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2 **Measurement of magnetostriction using dual laser**

3 **heterodyne interferometers: experimental challenges and**

4 **preliminary results**

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11 **Abstract**

12 *Vibrations and noise of electrical machines and transformers may be caused by Lorentz*

13 *forces and/or by magnetostriction. Here we only focus on the vibrations and noise due*

14 *to magnetostriction. Electrical machines and transformers have magnetic cores of*

15 *ferromagnetic material. Magnetostriction can be seen as a reaction of the ferromagnetic*

16 *material to the presence of a magnetic field in the material and it leads to unwanted*

17 *noise. The magnetostriction varies from material to material and is dependent on the*

18 *magnetic field (or the magnetic induction) and on external stresses applied to the*

19 *material. For every different material, the magnetostriction properties have to be*

20 *obtained experimentally, usually by means of magnetostriction strain measurements. In*

21 *the past a measurement set-up using strain gauges was developed at the Electrical*

22 *Energy Laboratory (EELAB). In this paper a new magnetostriction measurement set-up*

23 *using a dual laser heterodyne interferometer is proposed which avoids the drawbacks of*

24 *the strain gauge set-up. The preliminary measurements already show some promising*

25 *results. The experimental challenges and future work are explained at the end.*

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## 40 **Introduction**

41 In our modern, industrialized world, people are experiencing more and more the negative effect  
42 of man made noise. One of the sources is the noise of electrical machines and transformers,  
43 which are often used in industrial applications. Technically spoken, the noise of electrical  
44 machines and transformers can be subdivided into three classes: purely mechanical noise,  
45 aerodynamic noise and magnetic noise. In this work, we will concentrate on the magnetic noise.  
46 This noise is caused by the magnetic forces and the magnetostriction in the magnetic cores of  
47 electrical machines and transformers. While the magnetic forces are a widely known  
48 phenomenon, magnetostriction is a rather unknown phenomenon for the broader public.  
49 Nonetheless, magnetostriction can result in a large contribution to the magnetic noise, especially  
50 in the case of transformers. Magnetostriction can be seen as a reaction of the ferromagnetic  
51 material of the magnetic core to the presence of a magnetic field in the material. This reaction  
52 consists of a deformation of the material and must not be confused with the deformation of the  
53 material due to the magnetic forces.

54 The knowledge of the magnetostrictive behaviour of ferromagnetic materials is of essential  
55 importance for the calculation of the vibrations and noise of electrical machines and transformers  
56 in the design stage. Because the magnetostriction strain is very small (order of  $\mu m / m$ ), the  
57 measurement of magnetostriction under various magnetization circumstances poses a rather  
58 complex problem. In the past, efforts have been made at the Electrical Energy Laboratory  
59 (EELAB) to measure magnetostriction by means of strain gauges. Although fairly good results  
60 were obtained, a need for more accurate results is present. In this paper, a new magnetostriction  
61 measurement system, based on dual laser heterodyne interferometers, is proposed. Before going  
62 into detail about this new set-up, the problem of the magnetic noise and the magnetostriction will  
63 be elaborated in the following paragraphs.

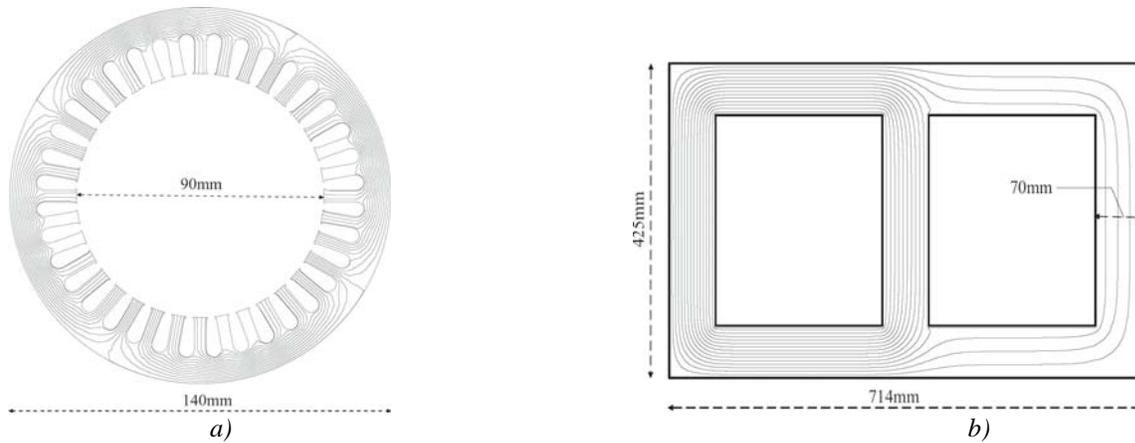
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## 66 **1. Magnetic noise in electrical machines and transformers**

