of almost constant volume MS yields the tendency of both positive strain $\lambda_{TD}$ in transverse direction and $\lambda_{ND}$ in normal direction.

For $B_{RD} > 1.8$ T, most of the walls of the bar domains are annihilated, and the moments $m$ rotate towards the direction RD of the applied magnetization. The concentration of the lancets decreases and finally becomes zero. These are the reasons for the fact that finally $\lambda_{RD}$ becomes positive - compared to the demagnetized state where oblique domains are present.

Fig.1 includes also the corresponding virgin curve of peak-to-peak strain $\lambda_{RD,PP}(B_{RD})$. In principle, it increases for rising induction. However, as visible in the figure, a zero slope arises for the induction interval between the negative extreme and the zero-axis crossing.

In fact, the above quasi-DC virgin curves have little relevance for practice which is characterized by dynamic steady-state magnetization. Fig.4 shows corresponding so-called butterfly curves $\lambda_{RD}(B_{RD})$ [38] as determined by our rotational single sheet tester. In its principle, we find tendencies of negative extremes round 1.6 T also here, however, in connection with rather complex effects of hysteresis. For magnetization beyond 1.6 T, the positive part of the virgin curve becomes relevant. This yields a butterfly curve with "broken wings". The curves result from ambiguous domain reconstructions in the course of dynamic AM.
Hysteresis means that also peak-to-peak strain $\lambda_{RD,PP}(B_{RD})$ becomes ambiguous. For Fig. 5, we tried to determine average values for the two given types of material. Actually, we find the tendencies of the virgin curves of Fig. 1. However, for the CGO material, the expected zero slope above 1.6 T is mantled through effects of hysteresis. The curve shows a strong rise up to the order of 1 ppm. On the other hand, HGO-values remain below 0.5 ppm which illustrates their superior practical performance.

All above strain values concern the rolling direction (RD). Of course, strain is not restricted to the RD but will arise in all directions of the plane. While the RD tends to be shortened - compared to the demagnetized state - the transverse direction (TD) tends to exhibit elongation of lower intensity. AM can be interpreted as rotational magnetization (RM) of axis ratio $a = 0$. Thus corresponding angular strain distribution will be similar as shown in Fig. 10c for the case of weak RM of $a = 0.1$. Finally, assuming zero volume MS, the off-plane normal direction will show some elongation as well, i.e. the lamination thickness increases in dynamic ways.
C. Magnetostriction for Alternating Magnetization (AM) in various Directions

In transformers, alternating magnetization is restricted to the rolling direction (RD). However, AM in other directions is of interest from a theoretical point of view. An earlier work [21] concerned long strip samples of CGO grade which were cut and magnetized up to 1.8 T in different angles $\psi$ to the RD. In this direction, the MS-caused strain $\lambda_{\psi}(B_{\psi})$ was measured by means of a strain gauge. The results indicated strongly enhanced magnetostriction - with values up to 10 ppm - for rising $\psi$, in special for induction values $B_{\psi}$ above 1 T.

Contrary to non-oriented materials, results from rotational magnetization had indicated that the main axes of strain do not rotate in the case of oriented transformer steel [18]. This means that they are "frozen-in" in RD and TD, respectively, independent from the instantaneous value $\psi$. More recent investigations on AM revealed that the same behavior is given also here. Multi-directional strain measurements were made by means of three strain gauges, as closer discussed in the following section D.

A first study [61] was made in Japan on a square CGO sample magnetized up to 1.1 T. It revealed strong increases of MS with rising $\psi$. However, for $\psi = 90^\circ$ (TD), values up to 30 ppm - corresponding to saturation MS - were reported for $B_{TD} = 1.1$ T which is not compatible with physics. In the following, we studied a hexagonal sample for higher induction values. According to Fig.6, for $B_{TD} = 1.1$ T, it revealed an order of $\lambda_{RD}$ close to 10 ppm which sounds reasonable. An order of 20 ppm is reached for 1.7 T.

Both studies confirm that the main axes are fixed and that maximum strain values arise for the RD, considerably lower ones for the TD. And both studies revealed a complex behavior for $\psi$ close to the hard directions of about 55° (Fig.2). Probably, this can be attributed to very high field
demand. Even higher values would arise for highly grain oriented materials which however have not been investigated so far.

Finally it should be stressed that magnetization in large angles out of the RD may occur in specific butt joints like that of shunt reactors. However, they never will occur in mitred corners of transformer cores. As already mentioned further above, AM is restricted to $\psi = 0$, apart from minor deviations close to overlaps of laminations in corners and T-joints. Results of measurement for other angles can be used to estimate the intensity order of MS as to be expected for rotational magnetization (RM). However, the relevance of MS for noise involves the harmonic composition. It depends on the history of magnetization. This means that AM studies cannot replace RM studies as discussed in the following sections.
D. Multidirectional Instantaneous Magnetostriction for Rotational Magnetization (RM)

According to chapter I, a full assessment of MS for rotational magnetization (RM) can be attained by means of three sensors, applied in three different, arbitrary chosen directions \( \alpha \). For the present work, three strain gauges were used in RD, TD and ID. We define ID as the "intermediate direction" which was chosen with 30° according to Fig. 7a. As shown by an example for elliptic RM in Fig. 7b, the sensors yield three signals which reflect the values \( \lambda_{RD} \), \( \lambda_{ID} \) and \( \lambda_{TD} \) as the strain values in the three independent directions RD, ID and TD. In special, for the instants \( \psi = 0^\circ \) and \( 180^\circ \), very significant errors tend to arise from almost unavoidable strain-bias. The latter may arise from non-precise demagnetization processes, but also from uncontrolled mechanical stress on the sample, possibly even due to magneto-static forces from the start of magnetization of the sample. For Fig. 7b, some corrections were made, based on theoretical considerations.

