Magnetostriction strain measurement: heterodyne laser interferometry versus strain gauge technique

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Abstract

Deformation of the ferromagnetic material, known as magnetostriction, causes vibrations and noise of electrical machines and transformer cores. A setup by using heterodyne laser interferometers has been built to measure the magnetostriction strains as a function of the applied magnetic field. The measurement results on a sample of nonoriented electrical steel are presented in this work. These results are compared with those obtained by using a strain gauge setup. The laser measurements are less disturbed by noise, especially for measurements under low amplitude magnetisation. In addition, contrary to the strain gauge samples, the sample preparation for the laser setup does not require removal of the protective coating. Measurement results on the coated samples are highly helpful for the calculation of the magnetostriction noise of the device. The coated samples show smaller deformation, since the coating applies tensile stress to the material. For the case of the same nonoriented material the reduction of the magnetostriction strains in amplitude is about 20%.

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Introduction

Environmental concerns on noise reduction have gained more attention during the last years. Looking at the electrical aspects, electrical machines and transformers are one of the sources of noise. Studies have been done on different causes of the noise generation of the aforementioned devices [1,2]. Both mechanical structure and the cooling system generate noise. However, inside these devices there are cores, so called the magnetic cores, which are built out of ferromagnetic materials (mostly electrical steel). For electrical and material engineers, the noise generated due to the magnetic properties of the material of the magnetic cores is of high interest. More about the magnetic noise is reported previously e.g. in [3].

When a magnetic field is applied to the magnetic core, the ferromagnetic material of the core deforms, which is known as magnetostriction. The magnetostriction strains of ferromagnetic materials are of the order of micrometer per meter. Such small deformations require an accurate measurement setup to detect them. In the past several strain measurement techniques have been used such as the strain gauge technique, which is one of the most common approaches. Therefore in the past, a strain gauge setup was developed in our lab, where two strain gauges (1cm × 1cm) were attached to the sample [4]. The magnetostrictive behaviour of electrical steel samples with different grain textures were measured under an applied magnetic field. For the proper attachment of the strain gauges, a partial coating removal of the samples was necessary. However, the knowledge of the magnetostrictive behaviour of the coated material, as they are used in the electrical machines and transformers, is helpful for further studies on the magnetic noise. To this end, a new setup with a non-contact approach by using lasers was developed. Dual heterodyne laser interferometers (Polytec IVS200), calibrated for 5 mm/s/V, measure the vibrational velocity of the electrical steel sample. Early design of this setup and the improvements are reported elsewhere [3, 5, 6]. One of the advantages of the laser setup, contrary to the strain gauge setup, is the smaller signal noise. With the strain gauge measurements a filter to remove high harmonics is necessary, although even then, the noise is rather large. In general, the magnetostrictive strain measurements by using the laser setup provide higher accuracy results without any need for a coating removal. The latter is significantly essential for studying the magnetostrictive noise of transformers and electrical machines, where the laminations are coated.

In the next section the magnetostriction will be presented in more detail. The design of the laser setup and the measurement results on the samples of electrical steel by using the strain gauge setup and the laser setup will be presented next.

Magnetostriction

Magnetisation of the magnetic materials generates a three-dimensional deformation, known as magnetostriction. For ferromagnetic materials, the deformation is in the order of micrometer per meter. Magnetostrictive deformation depends not only on the applied magnetic field, but also on the material structure and any external stress to the material. The study of the microstructure and the domain theory of the materials explains how such deformation happens [7, 8]. The domain theory further states the sudden discontinuous movement of the domains, which as a result makes it rather impossible to numerically calculate the magnetostrictive strains under a random applied magnetic field. Thus, to study the magnetostrictive behaviour, measurement approaches are required. In this work, the magnetostriction strains of different materials only as a function of the applied magnetic field are measured. To this end, any external pressures to the sample are avoided since they can influence the behaviour. The setup measures two-dimensional stains in parallel and perpendicular direction to the applied magnetic field (shown as X and Y direction in

Figure 1). The magnetostriction strains of a sample and the coordinate system are shown in Figure 1. In the presence of a magnetic field, which induces a magnetic induction B in the material, the sample elongates parallel to the applied magnetic field and shrinks in the perpendicular direction to the field.