67 As mentioned, the noise of electrical machines and transformers can be subdivided in three  
68 classes. The focus of this work is on the magnetic noise. For information about the purely  
69 mechanical noise and the aerodynamic noise, we refer to [1].

70 Both electrical machines and transformers have a core built out of stacks of sheets of  
71 ferromagnetic material, so called electrical steel, see Figure 1. These magnetic cores are essential  
72 for an efficient operation of the devices. Without going much into detail, we can say that in the  
73 case of electrical machines, the core of the stator can be seen as a necessary item for building up  
74 a rotational magnetic field in an efficient way. This rotational magnetic field is used to create a  
75 torque on the rotor of the machines, which also has a magnetic core. In the case of transformers,  
76 the magnetic core is necessary to build up a pulsating magnetic field in an efficient way. Here,  
77 this magnetic field will provide the possibility of transfer of energy between the primary and the  
78 secondary windings. It should be noticed that in both cases, time-varying magnetic fields are  
79 used. For more details about the working principles of electrical machines and transformers, we  
80 can refer to [2].

81



**Figure 1:** Ferromagnetic core of a) Electrical machine b) Transformer.

Roughly speaking, we can say that magnetic noise is caused by the pulsating magnetic flux in the magnetic cores of the electrical machines or the transformers. There are two different sources for this noise:

- The magnetic forces have the parasitic effect that they tend to deform the geometry of the magnetic core. Combined with the pulsating behaviour of these forces, this leads to vibrations, which will be transferred to other parts of the machine. The vibrations of the outer hull of the machine subsequently cause a noise radiation.
- Ferromagnetic material (such as electrical steel) deforms when magnetized. This effect is called magnetostriction. The amount of the deformation strongly depends on the kind of the material and the magnetization. Since the magnetostriction depends on the magnetization, here also a pulsating magnetization will lead to vibrations, which will lead to noise.

The effect of the magnetic forces is well known and can be calculated on the basis of an analytical expression. The magnetostriction varies from material to material and is dependent on the magnetic field (or the magnetic induction) and on external stresses applied to the material.

For every different material, the magnetostriction has to be obtained experimentally by means of magnetostriction strain measurements.

## 2. Magnetostriction

As mentioned before, magnetostriction can be seen as a reaction of ferromagnetic material to the presence of a magnetic field in the material, and is dependent on the magnetization and applied external stresses. In general, the magnetostriction is denoted as a three-dimensional strain tensor.

For an orthonormal cartesian coordinate system, we get:

$$\varepsilon_{ms}^c = \begin{bmatrix} \lambda_{xx}^c & \lambda_{xy}^c & \lambda_{xz}^c \\ \lambda_{yx}^c & \lambda_{yy}^c & \lambda_{yz}^c \\ \lambda_{zx}^c & \lambda_{zy}^c & \lambda_{zz}^c \end{bmatrix} \quad (2.1)$$

When working with a one-dimensional magnetization of an isotropic ferromagnetic material, we will orient the coordinate system so that the x-axis is parallel to the direction of the magnetization, while the y-axis and the z-axis are perpendicular to the direction of the magnetization. In this case, we will use the following notation:

$$\varepsilon_{ms}^c = \begin{bmatrix} \lambda_{//}^c & 0 & 0 \\ 0 & \lambda_{\perp 1}^c & 0 \\ 0 & 0 & \lambda_{\perp 2}^c \end{bmatrix} \quad (2.2)$$

113 In this tensor, the non diagonal items are equal to zero, because the axes of the coordinate system  
114 are now coinciding with the principal directions of the material.