Fig. 7. For full assessment of MS, three strain gauges are placed in rolling direction (RD) \( \alpha = 0^\circ \) (RD), intermediate direction (ID) 30° and transverse direction (TD) 90°. (a) Arrangement of the strain gauges. (b) Example of sensor signals (with consideration of bias to demagnetization) for CGO-material magnetized with \( B_{RD} = 1.7 \) T and \( a = 0.3 \). Below: the instantaneous direction \( \psi \) of \( B \).

As closer discussed in earlier papers [11,12,16], instantaneous strain in all directions \( \alpha \) of the plane can be derived from the strain tensor which easily can be calculated from the three sensor signals, considering the three sensor angles. Finally, the assumption of zero volume magnetostriction allows for an estimation of the strain \( \lambda_{ND} \) in the off-plane normal direction (ND), as reported in [16].

Fig. 8 shows an example of \( \lambda(a, \psi, t) \) as mentioned for elliptic rotational magnetization (\( a = 0.3; B_{RD} = 1.7 \) T) of a CGO-sample, for four instants of time. Each instant is characterized by a "quatrefoil curve"[11]. For \( B \) in RD, i.e. \( \psi = 0^\circ \), \( \lambda \) shows minimum values. The RD (\( \alpha = 0^\circ \)) shows a shrinking by about -1 ppm, the TD (\( \alpha = 90^\circ \)) elongation by about +0.5 ppm.
Increasing deviation of $B$ from the RD - up to $\psi = 90^\circ$ - yields gradual, very strong increases of strain values. Maximum values arise for $B$ in TD. Then we find strong negative strain of about -6 ppm in RD and +4 ppm in TD. Assuming zero volume-MS, would mean that the off-plane (normal) direction is positively strained by about +2 ppm.

Fig. 8. Quatrefoil curves for CGO material (detected by means of three strain gauges) corresponding to four different angles $\psi$ between the vector $B$ and RD. In all cases, the RD shows shrinking (-) (compare Fig.7).

Qualitatively, the behavior can be interpreted by results of domain studies performed at the RSST with Kerr effect technique. For $\psi = 0^\circ$, bar domains show uneven width (Fig.9a). To reduce the stray field energy, more lancets than in the demagnetized are generated (not visible in the figure), corresponding to the detected shrinking in RD. On the other hand, for $\psi$ close to the TD, most grains - like the right one in the Fig.9b - show plate domains which are magnetized in oblique directions [100] or [010]. The corresponding magnetic moments are withdrawn from the RD which explains its very strong instantaneous shrinking. On the other hand, the TD is elongated, but with reduced intensity due to the tilt of moments.

The hard directions remain almost unstrained throughout the period. This proves to be valid in a general way for grain oriented transformer steel. As well, the type of quatrefoil curves according to Fig.8 proves to be valid in general, i.e. also for highly grain oriented materials.
Fig. 9. Kerr effect domain images of HGO material for two different angles $\psi$ between the vector $B$ and RD, for quasi-dynamical elliptic RM ($f \gg 0$) with $B_{rd} \approx 1.3$ T and $a = 0.3$. (a) $\psi = 0^\circ$. (b) $\psi = 117^\circ$ (after [47]).
E. Multidirectional Peak-to-peak Magnetostriction for RM

The above discussed evaluation of instantaneous strain distributions offers a full assessment of MS, in special since enabling the evaluation of MS harmonics for all directions $\alpha$. As a disadvantage, presentations like Fig.8 lack compactness since a quatrefoil curve results for every instant of time. Further, the curves present strain as related to the non-magnetized state (demagnetized or remanent, respectively). On the other hand, industrial relevance is rather given for peak-to-peak values as arising from steady-state magnetization.

For every direction $\alpha$, the peak-to-peak value of $\lambda_{\alpha,PP}$ results as the difference of maximum strain intensity as usually arising for $\psi = 90^\circ$, and minimum intensity as arising for $\psi = 0^\circ$. This yields a single quatrefoil curve which now does not include negative sections. Fig.10 presents results for CGO material under RM of elliptic shape for $B_{RD} = 1.7$ T and different axis ratios $a$. Also here, maximum values up to 12 ppm are given for the RD, relative maxima up to 7 ppm for the TD, and minima for the hard directions.

![Quatrefoil peak-to-peak curves showing multidirectional MS $\lambda_{\alpha,PP}$ for CGO material under elliptic RM with $B_{RD} = 1.7$ T. (a) $a = 0.5$, (b) $a = 0.3$ and (c) $a = 0.1$ (where the lower part of diagram is not relevant).](image-url)
**F. Bidirectional Magnetostriction as a Function of Axis Ratio of Elliptical Rotational Magnetization**

As already mentioned, grain-oriented transformer steel shows main strain axes which are "frozen-in", that is they do not rotate with rotational magnetization (RM). This is due to extreme anisotropy corresponding to extremely high values of field $H$ for $B$ in the hard directions (HDs) (see Fig.11). In all cases, maximum negative strain arises in RD, and maximum positive one in TD. In special, Fig.8 illustrates that the HDs do not exhibit any strain, i.e. $\lambda$ passes through zero. As a general rule, the highest peak-to-peak magnetostriction (MS) is given in the RD. A relative maximum arises for the TD. Due to quasi-zero volume MS, we can expect a similar relative maximum for the off-plane direction.