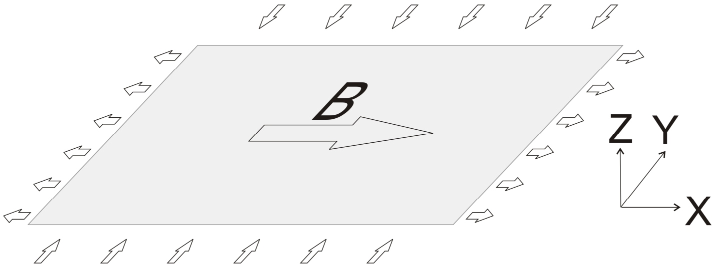

Figure 1: *A two-dimensional demonstration of magnetostriction and the coordinate system*

Heterodyne laser interferometer setup

In the laser setup two heterodyne laser interferometers (Polytec IVS 200), each calibrated for 5 mm/s/V are used. The magnetic measurements are performed by using a Single Sheet Tester (SST), as shown in Figure 2. In the SST, the magnetisation and the measurement coil are wound around the sample. The sample is then placed between two yokes with high magnetic permeability in order to close the magnetic flux path. The lasers measure the vibrational velocity of two small mirrors, which are glued on the sample. In the early design the mirrors were placed on one side of the sample, shown in Figure 3.a) [3]. However, due to the out of plane vibrations which caused the titling of the sample, the measurement results were somehow unrepeatable. Thus, later the mirrors were attached on the two sides of the sample and their average velocity is used to calculate the deformation of the sample, as shown in Figure 3.b).

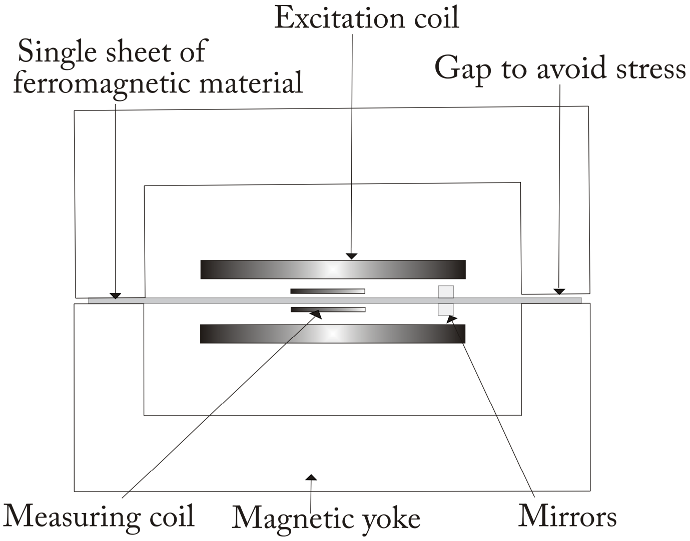

Figure 2: *The Single Sheet Tester (SST)*

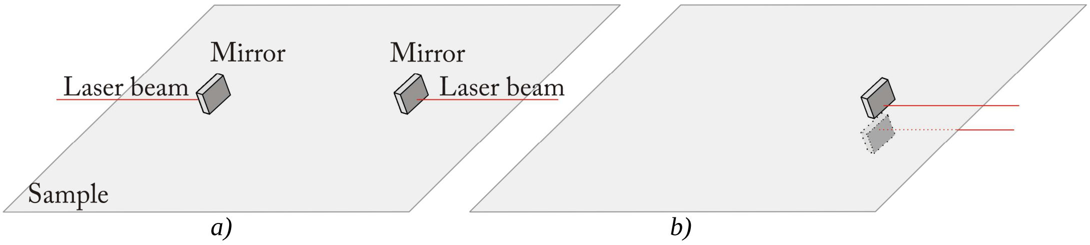

Figure 3: *Laser beams pointing at the mirror a) early design, b) optimal design*

This setup is controlled by a LabView program installed on a PC. The measurement length is the distance between the mirrors to the side of the sample that is clamped between the yokes. In this setup, the sample size is 17cm × 8cm and the measurement length is almost 12cm (in X direction shown in Figure 1). In the LabView program, a user can select the magnetisation signal type, amplitude and frequency. This signal is then amplified and sent to the magnetisation coil. The vibrational velocities measured by the lasers, along with the magnetic properties of the samples such as the magnetic induction B [T] and the magnetic field H [A/m] are measured and sent to the PC. There, the measured length of the magnetised sample and thus the relative length change compared with the non-magnetised length is calculated, i.e. the magnetostriction strain. The optical components of the setup are shown in Figure 4, where only the top yoke is shown. Specular reflective mirrors have the advantage of reflecting practically all the incident light to the laser provided they are perfectly aligned, but when the mirror is not perfectly at right angles to the laser beam only very little light returns to the vibrometer. We therefore do not use actual mirrors, but small metal plates covered with retro-reflective tape: reflectivity is a bit less, but alignment is much less critical than in case of a true mirror.

