Measurement of magnetostriction using dual laser heterodyne interferometers: experimental challenges and preliminary results

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Abstract

Vibrations and noise of electrical machines and transformers may be caused by Lorentz forces and/or by magnetostriction. Here we only focus on the vibrations and noise due to magnetostriction. Electrical machines and transformers have magnetic cores of ferromagnetic material. Magnetostriction can be seen as a reaction of the ferromagnetic material to the presence of a magnetic field in the material and it leads to unwanted noise. 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 properties have to be obtained experimentally, usually by means of magnetostriction strain measurements. In the past a measurement set-up using strain gauges was developed at the Electrical Energy Laboratory (EELAB). In this paper a new magnetostriction measurement set-up using a dual laser heterodyne interferometer is proposed which avoids the drawbacks of the strain gauge set-up. The preliminary measurements already show some promising results. The experimental challenges and future work are explained at the end.

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Introduction

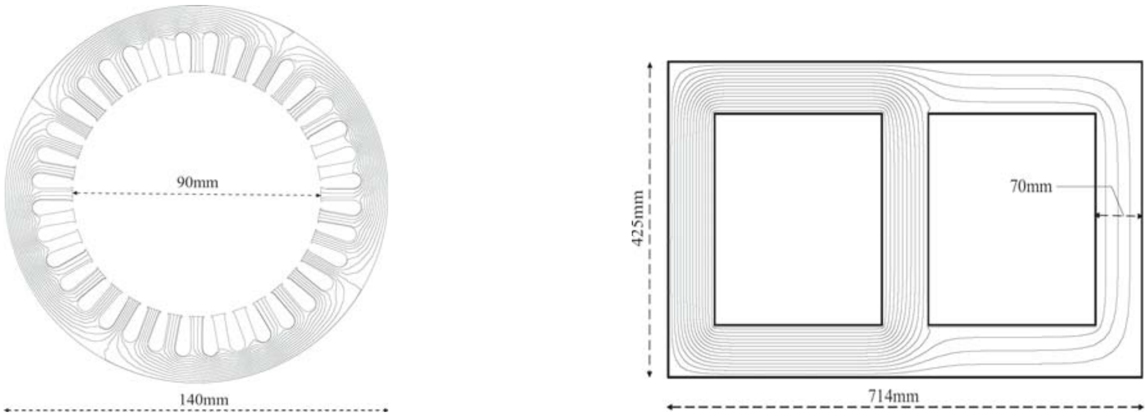
In our modern, industrialized world, people are experiencing more and more the negative effect of man made noise. One of the sources is the noise of electrical machines and transformers, which are often used in industrial applications. Technically spoken, the noise of electrical machines and transformers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

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

1. Magnetic noise in electrical machines and transformers

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

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



a) b)

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:

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

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:

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

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

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

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

Basically, we are interested in two quantities:

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

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

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

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

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

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

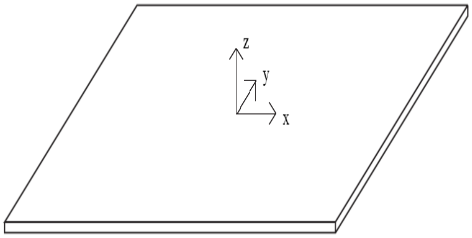


Figure 2: *Steel sheet with coordinate system*

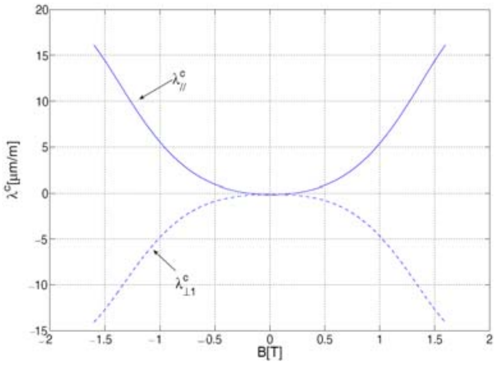


Figure 3: *Magnetostrictive behaviour of electrical steel under a quasi-static magnetization.*

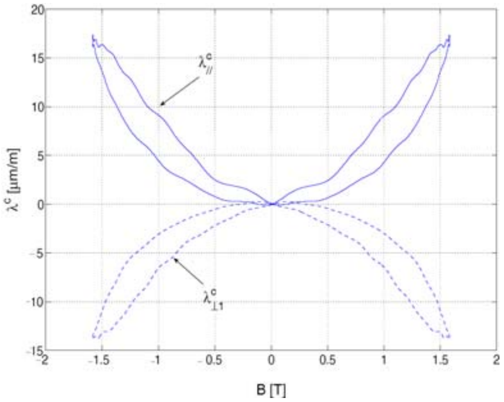


Figure 4: *Magnetic behaviour of electrical steel under non-quasi-static sinusoidal magnetization.*