![Elliptic induction pattern $B(t)$ and the corresponding field pattern $H(t)$ for elliptic RM of HGO material with $B_{RD} = 1.7$ T and $a = 0.5$.](image)

The above tendencies mean for industrial practice that the magnetostrictive performance of grain oriented materials can be characterized in compact ways by the peak-to-peak MS-values $\lambda_{RD,PP}$ and $\lambda_{TD,PP}$ as measured in RD and TD by means of just two sensors. The behavior in other directions can be estimated assuming quatrefoil distributions. As a draw-back, information on the course of time and thus also on harmonics are not available. In the following, bidirectional data is discussed for elliptic RM, as a function of the axis ratio $a$.

Apart from our study on rhombic RM (see section G), all so far published investigations on magnetostriction for RM were performed for the elliptical case, see [10,17,54,63]. Actually, literature has a focus on circular RM of non-oriented materials and also the rather few papers on grain oriented materials [10, 63] are concentrated on the circular case in connection with rather low $B_{RD}$. On the other hand, the following presents data for industrially relevant cases, i.e. for $B_{RD}$ between 1.3 T up to 1.7 T, and for values $a$ up to 0.5, as being possible in T-joint area of transformer cores.

Fig.12 shows a comparison of results for the CGO-case and the HGO-case, respectively. With increasing axis ratio, strong non-linear increases of $\lambda_{RD,PP}$ and $\lambda_{TD,PP}$ can be observed. As a reason, grains with misorientation out of the RD can easily
generate small values $B_{TD}$. On the other hand, strong values need the formation of oblique domains (lancet slopes or plates) with high portions of atomic moments in [100] and [010]. As a result, the material is expanded in TD while it shrinks in RD.

Increasing $B_{RD}$ causes strong increases of magnetostriction in a non-linear way. For example, for the HGO-case, we observe a rise of $\lambda_{RD,PP}$ of more than 60% for an induction increase of 30%. Also this tendency can be interpreted with a strongly increased portion of oblique domain structures. The value $\lambda_{TD,PP}$ is considerably smaller by about 30%. This difference can easily be explained by the fact that a withdraw of a magnetic moment from [001] results in its alignment either in [100] or in [010]. Since these directions are tilt in 45° to the plane, a shrinking of the RD by $-\Delta\lambda$ yields an elongation of the TD by $+\Delta\lambda/\sqrt{2}$. This results in the approximate function

$$\lambda_{TD,PP} = 0.7 \lambda_{RD,PP} \ . \ (1)$$

Though being based on very rough modelling, the relation proves to be qualitatively effective as demonstrated by Fig.13. However, the latter reveals 0.6 (instead of the factor 0.7) - performance which needs closer study. For practice, it indicates that MS in normal off-plane direction should be stronger than expected from domain theory.
The results of Fig.12 show that compared to HGO material, CGO material does not only show higher MS for AM, but also for RM. However, the increases of MS due to RM are more pronounced in the HGO-case due to the stronger texture. This becomes evident if we do not consider absolute values in ppm, but relative ones. For that, we define related MS for the RD as 
\[ A_{RD} = \frac{\lambda_{RD,PP}(a > 0)}{\lambda_{RD,PP}(a = 0)} \]
This is in analogy to the local building factor of losses. However, the case of an "MS building factor" is disfavored by difficulties to determine the - usually very small - AM base value with sufficient precision. Anyhow, Fig.14 shows that MS of highly textured material is much more affected by RM than CGO-material. With increasing induction, the effect of the increased MS under RM becomes even stronger.

The above results for MS correlate well with the corresponding results of power loss (see e.g. [6]). For the values of both magnetostriction and loss, we find the following tendencies in comparison to CGO material:
(i) For alternating magnetization ($a = 0$), both values are distinctly smaller for the HGO material.
(ii) With increasing $a$, both values show strong increases.
(iii) The increases are more pronounced for the HGO case, i.e. the related increases are stronger.
However, with regard to (iii) it should be stressed that the strong texture of HGO material yields the tendency that T-joints exhibit restricted values $a$, as an advantageous effect of counter-balancing.
G. Impact of Rotational Magnetization Pattern

Another important factor which has strong impact on power loss is the shape of the magnetization pattern [63]. In literature, primarily two types of rotational magnetization patterns can be found: the elliptic type (Fig. 15a) as arising at non-oriented stator cores of rotating machines and the rhombic type (Fig. 15b) as observable in T-joints and yokes of oriented transformer cores. These two important practical cases of patterns were simulated on the rotational single sheet tester and compared to each other.

Fig. 15. Comparison of two important rotational magnetization patterns.
(a) Elliptic pattern as usually being studied but lacking practical relevance for transformers. (b) Rhombic pattern as being typical for modern transformer cores. It is characterized by lower induction values in the hard directions (HD1 and HD2).

Fig. 16 illustrates $\lambda_{RD,PP}$ as a function of axis ratio $a$ for both shapes. For the rhombic case, we see a tendency of lower magnetostriction, the difference increasing with increasing $a$ and decreasing with increasing $B_{RD}$. The effect can be related to the fact that rhombic RM involves distinctly lower $B_{HD}$ in the hard directions. An interpretation would need closer studies on the corresponding domain reconstructions.

Fig. 16. Peak-to-peak MS in RD for a HGO-sample magnetized with $B_{RD} = 1.3$ T and $B_{RD} = 1.7$ T as a function of axis ratio $a$. A comparison is given for elliptic and rhombic RM.