115 For applications related to this work, we have chosen the coordinate system to be as is indicated  
116 in Figure 2. Also, a two-dimensional approach was chosen for the calculation of the mechanical  
117 problem (i.e. calculation of potential vibrations of electrical machines and transformers on the  
118 basis of magnetostriction data), which was used in previous articles of some of the authors [3,4].  
119 The two-dimensional approach is sufficient because of the geometry of the thin sheets of the  
120 electrical steel. This leads to the final form of the magnetostriction strain tensor used in this  
121 article:

$$\varepsilon_{ms}^c = \begin{bmatrix} \lambda_{//}^c(B) & 0 \\ 0 & \lambda_{\perp 1}^c(B) \end{bmatrix} \quad (2.3)$$

123 Basically, we are interested in two quantities:

- 124 •  $\lambda_{//}$ : the magnetostriction strain in the direction parallel to the direction of the magnetization
- 125 •  $\lambda_{\perp}$ : the magnetostriction strain in the direction perpendicular to the direction of the  
126 magnetization.

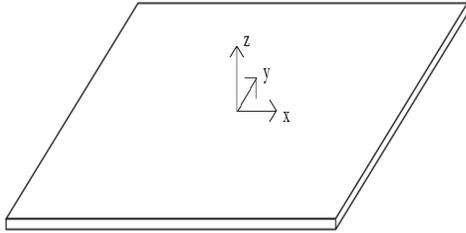
127 Although both quantities are dependent on the magnetization and applied external stresses, we  
128 will focus here on the influence of the magnetization only. The macroscopic behaviour of  
129 magnetostriction will be described here, for the microscopic causes we refer to [5,6].

130 The magnetostriction strain differs from material to material. For electrical steels, generally  
131 spoken, a magnetized sheet will elongate in the direction parallel to the direction of the  
132 magnetization and will shrink in the direction perpendicular to the direction of the magnetization.  
133 When applying a quasi-static sinusoidal magnetization to a sheet of electrical steel, the  
134 magnetostrictive behaviour of the sheet can be as shown in Figure 3. An important fact is that the  
135 magnetostriction is independent on the sign of the magnetization.

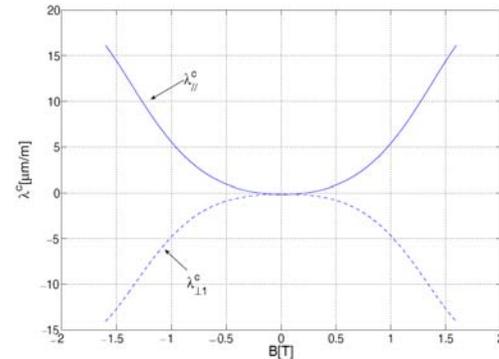
136 A lot of factors have an influence on the magnetostrictive behaviour of a material:

- 137 • The constitution of the magnetic material has a very important influence on the  
138 magnetostriction.
- 139 • External stresses applied on the material will change the magnetostrictive behaviour. In the  
140 case of electrical steels, an applied elongating strain will lead to lower magnetostrictive  
141 strains.
- 142 • The frequency of the magnetizing field is an important factor. When using non-quasi-static  
143 frequencies the magnetostriction will show hysteretic behaviour, as shown in Figure 4. With  
144 higher frequencies, the hysteresis will grow. The obtained curves in Figure 4 are often  
145 referred to as "magnetostriction loops" or "butterfly loops".
- 146 • Harmonics in the magnetizing waveform will lead to minor loops in the magnetostriction  
147 loops (see Figure 5). It is clear that these extra harmonics in the magnetostriction waveform  
148 will lead to extra harmonics in the vibrations and thus also in the noise radiation. In Figure 5  
149 we see that the magnetostriction becomes negative at certain places of the magnetostriction  
150 loop. This is due to the inertia of the sample sheet since the base frequency here is quite high  
151 compare to the other cases.

