Requirements for 3-D magnetostriction measurement instruments

Requirements for 3D Magnetostriction Measurement Instruments

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***Abstract*—This paper concerns the requirement analysis and implementation of a measurement instrument which can identify the 3D magnetostriction strain. To measure magnetostriction, a high-accuracy magnetic flux density and strain measurement are required, while the mechanical stress in the sample is minimized. The Full Block Tester (FBT) is proposed as a measurement instrument. In this instrument, homogeneity of flux density within the measured sample and the strain measurement resolution are sufficient, but stress caused by magnetic forces is higher than required.**

***Index Terms*—magnetostriction, parameter extraction**

I. INTRODUCTION

Magnetostriction is a parasitic phenomenon of interest to the high-precision industry, where ferromagnetic materials are used in constructions. Deformation resulting from magnetostriction reduces the position accuracy. The deformation is caused on a microscopic scale by magnetic field induced strain of single magnetic domains [1], redistribution of domains with unequal strains, and rotation of magnetization within domains [2]. Compensation of the deformation requires a three-dimensional description of magnetostriction.

Both magnetic forces and magnetostriction cause strains in ferromagnetic materials. In 2D magnetostriction measurement instruments for strips, the strains resulting from magnetic forces act in the direction perpendicular to the magnetostriction measurement directions [3]. No measurement method for 3D magnetostriction of blocks is given in literature [4] [5]. For 3D magnetostriction measurement instruments, a different method is required to differentiate between the strains caused by magnetic forces and magnetostriction.

The measurement of magnetostriction is challenging since only the combination of strain caused by magnetic forces and magnetostriction can be measured, and the strain caused by magnetic forces can be of the same order of magnitude as the magnetostriction strain. Additionally, the mechanical stress caused by the magnetic forces affects the magnetostriction.

In this paper, the measurement of 3D magnetostriction on a cuboidal sample of Invar using the Full Block Tester (FBT) is discussed. General requirements for measurement instruments which can measure the 3D magnetostriction are analyzed. Firstly, the mechanical design of a measurement instrument which allows to separately identify the strain tensor elements is given. Secondly, the magnetic design, which is required to obtain a homogeneous magnetic flux density and low magnetic forces, is shown. Finally, indications on how to improve the performance of the FBT, and design suggestions for 3D magnetostriction measurement instruments are given.

II. DESCRIPTION OF MAGNETOSTRICTION

Magnetostriction is a local strain induced in ferromagnetic materials as function of the local magnetic flux density $\mathbf{B}$. This strain is also dependent on the local mechanical stress $\boldsymbol{\sigma}$. Magnetostriction strain can be described as a strain tensor by

$$\boldsymbol{\varepsilon}^{\mathrm{ms}}(\mathbf{B},\boldsymbol{\sigma}) = \begin{bmatrix} \varepsilon^{\mathrm{ms}}_{\mathrm{xx}}(\mathbf{B},\boldsymbol{\sigma}) & \varepsilon^{\mathrm{ms}}_{\mathrm{xy}}(\mathbf{B},\boldsymbol{\sigma}) & \varepsilon^{\mathrm{ms}}_{\mathrm{xz}}(\mathbf{B},\boldsymbol{\sigma}) \\ \varepsilon^{\mathrm{ms}}_{\mathrm{xy}}(\mathbf{B},\boldsymbol{\sigma}) & \varepsilon^{\mathrm{ms}}_{\mathrm{yy}}(\mathbf{B},\boldsymbol{\sigma}) & \varepsilon^{\mathrm{ms}}_{\mathrm{yz}}(\mathbf{B},\boldsymbol{\sigma}) \\ \varepsilon^{\mathrm{ms}}_{\mathrm{xz}}(\mathbf{B},\boldsymbol{\sigma}) & \varepsilon^{\mathrm{ms}}_{\mathrm{yz}}(\mathbf{B},\boldsymbol{\sigma}) & \varepsilon^{\mathrm{ms}}_{\mathrm{zz}}(\mathbf{B},\boldsymbol{\sigma}) \end{bmatrix}, \quad (1)$$

which is a symmetric matrix. Each element of the strain tensor describes a normal (diagonal elements) or shear (off-diagonal elements) strain. The goal of this research is to identify the elements of the magnetostriction strain tensor for a static magnetic field. To limit the scope of the initial measurements, the magnetostriction strain values are determined in the absence of mechanical stress. The range of interest of the magnetic flux density is 50 mT to 1.0 T.