As a conclusion, with respect to MS, the effect of shape of rotational magnetization is rather small. On the other hand, effects on losses are significant. The much higher loss values
for the elliptic case can be interpreted by higher hysteresis loss in the course of the complex, stronger magnetization in the hard directions.

H. Impact of Dynamics of Rotational Magnetization

It is evident that the power loss of grain oriented SiFe shows distinct increases in cases of enhanced dynamics of magnetization. For alternating magnetization (AM), this is valid for distortions. As well, it is valid for rotational magnetization (RM) due to the more pronounced eddy currents losses, if the induction vector $\mathbf{B}$ shows high values of maximal angular velocity $\omega_{\text{MAX}}$ [63].

![Diagram](image.png)

Fig. 17. Examples of elliptic magnetization pattern with $B_{\text{RD}} = 1.7$ T and $a = 0.3$ with different dynamics of $\mathbf{B}(t)$ expressed in different maximal angular velocities $\omega_{\text{MAX}}$. (a) Case of constant angular velocity ($\omega_{\text{MAX}} = 18 \, ^\circ/\text{ms}$). (b) $\omega_{\text{MAX}} = 50 \, ^\circ/\text{ms}$. (c) $\omega_{\text{MAX}} = 100 \, ^\circ/\text{ms}$. (d) $\omega_{\text{MAX}} = 300 \, ^\circ/\text{ms}$. (e) Corresponding time-domain diagram of angular velocities (after [57]).

Fig. 17 illustrates the phenomenon of varying dynamics by indication of the distribution of 20 instants of time corresponding to twenty 1 ms spaced instantaneous positions of the induction vector $\mathbf{B}$ rotating with 50 Hz. Since rhombic and elliptic patterns exhibit similar MS values (compare previous section) and since the elliptic shape can be mathematically defined in a more simple way, the simulation of dynamics was restricted to this shape. In our work, we express RM dynamics through the maximum angular velocity $\omega_{\text{MAX}}$ as arising during the period of magnetization. Fig. 17a shows the case of
constant $\omega_{\text{MAX}} = \omega = 18^\circ/\text{ms}$, Fig. 17b the "even" case of low $\omega_{\text{MAX}} = 50^\circ/\text{ms}$, as resulting from sinusoidal induction components, and as investigated by most authors. However, both cases lack practical relevance. Model core tests (compare Fig.26) revealed that practice exhibits high dynamics, corresponding to $\omega_{\text{MAX}}$ of at least $100^\circ/\text{ms}$ (Fig.17c) in the interval when $B$ passes the TD.

Fig.18 shows examples for peak-to-peak magnetostriction $\lambda_{\text{RD,PP}}$ in RD and $\lambda_{\text{TD,PP}}$ in TD as a function of $\omega_{\text{MAX}}$. In a complex way, both materials exhibited irregular variations of strain for $\omega_{\text{MAX}} < 100^\circ/\text{ms}$. Furthermore increased values show a tendency of decreasing MS, especially for high $B_{\text{RD}}$. The quite weak tendency arises for all types of grain oriented materials. Finally, closer study revealed that this rather unexpected behaviour is due to changes of the harmonic composition.

![Graph showing peak-to-peak magnetostriction as a function of $\omega_{\text{MAX}}$.](image)

**Fig. 18.** Peak-to-peak magnetostriction as a function of $\omega_{\text{MAX}}$ for elliptic magnetization with $B_{\text{RD}} = 1.7$ T and axis ratio $a = 0.3$ for CGO material and HGO material. (a) $\lambda_{\text{RD,PP}}$ in RD (after [57]). (b) $\lambda_{\text{TD,PP}}$ in RD.

![Graph showing examples of the amplitude spectrum of $\lambda_{\text{RD}}$.](image)

**Fig. 19.** Examples of the amplitude spectrum of $\lambda_{\text{RD}}$ for elliptic magnetization with $B_{\text{RD}} = 1.7$ T and $a = 0.3$ of HGO electrical steel for the cases (a) $\omega_{\text{MAX}} = 50^\circ/\text{ms}$, (b) $\omega_{\text{MAX}} = 200^\circ/\text{ms}$, and (c) $\omega_{\text{MAX}} = 300^\circ/\text{ms}$. The spectral lines of 200 Hz, 300 Hz and 400 Hz components are related to the 100 Hz-component.

For a corresponding closer study, we analysed the harmonic distribution of the courses of time $\lambda(t)$ as a function of
changing dynamics. It is well known that the fundamental component of MS is 100 Hz. However, the amplitudes of the higher harmonics are more important for the auditory noise. Fig. 19 shows examples of amplitude spectra for different $\omega_{\text{MAX}}$. The higher harmonics $\varepsilon_k$ ($k = 2, 3, 4$) corresponding to 200 Hz, 300 Hz, 400 Hz are given related to the basic one ($k = 1$). The results indicate that although the total intensity of MS decreases with higher dynamics, the spectral lines are increasing with increasing maximum angular velocity. This is as to be expected from more distorted time signals $\lambda(t)$.