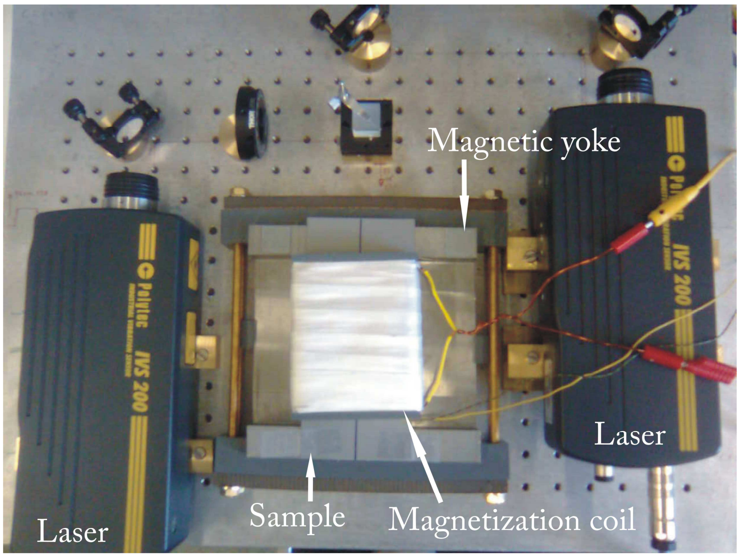

Figure 4: *Optical components and the SST of the hyeterodyne laser interferometer setup*

Measurement results by using the strain gauge setup and the laser setup

Samples of grain-oriented and nonoriented electrical steel are measured by using the two setups. Since the coating of the samples for the measurements by using the strain gauge setup are removed, for a comparison between the results, the coating of the samples for the laser setup are also removed. Magnetostriction strains versus the magnetic induction, namely “butterfly curves”, for a nonoriented sample type under magnetisation with peak magnetic induction of 0.6T and 1T are presented in Figure 5 and Figure 6, respectively. The solid line shows the laser measurement and the dash line shows the strain gauge measurement. The measurement results presented are performed under a sinusoidal excitation with a frequency of 50Hz. The magnetostriction strain measurements are analyzed in the frequency domain. By using a Fast Fourier Transform (FFT), the frequency spectrum of the measured strain signal is calculated. For the 50Hz excitation, the dominant response frequency is 100Hz, which is twice the magnetisation frequency. From the frequency spectrum the odd harmonics are removed and then the time pattern of the even harmonics is reconstructed by an inverse FFT program [4]. The magnetostriction strains measured by the strain gauge method are filtered for harmonics higher than 40 times the base frequency in the frequency spectrum before reconstructing the time pattern. Looking at these butterfly curves, still some noise can be observed. The noise influence is relatively larger for the measurements under magnetisation with peak amplitude smaller than 0.8T and thus these results are less accurate. The laser setup provides accurate magnetostriction strain measurement results under a magnetisation with peak amplitudes as low as 0.5T and shows a high repeatability. In Figure 5, the magnetostriction strains measured by using the strain gauge setup for a magnetic induction of 0.6T are highly influenced by noise even after filtering. Such filtering is not applied for the laser measurement and is not needed. One of the advantages of this setup over the strain gauge setup is the significant reduction of noise on the measured data.

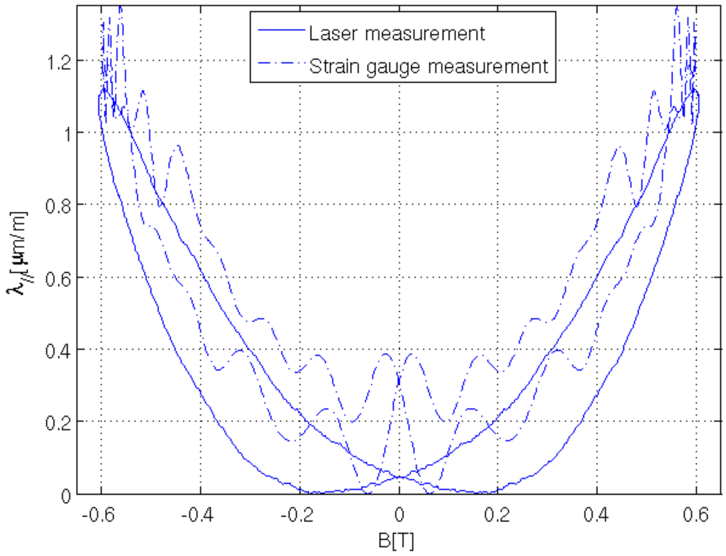

Figure 5: *Magnetostriction strains in parallel direction to the magnetic field of a non-coated sample of nonoriented steel by using the strain gauge setup and the heterodyne laser vibrometer setup* $B_{peak}=0.6T$ *and* $f=50Hz$