III. MEASUREMENT INSTRUMENT AND REQUIREMENTS

To measure the magnetostriction, the Full Block Tester (FBT), shown in Fig. 1, was designed and built. The principle

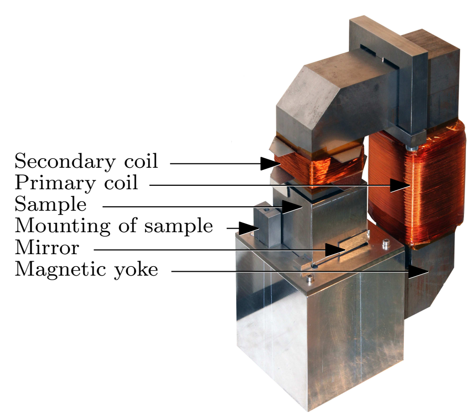

Fig. 1. Full Block Tester (FBT).

of the FBT is as follows. The primary coil is excited with a constant current I, in a sequence of $\{0, I, 0, -I\}$ with a duration per sequence of 8 s. The FBT generates a quasi-static homogeneous magnetic flux density in the ferromagnetic cuboidal sample. The homogeneity of the flux density is maximized by the dimensions of the magnetic yoke. The flux density within the sample is determined using the secondary sensing coil. The sample is mounted such that separate elements of the strain tensor can be derived with a minimum number of measurement points. A laser interferometer system measures the displacement of several points of the sample to which mirrors are attached. Strains are calculated from the measured displacements.

To compensate for the deformation in the photolithographic application with sufficient accuracy, an accuracy of 0.005 ppm is required for the elements of the magnetostriction strain tensor. No measurement data of the shape magnetostriction of Invar is available. Therefore, the required accuracy of flux density measurement and maximum coupling between measured strain elements is estimated at 10% of the measured value. The effect of mechanical stress on magnetostriction of Invar is unknown.

A. Mechanical design of the FBT

The mechanical design should provide measurement of all strain elements, while mechanical stress in the sample is minimized. Thin strip measurement instruments often apply strain gauges, which can only achieve a 0.1 ppm accuracy. Therefore, for the FBT, a laser interferometer system consisting of an Agilent 5517D HeNe laser source, Hewlett-Packard 10706A plane mirror interferometers, and Agilent E1708 remote dynamic receivers have been used. The length, height, and width of the cuboidal sample are 50 mm, such that a 0.25 nm accuracy of displacement measurement is required, while the resolution of the interferometer system is 0.15 nm. Changes in air pressure and temperature result in low frequency noise in the measured displacement. The displacement is averaged over 200 measurements to achieve the required accuracy.

Mechanical stress in the sample can result from applied forces on the sample, a net magnetic force on the sample, local magnetic forces, or magnetostriction itself. Externally applied forces on the sample are prevented by an air gap between the sample and the yoke. The sample is mounted such that strain in any direction is not restricted since restriction of magnetostriction strain leads to mechanical stresses.

The displacement of a point of a body is defined by the 12 independent parameters of translation, rotation and strain. The translation and rotation of the sample are minimized by restricting the rotation around all three axes and the displacement of a single point of the sample in all directions. Under these conditions, displacement is only dependent on strain, and the six parameters of the strain tensor can be measured by six independent displacement measurements. Mirrors are attached to the sample, and their displacement is measured by the interferometer system.