![Graph showing relative increase $q$ of the fundamental component $\eta_1$ and the MS-harmonics $\eta_2$, $\eta_3$, $\eta_4$ related to the harmonics of the low dynamics case with $\omega_{\text{MAX}} \approx 50^\circ/\text{ms}$ of peak-to-peak magnetostriction in RD as function of $\omega_{\text{MAX}}$ for $B_{\text{RD}} = 1.7$ T and $a = 0.3$ of highly grain oriented electrical steel (after [57]).](image)

Fig. 20 shows percentage increases $q_k=100\%\left[\frac{\eta_k(\omega_{\text{MAX}})}{\eta_k(\omega_{\text{MAX}}=50^\circ/\text{ms})}\right]-1$, for $k = 1, 2, 3$ and 4 of harmonics $\eta_k$ as arising from increased values of $\omega_{\text{MAX}}$ compared to harmonics for the low dynamics case $\omega_{\text{MAX}} \approx 50^\circ/\text{ms}$. For the fundamental component (100 Hz), a 50% decrease was observed for very high $\omega_{\text{MAX}}$. It explains the above reported decrease of total MS, since the fundamental component has the greatest impact on the MS intensity.

Higher harmonics exhibit strong increases up to 300% for increased dynamics. In spite of rather low intensities compared to the fundamental harmonic, the increase of higher harmonics has practical relevance since they contribute to audible noise in distinct ways, considering the physiological characteristics of the human ear. A second reason is that the audible noise is proportional to the velocity of vibrations and not the vibration displacements.
I. Impact of Mechanical Stress

A further impact factor for magnetostriction (MS) is given by mechanical stress. The corresponding effects depend on several parameters and in special on the direction of stress. In industrial practice, the latter may vary in complex ways, e.g. due to clamping in connection with torsion of laminations.

For RSST-simulation, the hexagonal sample was loaded via four threads through four holes, the strain in the sample center being estimated by means of the strain gauge attached in RD. Fig.21a shows increases $A$ of MS in RD related to unstressed AM for the case that stress $\sigma$ acts in RD (after [15]). In the case of alternating magnetization (AM), tension ($\sigma > 0$) in RD tends to yield slight decreases of MS, compression ($\sigma < 0$) strong increases. On the other hand, the case of rotational magnetization is characterized by an opposite behavior: Tension yields strong MS-increases, compression yields decreases as far as it is of weak intensity. However, strong compression causes MS-increases, especially for small $a$ (corresponding to approaching AM).

Fig. 21. Relative increase $A$ of magnetostriction compared to stress-less AM ($a = 0$) - due to mechanical compressive and tensile stress $\sigma$ in RD of HGO-material.
(a) For $B_{RD} = 1.7$ T and two values of axis ratio $a$.
(b) For $a = 0.4$ and three values of $B_{RD}$ (after [15]).

Fig.21b indicates that stress effects are most pronounced for small induction $B_{RD}$. Compared to AM, strong tension may yield relative MS-increases $A$ that exceed the extremely high value 100. Here it should be stressed that such strong effects are restricted to highly grain oriented (HGO) materials. Maximum values $A$ are up to about 10 for the CGO-case and up to about 5 for the non-oriented case.
As a conclusion, stress proves to increase MS in a general way. This is in contrast to power loss where tension in RD has positive effects on losses for AC magnetization in RD, as utilized for stress coatings in well known ways. On the other hand, stress has been shown to yield general increases of loss for the case of RM [50]. This means that the performance is analogous to magnetostriction at least in a qualitative way.

### J. Impact of DC-bias

Finally, also the effect of DC-bias of RM on MS was investigated. Rising implementation of electronics in electric power delivery yields DC-bias as a significant impact factor on the magnetic performance of transformers. For simulations, we characterize the intensity of bias by an excitation ratio:

\[
    r_{DC} = \frac{(N_{DC} \cdot I_{DC})}{(N_{AC} \cdot I_{AC})}
\]

with \(N_{DC}\) the number of DC magnetization winding turns, \(I_{DC}\) the DC current imposed in RD, \(N_{AC}\) the total number of AC winding turns and \(I_{AC}\) the sum of the RMS value of AC currents from the 6 coils of the rotational single sheet tester for \(I_{DC} = 0\). For geomagnetically induced currents (GICs; [7]), the order of \(r_{DC}\) may be up to 10 as short time events. On the other hand, it tends to be below 1 for long term events of the already mentioned, non-compensated thyristor switches or imperfect transistor sets.

Fig. 22. Simulated elliptic magnetization pattern with \(B_{RD} = 1.7\) T and \(a = 0.4\) for CGO (30M5). Mere AC (solid lines) is compared with AC + imposed DC in RD with weak \(r_{DC} = 0.1\) (dotted). (b) Corresponding magnetic field patterns (after [64]).

For an illustration, Fig. 22 shows the impact of weak bias with \(r_{DC} = 0.1\) on the induction pattern \(B(t)\) and the corresponding field pattern \(H(t)\) of CGO material. We see that a small shift \(\Delta B_{RD}\) is linked with strong asymmetry of the field pattern. The following results concern stronger, but still quite moderate bias with \(r_{DC}\) between 0.5 and 1.
Fig. 23. Relative MS-increase \( \Lambda \) in % due to imposed DC-bias in RD with two different excitation ratios \( r_{DC} = 0.5 \) and \( r_{DC} = 1 \) and for different axis ratios \( a \).

(a) For HGO material with \( B_{RD} = 1.7 \) T. (b) For HGO material with \( B_{RD} = 1.3 \) T. (c) For CGO material with \( B_{RD} = 1.7 \) T (after [60]).