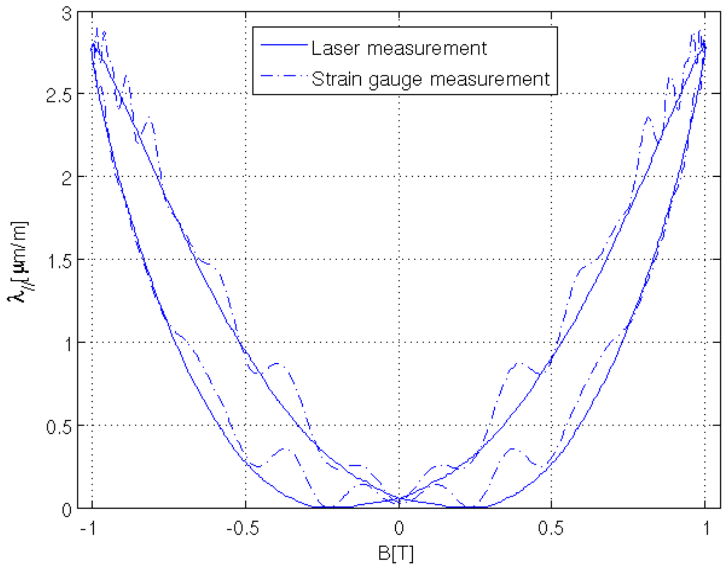

Figure 6: *Magnetostriction strains in parallel direction to the magnetic field of a non-coated sample of nonoriented steel by using the strain gauge setup and the heterodyne laser vibrometer setup* $B_{peak}=1T$ *and* $f=50Hz$

The measurement results on the coated samples show less deformation. The coating is used to isolate the laminations and reduce losses. However, the coating applies tension to the material, which as a result decreases the deformation. Figure 7 shows the measurement results of a coated and non-coated sample of the same nonoriented material, both measured by using the laser setup. The coated sample shows around 20% less deformation, which proves that the coating tensile stress is beneficial in the reduction of the deformation [9, 10].

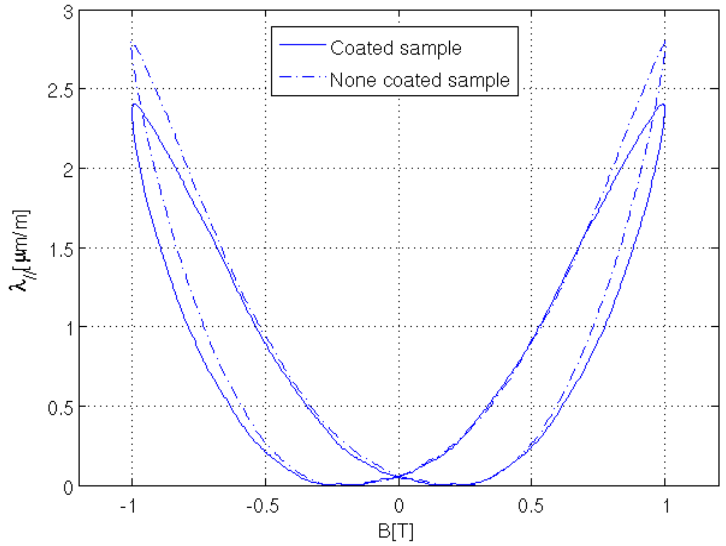

Figure 7: *Magnetostriction strains in parallel direction to the magnetic field of a coated and non-coated sample of nonoriented steel by using the heterodyne laser vibrometer setup* $B_{peak}=1T$ *and* $f=50Hz$

Conclusion

A magnetostriction strain measurement setup by using a heterodyne laser interferometer technique has been built. In this work, the measurement results of a nonoriented electrical steel type are presented. We can conclude that the results by using the laser setup, compared to the previously used strain gauge setup, show several advantages. In general, the laser setup is more accurate especially for the measurements under magnetisations with low amplitude, e.g. 0.5T. The sample preparation for the strain gauge setup requires a partial coating removal. However, for the laser setup the coating removal is not needed. The easier sample preparation and the possibility of measuring coated samples are other advantages of this laser setup. The measurements on the coated samples as they are used in electrical devices are especially interesting for us. Such results are highly beneficial for the calculation of magnetostriction noise generation of electrical machines and transformers.

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