The rotation of the sample around axis $\mathbf{q}_\mathrm{r}$ is constrained by the restriction of displacement in direction $\mathbf{a}$ of two points of the sample, $\mathbf{r}_1$ and $\mathbf{r}_2$, with

$$\mathbf{q}_\mathrm{r} = (\mathbf{r}_1 - \mathbf{r}_2) \times \mathbf{a}. \tag{2}$$

Displacement of points $\mathbf{r}_\mathrm{a}$, $\mathbf{r}_\mathrm{b}$, and $\mathbf{r}_\mathrm{c}$ of the sample are restricted from moving in the directions indicated by the bold arrows in Fig. 2, in order to achieve restriction of rotation around all axes. Table I shows which combinations of restriction prevent rotation around which axis. The restrictions of displacement of the three points of the sample are implemented by connecting the sample to the table differently at each point,

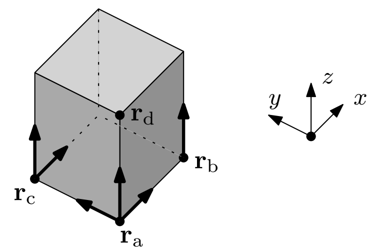

Fig. 2. Mounting of the sample in order to restrict rotation around all three axes. Bold arrows represent the directions in which the displacement of the points $\mathbf{r}_\mathrm{a}$, $\mathbf{r}_\mathrm{b}$, and $\mathbf{r}_\mathrm{c}$ are restricted. Point $\mathbf{r}_\mathrm{d}$ is not restricted.

TABLE I
RESTRICTIONS OF ROTATION.

Restricted rotation $\mathbf{q}_\mathrm{r}$	point $\mathbf{r}_1$	point $\mathbf{r}_2$	direction of restr. $\mathbf{a}$
$\mathbf{e}_x$	$\mathbf{r}_\mathrm{a}$	$\mathbf{r}_\mathrm{c}$	$\mathbf{e}_\mathrm{z}$
$\mathbf{e}_y$	$\mathbf{r}_\mathrm{a}$	$\mathbf{r}_\mathrm{b}$	$\mathbf{e}_\mathrm{z}$
$\mathbf{e}_z$	$\mathbf{r}_\mathrm{a}$	$\mathbf{r}_\mathrm{c}$	$\mathbf{e}_\mathrm{x}$

as illustrated in Fig. 3. The translation of point $\mathbf{r}_\mathrm{a}$ in the x-, y-, and z-directions is restricted by mounting the point rigidly to the stationary table. The translation of point $\mathbf{r}_\mathrm{b}$ in the z-direction is restricted by a sliding contact which allows displacement in the x- and y-directions. The translation of point $\mathbf{r}_\mathrm{c}$ in the x- and z-directions is restricted by attaching a flexure between the sample and the table which only allows displacement in the y-direction [6]. The bottom of the sample is not supported by the table, since there is a hole in the table slightly wider than the sample. With the described restrictions, only the expansion in the y-direction is restricted to some extent by the stiffness of the flexure.

If the strain in the sample is homogeneous, the rotation of the sample around all axis is restricted, and the point $\mathbf{r}_a$ has zero displacement and is located in the origin of the coordinate system, the displacement $\mathbf{u}$ of a point $\mathbf{r}$ in the sample is given by

$$\begin{bmatrix} \mathrm{u_x} \\ \mathrm{u_y} \\ \mathrm{u_z} \end{bmatrix} = \begin{bmatrix} \varepsilon_\mathrm{xx} & 0 & 2\varepsilon_\mathrm{xz} \\ 2\varepsilon_\mathrm{xy} & \varepsilon_\mathrm{yy} & 2\varepsilon_\mathrm{yz} \\ 0 & 0 & \varepsilon_\mathrm{zz} \end{bmatrix} \begin{bmatrix} \mathrm{r_x} \\ \mathrm{r_y} \\ \mathrm{r_z} \end{bmatrix}. \tag{3}$$

Hence, the strain matrix can then be derived from the displacement of points $\mathbf{r}_\mathrm{b}$, $\mathbf{r}_\mathrm{c}$, and $\mathbf{r}_\mathrm{d}$. The double value of the shear strain elements results from the applied restrictions. Displacement in the z-direction cannot be measured, since the yoke obstructs the measurement in this direction. The strain in the direction of the applied field can be derived from the measurement of other strain elements, if the volume magnetostriction is assumed negligible.