Fig.23 shows measurements results for the two types of material for elliptic rotational magnetization of axis ratio \( a \) varied up to 0.5. The DC-caused MS-increase \( \Lambda = 100\%[\lambda(AC+DC) / \lambda(AC) - 1] \) in RD is expressed in percent on the ordinate. Both materials prove to show a tendency of strongly increasing MS for small \( a \). Roughly, \( r_{DC} = 1 \) yields doubled MS for \( a = 0.1 \). On the other hand, with increased axis ratio, the effects become weaker in a non-linear way. For \( a = 0.5 \) they are without practical relevance. This means that in transformer cores, effects of DC can be expected in the limbs while they should be weak in the T-joints. In fact, this tendency is confirmed by experiments as described in the following chapter III.
III. MODEL TRANSFORMER CORE EXPERIMENTS

As already mentioned in the introduction, literature does not report measurements of MS on different locations of transformer cores. Earlier, we reported some first results of model core investigation in reference [32]. The following describes measurements on both a 1-phase core and a 3-phase core. In both cases, the results are compared with that of the above described results of rotational single sheet tester simulations, including also those for DC-bias.

A. Experimental Set-up

Our study concerned two different types of model transformer cores according to the following:

(i) 2-limb, 1-phase core - The core size was 400 mm x 320 mm with lamination width of 80 mm. The core was stacked from 70 layers of highly grain oriented SiFe of type 23ZH90. AC magnetization was induced by means of 108 winding turns. For DC-bias, 60 extra turns were used. This is not according to practice, but it can be assumed to yield identical effects if identical ratios \( r_{DC} \) are considered.

(ii) 3-limb, 3-phase core - The core size was 1000 mm x 1000 mm with lamination width of 200 mm. It was stacked from 44 layers of conventional grain oriented SiFe of type 30M5. The core was AC-magnetized by 50 winding turns per limb. DC-bias was impressed in unbalanced way into the middle limb by means of an extra coil of 74 turns. As well known, unbalanced bias proves to be more effective, thus offering experiments with small DC-intensities linked with the advantage of restricted side-effects of heat generation.

Local strain distributions in different regions of the model cores were analyzed by means of strain gauges of type LY42-50/120. Their length was chosen with 50 mm. As a compromise, this should yield sufficient averaging over the large grains of material, but also should allow for sufficient local resolution. The sensor signals were amplified by a measuring amplifier (HBM, Spider 8). The spectral lines for the fundamental component (100 Hz) and the higher harmonics (200, 300, 400 Hz) were filtered and synthetically used for the estimation of the strain intensity \( \lambda \). This procedure proved to be necessary to overcome signal noise from various sources of side effects. To check their evidence, two sensors were applied in parallel in selected positions (e.g. middle limb in Fig.23). All signal processing and evaluations of results were performed in MATLAB.
B. Single Phase Core

As indicated by Fig.24, the strain distribution was analyzed by means of 12 strain gauges. Fig.24a shows results for a nominal induction $B_{\text{NOM}} = 1.7$ T without DC-bias. Peak-to-peak values $\lambda_{\text{RD,PP}}$ in rolling direction are given for nine positions, values $\lambda_{\text{TD,PP}}$ in transverse direction for three ones.

The presented results of strain measurement concern an ideal state of core clamping. The latter proved to be the most critical part of experiments. They revealed the following tendencies:

(a) Weak clamping resulted in a most heterogeneous distribution of strain values. Locally, some values exceeded 30 ppm which means that they are not due to magnetostriction but rather caused by inter-laminar dynamic forces between free components of laminations.

(b) Also very strong clamping resulted in values of very high intensity at singular locations. This can be interpreted by mechanical bending and torsion of laminations as a source of tensile and compressive stress. According to section II.1., this may result in strong increases of magnetostriction.

(c) Finally, by very careful preparation of locally balanced clamping, an "ideal" state could be reached which is characterized by rather homogeneous distributions of regional magnetostriction values. Obviously this state represents a compromise between moderate force-caused vibrations and also moderate stress.

The following presents results from this "ideal" state (c).

---

![Fig. 24. Measured peak-to-peak MS on the surface of the single-phase transformer core assembled from laser scribed material, magnetized with 1.7 T.](image)

(a) For pure AC excitation. All strain values are given in ppm.
(b) With moderate bias according to $r_{\text{DC}} = 1$. Only the increases of magnetostriction are given (in italics).

For the rolling direction of limbs and yokes, Fig.24a indicates MS-values $\lambda_{\text{RD,PP}}$ below 0.5 ppm which corresponds well with results of RSST simulation. $\lambda_{\text{TD,PP}}$ is somewhat smaller which corresponds as well. The values in corners
indicate some higher strain in both RD and TD up to 0.8 ppm. This cannot be explained by effects of mere magnetostriction, apart from possible effects of very weak sectional rotational magnetization. Rather, effects of magneto-static forces acting between the laminations of limb and yoke should be considered. According to earlier work [4], attractive forces are not restricted to the lamination area, but inter-laminar off-plane flux close to air gaps exist as well, as a source of local, cyclic bending of lamination ends [32]. Fig.24b shows results for superimposed DC-bias. The local increases of $\lambda_{RD,PP}$ and $\lambda_{RD,PP}$ are given in %. The corresponding effects will be discussed in Section D.

C. Three Phase Core

Fig.25a shows results for the 3-limb, 3-phase core. Compared to the 1-phase case, all strain values are higher which is due to the worse magnetostrictive behaviour of the given CGO material compared to HGO material, especially under AM. In all the regions, the strain in rolling direction is higher than in the transverse one, according to theory. In limbs, $\lambda_{RD,PP}$ is below 1 ppm which corresponds well with the results of rotational single sheet tester (RSST) simulations. Differences between individual strain gauges of identical regions can be attributed to lacking homogeneity of material and induction, respectively, but also to imperfect mounting.
Fig. 25. (a) Local values of peak-to-peak magnetostriction (in ppm) on the surface of the 3-limb, 3-phase model core stacked from CGO material 30M5, for $B = 1.7$ T without bias (after [60]). (b) Regional percentage increases of MS (given in italics) due to moderate bias ($r_{DC} = 1$) imposed in the middle S-limb (unbalanced case).