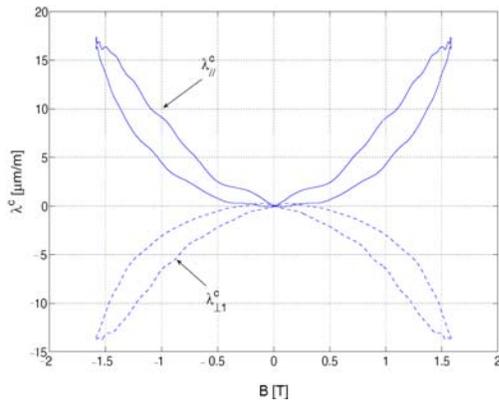
152 It must be mentioned that this list is not complete, although the main issues are captured. Due to  
 153 the complex nature of magnetostriction, an analytical calculation method is not available.  
 154 Therefore, magnetostriction measurements have to be made for each material that is considered  
 155 for the calculations of vibrations.



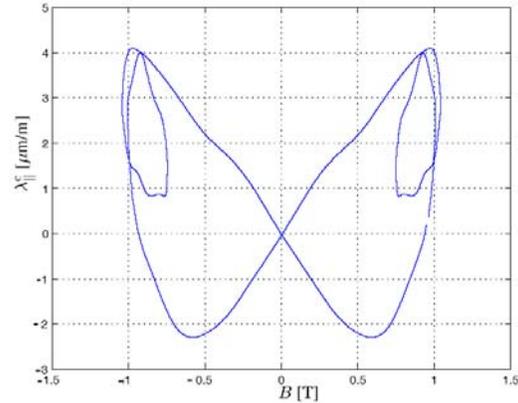
156  
 157 **Figure 2:** Steel sheet with coordinate system  
 158  
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**Figure 3:** Magnetostrictive behaviour of electrical steel under a quasi-static magnetization.



160  
 161 **Figure 4:** Magnetic behaviour of electrical steel  
 162 under non-quasi-static sinusoidal magnetization.  
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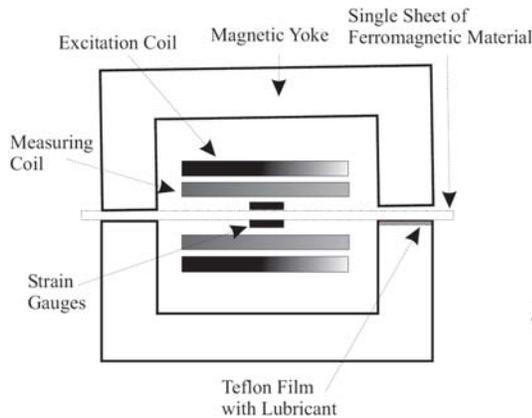
**Figure 5:** Minor loops in the magnetostriction loops due to harmonics for  $\lambda_{||}^c$

### 165 3. Magnetostriction measurements by using strain gauges

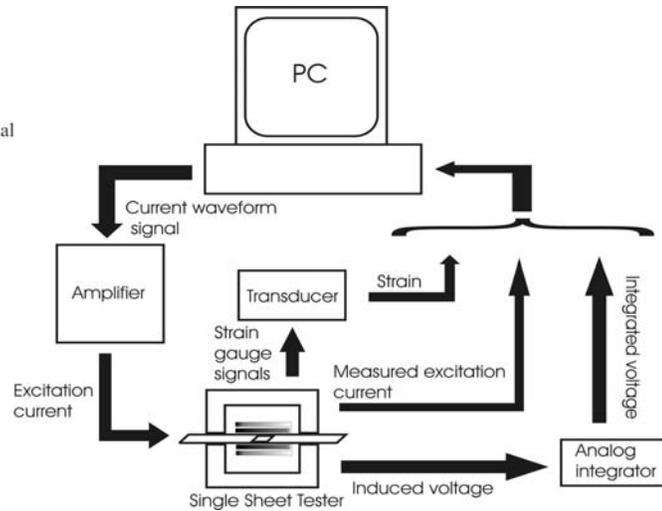
166 In the past a magnetostriction measurement set-up, based upon the technique of strain gauges,  
 167 was built at the EELAB. Before introducing the proposed new method, we will describe this  
 168 previous set-up, in order to indicate the drawbacks of this older system and to motivate the  
 169 necessity of a new set-up type.  
 170