The displacements of three points are measured simultaneously by the interferometer system. The sample can be rotated in 90 degree steps around the z-axis to obtain all required displacement measurements without altering the interferometer system. By re-mounting the sample on the table, after rotating it by 90 degrees around the x- or y-axis, strain in the z-direction as function of flux density in the x- or y-direction can be measured.

The elements of the strain matrix can be determined sepa-

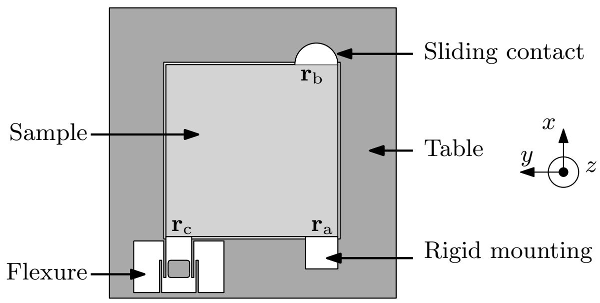

Fig. 3. Top view of the mounting of the sample. The sample is connected to the table at three points only.

rately if the displacements of the sample in the FBT satisfy (3). Three sets of mechanical FEM simulations of the deformation of the sample have been performed to determine the coupling between the measured elements of the strain tensor. In these simulations, all components of the strain tensor were set to zero, except one of the the normal strains, which was set to 10^{-6} in the volume of the sample. Figure 4 shows the result of the simulations in which $\varepsilon_{\mathrm{xx}}^{\mathrm{ms}} = 10^{-6}$ (top), $\varepsilon_{\mathrm{yy}}^{\mathrm{ms}} = 10^{-6}$ (middle), and $\varepsilon_{\mathrm{zz}}^{\mathrm{ms}} = 10^{-6}$ (bottom).