Compared to limbs, the corners show higher MS, analogous to the 1-phase case obviously due to magneto-static forces. Rather low values of MS are given in the straight parts of the yoke in spite of weak rotational magnetization (RM). According to Fig.26a which shows results of induction measurements by means of search coils, RM shows local axis ratios $a$ up to the order of 0.15. However, in a non-clarified way, this is not reflected by local increase of MS.

Maximum values up to $\lambda_{RD,PP} = 6$ ppm arise in the T-joint. The corresponding values of $a$ are up to 0.3, Fig.26b indicating that high dynamics (angular velocities up to 100 °/ms) are present. A comparison with RSST results in Fig.12a reveals that RM can be assumed as the major impact factor. With these high values of magnetostriction, T-joints can be considered as major sources of magnetostriction-caused strain. We can conclude that they represent regional "noisy spots" of noise generation, analogous to hot spots of power loss.
Fig. 26. Results of local measurements of flux densities in RD and in TD as detected by means of a total of 68 search coils (for a global magnetization with 1.7 T).

(a) Local $B$-patterns and the corresponding local values of axis ratio $a$.
(b) For the central region of T-joint, the $B$-pattern with indication of 20 instantaneous vector positions within the period of 20 ms. At right, the corresponding time course of angular velocity.

For a rough estimation of consequences on the over-all yoke expansion, we can assume that T-joints represent about 20% of total length. Assuming 5-fold mean regional magnetostriction would mean that over-all expansions are doubled. Roughly, the noise generation from the yoke end areas can be expected to be increased by about 3 dB, an effect which is of practical relevance.
D. Cores Under DC-bias

The above reported model core experiments were also performed with DC-bias. Fig.24b and Fig.25b show the relative increase of peak-to-peak MS percentage due to moderate bias according to $r_{DC} = 1$ for each local strain gauge for 2-limb, 1-phase and 3-limb, 3-phase core respectively. The results reveal increases of the peak-to-peak magnetostriction for both RD and TD in almost all regions of the core with high scatter. In order to obtain a better overview and due to the scatter of the increases, regional average values for the RD are presented in Table I. For the 1-phase core, limbs and corners show about 30% increase of peak-to-peak MS, yokes about 70%. The results are in rough correlation with the rotational single sheet tester simulations.

Table I
Regional increases of magnetostriction due to DC-bias

<table>
<thead>
<tr>
<th>Model core</th>
<th>Yoke</th>
<th>Corner</th>
<th>Outer limbs</th>
<th>Middle limb</th>
<th>T-joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 limb 1 phase</td>
<td>+70 %</td>
<td>+30 %</td>
<td>+25 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 limb 3 phase</td>
<td>+150 %</td>
<td>+60 %</td>
<td>+130 %</td>
<td>0 %</td>
<td>+70 %</td>
</tr>
</tbody>
</table>

Fig.25b depicts the case of CGO 3-phase core being DC-biased with $r_{DC} = 1$ in the middle limb, as already mentioned corresponding to the so-called unbalanced case which tends to be more effective than the balanced case (without magnetic surrounding, like tank material). From Table I we see significant increases with strong regional differences in all regions except the middle limb. An order of 150% in RD resulted for outer limbs and yokes of very low $a$. About 70% resulted for the T-joint where the mean value of $a$ may be close to 0.15. This is in rough agreement with the results of rotational single sheet tests in Fig.23a. Similar increases resulted for the TD.
Fig. 27. Mean amplitude spectra of the 3-phase CGO core. All harmonics are related to the fundamental component (100 Hz) of the non-biased case. The dark lines concern moderate bias ($r_{dc} = 1$). (a) Outer limb. (b) T-joint.

Fig. 27 illustrates the mean amplitude spectrum of the sensors placed in RD in the outer limb and in the T-joint, respectively. The mere AC-case is compared with unbalanced bias imposed into the middle limb. The results reveal that the impact of bias is weaker in the T-joint region, corresponding to an over-all balancing effect. This is also valid for the harmonics. They are significantly increased in the limb which a priori shows almost sinusoidal magnetostriction. According to theory, bias yielded also odd harmonics. However their intensity was very small and mantled by restricted resolution of measurement. Finally it should be noted that the observed performance has relevance for audible noise considering the physiologic characteristics of the human ear.
IV. DISCUSSION AND CONCLUSIONS

A. Magnetostriction Versus Power loss

According to the introduction, the present study was aimed on a comparison of the relevance of several impact factors of RM on magnetostriction (MS) on one hand, and power losses on the other hand. For an overview, Table II summarizes the observed corresponding tendencies.