#### 171 a) The magnetostriction measurement set-up

172 This older test set-up consists of a small single sheet tester (SST), shown in Figure 6. An SST  
 173 consists of a sample sheet which is placed between two yokes with a high magnetic permeability  
 174 that provide a return path for the magnetic flux. A magnetizing coil magnetizes the sample sheet,  
 175 while another coil is used to measure the magnetic induction. The SST and the strain transducer  
 176 are part of a PC-based measuring system shown in Figure 7.  
 177



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180 **Figure 6:** *The single sheet tester (SST)*



181  
182 **Figure 7:** *Magnetostriction measurement set-up using strain gauges*

182 Here, strain gauges are applied on the rectangular sample sheet. The strain gauges have multiple  
183 measuring grids, enabling strain measurements in directions both parallel and perpendicular to  
184 the direction of the magnetization. Besides the strain in two directions, also the magnetic  
185 induction and the excitation current are measured. The excitation coil is supplied with a  
186 programmable excitation current.

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188 *b) Some measurement results*

189 Figure 8 shows the magnetostriction measurements for electrical steel, both in parallel and  
190 perpendicular direction, for a sinusoidal induction with amplitude of 1.4T and different  
191 frequencies.

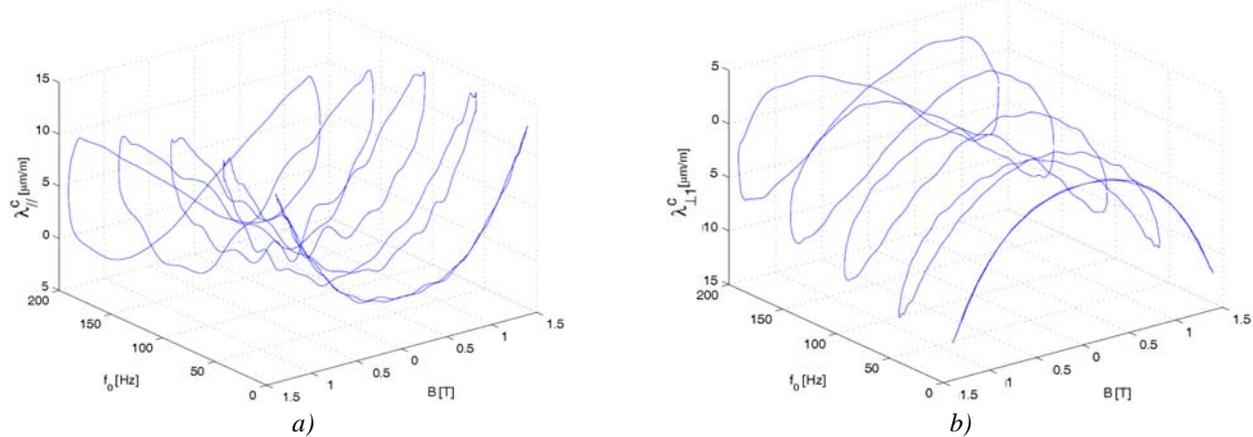
192  
193 *c) Advantages and drawbacks of the method*

194 The strain gauge set-up explained above, shows a rather good performance. We can measure the  
195 magnetostriction behaviour of electrical steels for various magnetizing waveforms. The  
196 measurements can be performed for different frequencies and amplitudes.

197 Applying strain gauges on a sample sheet however, is a delicate task and should be done by an  
198 experienced person. The accuracy of the application procedure of strain gauges can have an  
199 influence on the measurement results. This application procedure also demands that the coating  
200 of the sample sheet should be removed. Since the coating of the steel sheet can have an influence  
201 on the magnetostriction, this procedure may influence the correctness of the magnetostriction  
202 measurements.

203 In addition, the measurement results show a limited accuracy when low amplitudes for  
204 magnetization are applied (e.g. less than 0.8 T).

205 To avoid these drawbacks in magnetostriction measurements with strain gauges, we propose a  
206 new magnetostriction measurement set-up. This new set-up and the general working principle  
207 will be explained in the next part.