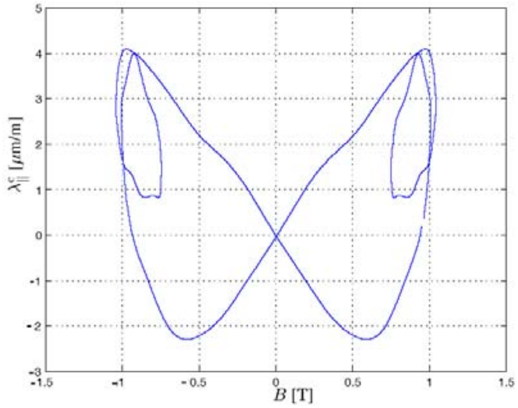


Figure 5: *Minor loops in the magnetostriction loops due to harmonics for* $\lambda^c_{//}$

3. Magnetostriction measurements by using strain gauges

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

a) The magnetostriction measurement set-up

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

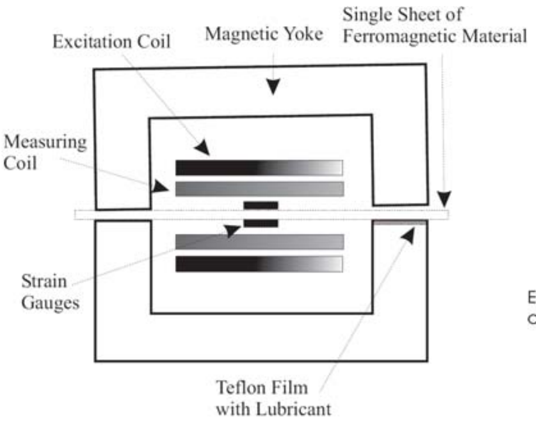


Figure 6: *The single sheet tester (SST)*

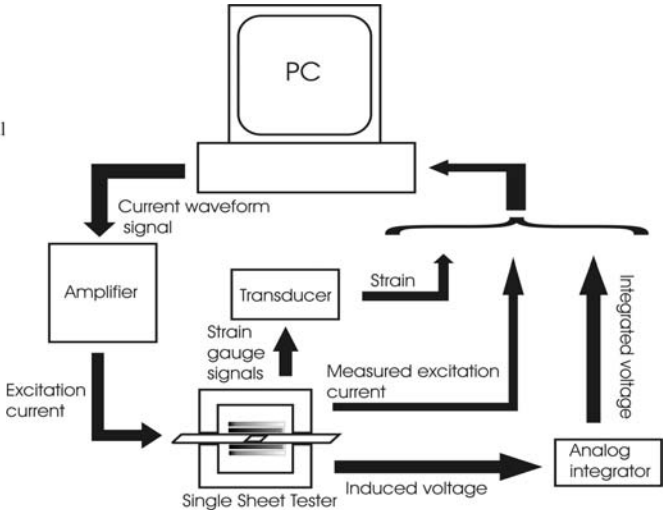


Figure 7: *Magnetostriction measurement set-up using strain gauges*

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

b) Some measurement results

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

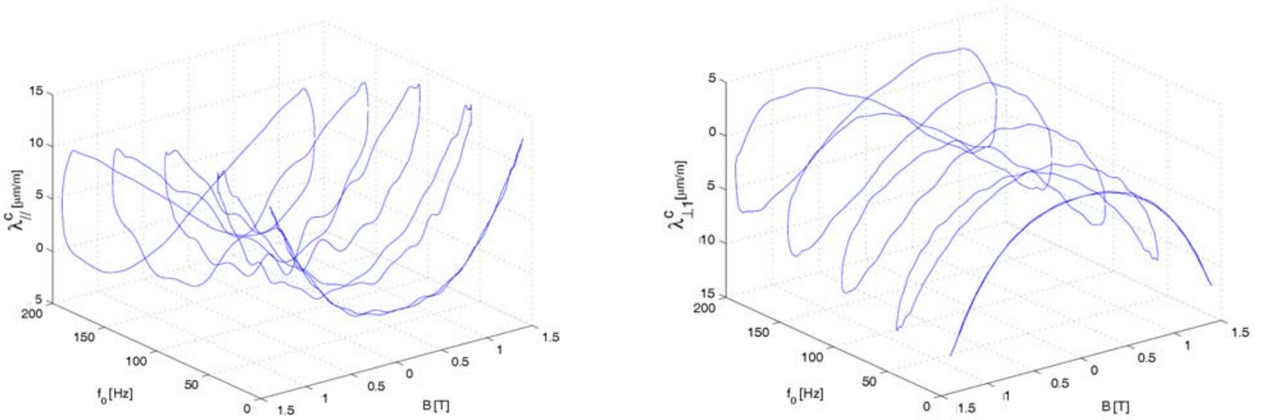
c) Advantages and drawbacks of the method

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

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

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

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



a) b)