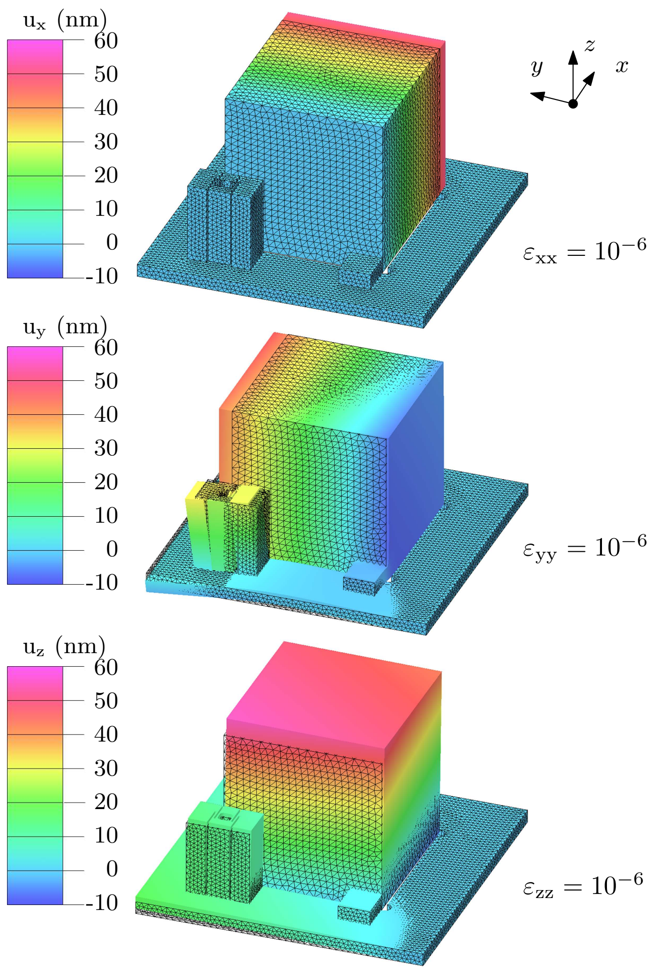

Fig. 4. Simulations showing deformation, meshed: original shape, solid: displacement magnified by a factor 10^5. The strain tensor is set to zero, except $\varepsilon_{\mathrm{xx}} = 10^{-6}$ (top), $\varepsilon_{\mathrm{yy}} = 10^{-6}$ (middle), and $\varepsilon_{\mathrm{zz}} = 10^{-6}$ (bottom).

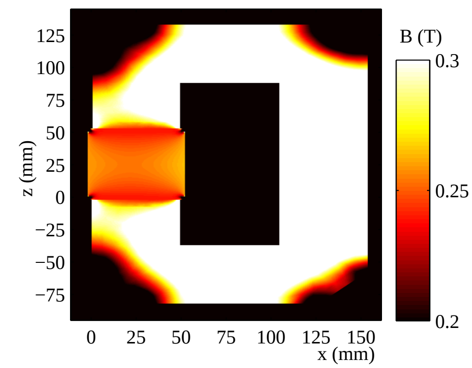

Fig. 5. Simulated magnetic flux density in the cross section through the center of the sample (center left) and C-shaped yoke, showing homogeneity of magnetic flux density in the sample.

With only strain in the x-direction, the simulated deformation is equal to the deformation in the idealized situation. This is mainly because no friction between sliding contact at $\mathbf{r}_\mathrm{b}$ and the table is assumed in the simulation. With only strain in the y-direction, the flexure restricts expansion, such that a 24% error occurs for the simulated displacement in the y-direction. In this case there is also a maximum coupling of 12% to the simulated shear in the xy-plane and a coupling of 13% to shear in the xz-plane. With only strain in the z-direction, the coupling to the simulated shear strains in the xz- and yz-planes are not within the requirement. Restriction of expansion of the sample at the facets that are connected to the mounting result in tilting of the sample. The simulations show that for four of the strain elements, the decoupling is not within the required 10%. Therefore, there will be a cross-coupling between the measured strain elements, and the error of the measured values of the strain elements cannot be guaranteed to be smaller than 10%.

B. Magnetic design of the FBT

The magnetic design of the measurement instrument should provide a homogeneous flux density in the sample while deformation of the sample resulting from magnetic forces is minimized. The yoke and sample are the only ferromagnetic parts of the FBT.

With a homogeneous magnetic flux density in the sample, the measured strain can be related directly to a value of flux density. A flux density with a standard deviation between 3.0% and 6.2% over the range of interest is achieved by placing a C-shaped magnetic yoke around the sample, with the sample placed symmetrically in the air gap. The dimensions of the yoke are optimized for maximum homogeneity using 3D FEM simulations, the dominant parameter being the area of the faces of the air gap. Figure 5 shows the flux density in the xz-plane through the center of the sample and yoke, where the homogeneity is lowest, for an average flux density of 0.26 T. In the FBT, the flux density in the sample is monitored during measurement by a secondary coil as a flux sensing coil. The sample can be demagnetized in-place after inserting ferromagnetic sheets in the air gap.

TABLE II
THE REQUIRED POSITIONING ACCURACY OF THE YOKE RELATIVE TO THE SAMPLE IN MM, AT A FLUX DENSITY OF 250 MT IN THE SAMPLE.