**Figure 8:** Measurements of magnetostriction strain in electrical steel for a sinusoidal induction with  $B_{\max} = 1.4 T$  and different frequencies a)  $\lambda_{||}^c$ , b)  $\lambda_{\perp}^c$ .

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#### 214 4. Proposed new measurement system

215 In this section the new set-up is explained and some preliminary results are shown. The  
216 experimental challenges at this stage of the research will be pointed out. At the end of this section  
217 some conclusions will be drawn concerning the future work to improve the measurement set-up.  
218

##### 219 a) Motivation for a new measurement system

220 The drawbacks of the strain gauge set-up like coating removal of the sample and the limited  
221 accuracy with low amplitudes motivated us to try a new measurement method. This new  
222 measurement set-up should allow us to measure the magnetostriction of steel sheets without  
223 removing the coating. Also, a higher accuracy of the measurements is desired. We hope to find  
224 these properties by building a measurement set-up based on dual laser interferometers.  
225

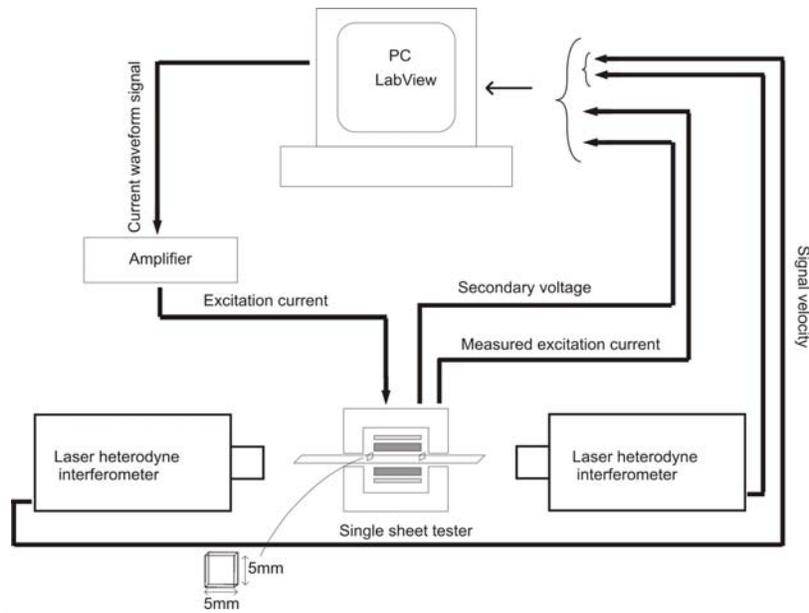
##### 226 b) The proposed magnetostriction measurement set-up

227 The new set-up uses two heterodyne laser interferometers to measure the magnetostriction strain  
228 of the sample under magnetization. The sample is placed in an SST. As mentioned in 3.a), the  
229 SST includes the sample sheet placed between two yokes, the magnetizing winding and the  
230 induction winding. The set-up is steered with a PC based system, as shown in Figure 9.

231 In the magnetostriction measurement set-up, the two lasers are placed in front of each other with  
232 the single sheet tester in the middle. To measure the strain, (elongation or shrinkage) of the  
233 sample under magnetization, the SST is placed in longitudinal or transversal direction to the  
234 lasers. Two mirrors are installed on the steel sheet in each direction in parallel to each other and  
235 with a certain distance between them. The mirrors are squares of  $5 \times 5$  mm cut from aluminium  
236 plates with a thickness of 1.6 mm. They are glued on the steel sheet, as shown in Figure 9.

237 In the laser method we can simply apply mirrors on the sample and measure the magnetostrictive  
238 behaviour. So, in contrast with the strain gauges, no special skills are needed to install the mirrors  
239 on the sample.