<table>
<thead>
<tr>
<th>Impact factor</th>
<th>effects on losses</th>
<th>effects on magnetostriction</th>
</tr>
</thead>
<tbody>
<tr>
<td>increase of axis ratio $a$</td>
<td>strong increase</td>
<td>strong increase</td>
</tr>
<tr>
<td>increase of $B_{rd}$</td>
<td>strong increase</td>
<td>strong increase</td>
</tr>
<tr>
<td>increase of $B_{hd}$ (rhombic $=&gt;$ elliptic)</td>
<td>strong increase</td>
<td>slight increase</td>
</tr>
<tr>
<td>increase of dynamics</td>
<td>weak increase</td>
<td>slight increase, followed by decrease, increase of harmonics</td>
</tr>
<tr>
<td>tension in RD</td>
<td>for AM slight decrease, for RM increase</td>
<td>for AM slight decrease, for RM increase</td>
</tr>
<tr>
<td>compression in RD</td>
<td>increase</td>
<td>decrease, followed by strong increase</td>
</tr>
<tr>
<td>DC-bias</td>
<td>increase</td>
<td>increase, strong increase of harmonics</td>
</tr>
</tbody>
</table>

As a rough tendency, we can observe that most of the investigated impact factors yield a general tendency to enhance both power loss and magnetostriction (MS). However, differences exist with respect to the intensity of consequences. In special, MS tends to be specifically affected by mechanical stress as well as by DC-bias. Further, a qualitative difference exists with respect to eddy currents. The latter have a dominant impact on losses, contributing about 60%, while almost no relevance is given for MS. In analogous ways, the shape of rotational magnetization patterns plays a significant role for losses, strong induction in hard directions enhancing hysteresis losses, while little impact is given on MS. Finally, in some few cases, a controversial behaviour is given for losses and MS, respectively.
**B. Industrial Relevance**

The present study demonstrates the importance of rotational magnetization for magnetostriction and noise in transformer cores. It is clear that the investigated mechanisms are relevant especially in transformers designed for extra low noise emissions. The more successful "other" methods of noise reduction are, the more important rotational magnetization will be. If for example the "classic" magnetostriction due to alternating magnetization is reduced by improved grain orientation as in the case of scribed HGO material, the relative effect of magnetostriction due to rotational magnetization (RM) is enhanced. The same effect is seen if the general level of AM-magnetostriction is reduced by designing to lower average flux density, then the relative magnetostriction increase by RM is enhanced. If on the other hand, the flux density is increased by design or by DC-bias, the basic magnetostriction and noise are already quite high a priori. Thus the relative increase caused by RM will be limited or even be insignificant.

It is also important to note that the final sound power level emitted by the transformer core is proportional to the vibration velocity of the core surface. A further significant, well known factor is the frequency-dependent sensitivity of hearing, which is considered by the standard A-filter as applied when measuring noise [65]. Automatically, these conditions bring more emphasis to the harmonics than to the fundamental tone. Hence a shift in the harmonic composition can cause a significant increase in the A-weighted noise level although the peak-to-peak value of magnetostriction may be constant or even reduced. This effect is quite often found at high flux densities. On the other hand, at low flux densities, the fundamental component of MS which corresponds well to the peak-to-peak amplitude, more often dominates the spectrum of transformer core noise.

According to the introduction, the present study should help to clarify the question whether impact factors for losses are valid also for magnetostriction in comparable ways. Table II confirms that quite similar global tendencies are given. However, the design of large power transformers tends to be specifically adapted to the special conditions of the customer. It has to consider both the environment of the transformer and the given grid conditions. In such cases, differences as indicated by Table II are taken under consideration in careful ways.
C. List of Main Conclusions

The main conclusions of the present study are the following:

1. The intensity of magnetostriction (MS) for alternating magnetization (AM), corresponding to a magnetization axis ratio \( a = B_{TD}/B_{RD} = 0 \), remains below 1 ppm in all cases.
2. For the AM-case, four cases of magnetostriction-curves should be distinguished: the quasi-DC virgin curve, the quasi DC peak-to-peak curve, the AC butterfly curve, and the AC peak-to-peak curve.
3. For rotational magnetization (RM), three sensors in three different directions of the sample plane are needed for a full assessment of magnetostriction.
4. A full documentation of behavior is possible by a series of instantaneous quatrefoil curves which reveal negative strain round the RD and positive strain round the TD.
5. In all cases of grain oriented transformer core materials, maximum intensity of (negative) strain appears in RD, a relative maximum of (positive) strain appears in TD and almost zero-strain for the hard directions.
6. The corresponding instantaneous values for the off-plane normal direction can be estimated assuming zero volume-magnetostriction yield similar increases as for the TD.
7. For industrial applications, peak-to-peak presentations are suggested, as given by a single quatrefoil curve of positive values for all directions.
8. For elliptic rotational magnetization (RM), magnetostriction increases in non-linear ways for both increasing \( a \) and increasing induction \( B_{RD} \) in rolling direction.
9. For elliptic RM, magnetostriction in TD proves to be approximately 60% of that in RD.
10. Related to AM, magnetostriction for RM shows much higher increases for highly grain oriented material compared to conventionally grain oriented one.
11. Compared to elliptic RM, magnetostriction is weaker for rhombic RM, in special for high \( a \).
12. Increasing maximum angular velocity of the induction vector yields increases of magnetostriction, followed by decreases. The harmonic content increases.
13. Mechanical stress tends to yield very strong increases of magnetostriction, with some exception.
14. DC-bias yields increases of magnetostriction, in special for low \( a \).
15. Local strain values on model transformer cores depend strongly on the state of clamping - being minimum for well balanced medium clamping intensity.
16. 1-phase core studies show minimum magnetostriction in limbs and yokes and higher values in corners, possibly due to magneto-static forces at overlaps.
17. 3-phase core studies show similar tendencies, however, revealing very strong magnetostriction in T-joints.
(18) Cores under DC-bias reveal strong increases of magnetostriction, especially in the limbs, in connection with increases of harmonics.

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