	$u_x(\mathbf{r}_b)$	$u_y(\mathbf{r}_b)$	$u_x(\mathbf{r}_c)$	$u_y(\mathbf{r}_c)$	$u_x(\mathbf{r}_d)$	$u_y(\mathbf{r}_d)$
$u_{x,yoke}$	0.085	0.019	0.014	0.0167	0.0005	0.011
$u_{y,yoke}$	0.18	0.021	0.038	0.064	0.011	0.012
$u_{z,yoke}$	0.0704	0.020	0.042	0.18	0.0012	0.089

Stress in the sample can result from the magnetic field in different ways. Firstly, if a total magnetic force on the sample exists, stresses occur on the mounting points of the sample, and elastic deformation results in displacement of points of the sample. This is a reluctance force, oriented such that the sample is displaced in the direction which reduces the total reluctance of the magnetic circuit. The displacement cannot be separated from magnetostriction, since both are a function of the amplitude of the magnetic flux density. The required positioning accuracy of the yoke relative to the sample, such that the displacement is smaller than the required measurement accuracy, was determined using FEA. The stiffness of the mounting of the sample was determined by mechanical FEA, and the magnetic force on the sample as function of relative displacement of the yoke from the position where the sample is exactly centered in the air gap was determined by magnetic FEA. The required positioning accuracy of the yoke relative to the sample, at a flux density of 250 mT in the sample, is given in Table II. From this table it is clear that the required positioning accuracy is in the order of several micrometers. The measured displacement of the point $\mathbf{r}_a$, which is required to be less than 10% of the measured magnetostriction, is in the order of 20-50nm at 250mT, which is 200-500% of the expected displacement resulting from magnetostriction.

Secondly, local magnetic forces appear where there are both, a high magnetizing field strength and a gradient of magnetic permeability present [7]. Therefore, magnetic forces occur on the top and bottom of the sample in the FBT. Stress caused by magnetic forces can be minimized by having the flux in a closed high-permeability path. The magnetic forces acting on the faces of the sample along the air gap cause mechanical stresses. These stresses affect the magnetostriction strain, as well as cause strain because of elastic deformation. The magnetic forces on the sample are decreased if the permeability of the air gap is increased, for example by filling it with a magnetorheological fluid. This requires a substance with a very low stiffness and a high permeability. Experiments showed that only a relative permeability of 2 could be reached, which is insufficient for decreasing the magnetic forces. Furthermore, the stiffness of the used magnetized fluid resulted in displacements of the yoke being transferred to displacements of the sample.

Thirdly, if the magnetostriction strain is inhomogeneous in the sample this can result in mechanical stresses, for example, this occurs if the center of the block expands more than the exterior. This effect has not been observed.

IV. Conclusions and discussion

In this paper the mechanical and magnetic design of a 3D magnetostriction measurement instrument were presented. The sample is mounted such that restriction of expansion and coupling between the measured elements of the strain matrix are minimized. A homogeneous magnetic flux density within the sample was required and obtained. Total and local magnetic forces disturb the measurement of magnetostriction. Improvements in the mechanical and magnetic design of the FBT are required to obtain a 3D magnetostriction measurement.

Displacement and rotation of the sample caused by magnetic forces are the main effects disturbing the magnetostriction measurement. Small forces on the sample cause large displacements of the sample because the mechanical path from sample to interferometer has a low stiffness. It is not feasible to position the sample with the required 0.5 μm accuracy to reduce the displacements caused by magnetic forces to levels much smaller than displacements caused by magnetostriction. Therefore, an alternative strain measurement method is required, which is not sensitive to rotation or translation of the total sample. This can be done either by adding measurement axes to determine translation and rotation, or by mechanically coupling the measurement device and sample such that they have no relative rotation and translation. The coupling between measured strain elements is higher than the required 10%. This could be solved by decreasing the contact area between mounting and sample, and improving the properties of the flexure.

Strain caused by magnetic forces should be either prevented by changes in the magnetic design, or by adding a facility to oppose the magnetic forces acting on the sample. An instrument in which the magnetic forces on the sample are sufficiently low can be designed if the magnetic force density can be evaluated. The stress caused by the magnetic forces cannot be evaluated for now. The magnetic force density can be determined by the virtual work method [8], for which an energy function of the material is required.

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