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**Figure 9:** Magnetostriction measurement set-up using dual laser heterodyne interferometers

244 In the SST, the magnetizing coils are in two pieces not to hinder the laser beam on the mirrors.  
 245 The lasers send a beam to the mirrors and the reflection is scattered back to the lasers. The  
 246 velocity signals measured by lasers are sent to a data acquisition card which is connected to a PC  
 247 and there, the two signals are added digitally together. An integration is done over the added  
 248 velocity signals to have the total displacement of the part of the sample sheet between mirrors.  
 249 Since magnetostriction is the relative length change in the material, we divide the calculated  
 250 displacement by the distance between the two mirrors in non-magnetized case, thus obtaining the  
 251 magnetostriction strain:

$$252 \quad \lambda = \frac{\Delta L}{L} \quad (4.1)$$

253

### 254 c) Experimental challenges

255 When magnetizing the sample in the new magnetostriction measurement set-up, there will be  
 256 some movement in the x-y plane and also in the perpendicular direction to the x-y plane (due to  
 257 vibration of the plate), as shown in Figure 2.

258 The vibrations and displacements of the sample in the single sheet tester (and thus vibrations of  
 259 the installed mirrors) lead to low repeatability of the measurement results. Measurements with  
 260 high amplitude and high frequency make more vibrations, so reinstallation of the sample sheet  
 261 and adjustment is necessary for every few measurements.

262 The biggest challenge is to find a system to keep the sample in place. It is necessary however, to  
 263 let the sample sheet move freely when magnetized. The sample should be able to shrink or  
 264 enlarge freely when magnetized and extra pressure to keep it in position would affect the  
 265 magnetostrictive behaviour of the sample. Finding a compromise between these two opposing  
 266 criteria is a big challenge.

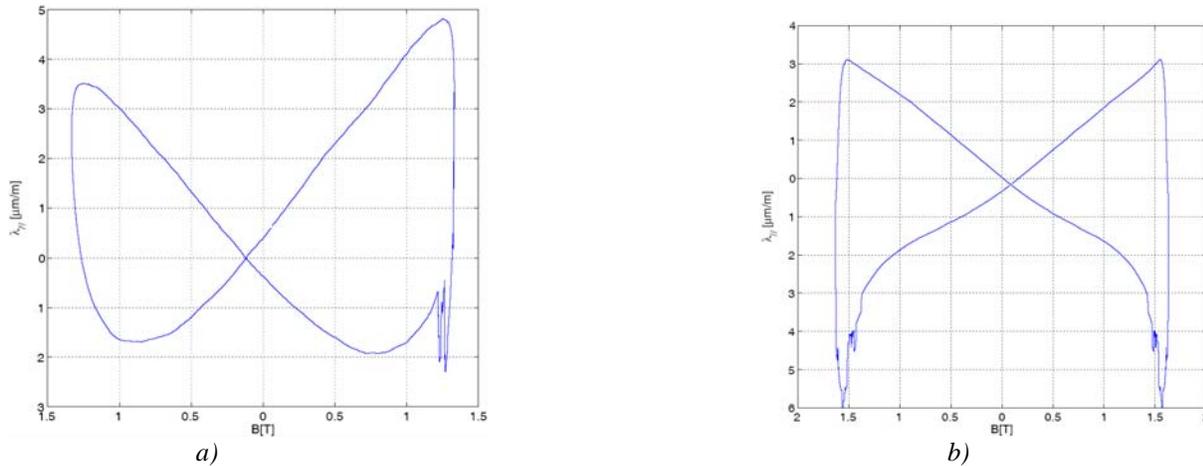
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268 *d) Some preliminary measurement results*

269 Some measurements are done in the direction parallel to the magnetization, and results are shown  
 270 below. To measure in the perpendicular direction, as mentioned before, the SST should be turned  
 271 90 degree in respect to lasers and the two other mirrors will be used.

272 At this stage we are investigating the performance of the new set-up and we will limit ourselves  
 273 to the parallel direction. In a later stage, both parallel and perpendicular measurements will be  
 274 made for different frequencies and various magnetizing waveforms.

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**Figure 10:** Magnetostriction measurement of electrical steel in  $\lambda_{||}^c$  a)  $B=1.3T$ , b)  $B=1.6T$ .

281 **5. Conclusions**

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283 A new magnetostriction measurement set-up using dual laser heterodyne interferometers is made.  
 284 The preliminary measurements already show some promising results. Still a lot of improvement  
 285 should be done to increase the repeatability of the measurements.

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