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)* $\lambda^c_{\perp}$ *.*

4. Proposed new measurement system

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

a) Motivation for a new measurement system

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

b) The proposed magnetostriction measurement set-up

The new set-up uses two heterodyne laser interferometers to measure the magnetostriction strain of the sample under magnetization. The sample is placed in an SST. As mentioned in 3.a), the SST includes the sample sheet placed between two yokes, the magnetizing winding and the induction winding. The set-up is steered with a PC based system, as shown in Figure 9.
In the magnetostriction measurement set-up, the two lasers are placed in front of each other with the single sheet tester in the middle. To measure the strain, (elongation or shrinkage) of the sample under magnetization, the SST is placed in longitudinal or transversal direction to the lasers. Two mirrors are installed on the steel sheet in each direction in parallel to each other and with a certain distance between them. The mirrors are squares of 5×5 mm cut from aluminium plates with a thickness of 1.6 mm. They are glued on the steel sheet, as shown in Figure 9.
In the laser method we can simply apply mirrors on the sample and measure the magnetostrictive behaviour. So, in contrast with the strain gauges, no special skills are needed to install the mirrors on the sample.

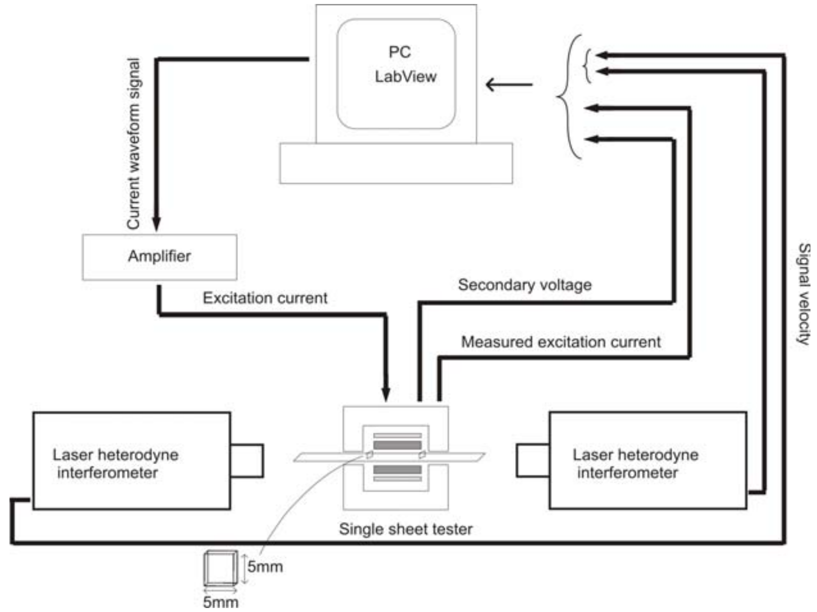


Figure 9: *Magnetostriction measurement set-up using dual laser heterodyne interferometers*

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

$$\lambda = \frac{\Delta L}{L} \tag{4.1}$$

c) Experimental challenges

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

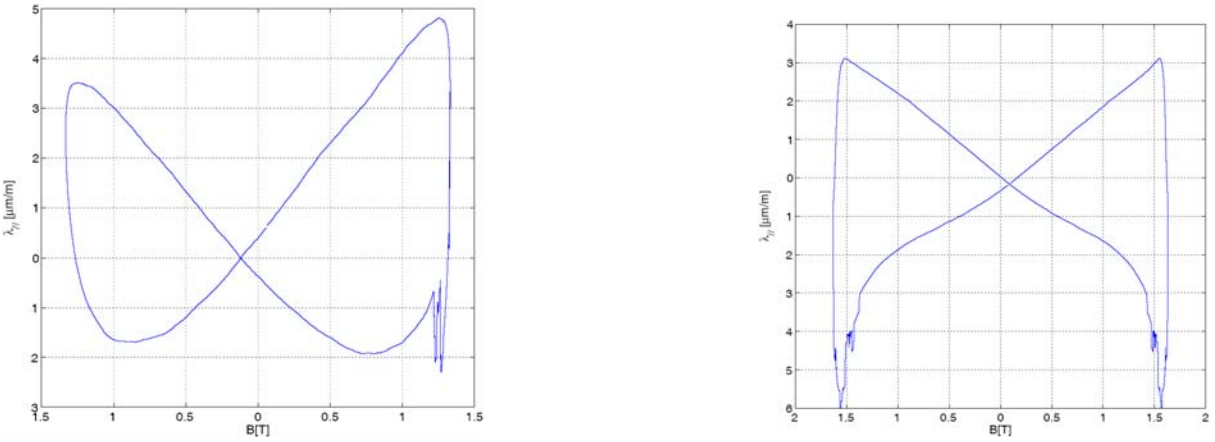
The vibrations and displacements of the sample in the single sheet tester (and thus vibrations of the installed mirrors) lead to low repeatability of the measurement results. Measurements with high amplitude and high frequency make more vibrations, so reinstallation of the sample sheet and adjustment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

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

d) Some preliminary measurement results

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

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



a) *b)*

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

5. Conclusions

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

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