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Non-contact strain measurements based on inverse magnetostriction

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ABSTRACT

For the detection of mechanical quantities such as strain or torque in sensor applications, inverse magnetostrictive materials are widely used. Commonly, the measurement is strongly dependent on the distance between the sensing coil and the magnetic material and the measurement range is restricted to rather low strains. A novel measurement principle to detect magnetostrictive responses based on frequency mixing is proposed that allows to overcome these limitations. For this purpose, a magnetic field consisting of two frequencies is used. The presence of a magnetic material produces new peaks in the Fast Fourier Transformation (FFT) spectra of the measurement signal that are specific to the materials non-linear magnetization curve. Since the magnetization curve is altered by strain, the amplitudes of the peaks reveal a characteristic dependence on the strain level of the material. To study the performance of this method, a nanocrystalline, soft magnetic material as inverse magnetostrictive material was investigated. The experimental data are supported by simulations based on a simple model of the inverse magnetostrictive effect. It is shown that this method allows measurements up to one percent strain and that it is insensitive to distance variations between the strained material and the sensing coil.

1. Introduction

The frequency mixing method has been used in various sensor applications for decades, e.g. [1,2]. Recently, it has been revived due to novel medical applications that seek to detect magnetic particles, e.g. beads of superparamagnetic markers in immunoassay applications [3,4] or tracers that are used for tomographic images [5]. Frequency mixing is advantageous in these applications because of its high selectivity. Only magnetic materials with a non-linear *B*–*H* dependence contribute to the measurement signal which also results in a high signal-to-noise ratio. The technique is however not only viable for detecting the presence of magnetic materials but also for detecting the magnitude of magnetic properties, such as the susceptibility of a material. In case of inverse magnetostrictive materials, this is equivalent to detecting their stress, strain or torque level. Magnetostrictive sensors for measuring these mechanical quantities are already well established in numerous applications [6–8] and the advantage of remote interrogation via driving and pick-up coils is used in diverse environments [9,10]. Magnetostrictive delay lines [11], bilayer sensors [12] or double coil systems [13] contribute furthermore to the versatile field of application of magnetostrictive materials. In most cases, the magnetostrictive component is placed as core material of an inductivity (sensing coil) that is part of an oscillating circuit, hence it can change the circuit's resonant frequency which is detected. This non-contact measurement is however sensitive to the distance between the sensing coil and the magnetic material. Thus, in order to improve sensor reliability efforts have to be made to obtain a constant signal even at small variations of the distance [14,15]. A possibility of avoiding the distance dependence is to create an invariant resonant circuit that is read out via electromagnetic radiation [16]. The concept is also used in anti-theft labels [17].

In this work, the principle of frequency mixing is applied for non-contact strain measurements using inverse magnetostrictive materials. It is based on previous work by Tewes et al. [9] with the intention to obtain both a highly sensitive and distance-independent non-contact measurement of strain. This paper will present a new approach to sense the strain of a material using certain characteristics of the FFT spectrum. The experimental results will be discussed in comparison to simulation results.

2. Experimental

A ribbon (18 μm thickness, 4 mm width) of a nanocrystalline, soft magnetic material was used in this study as inverse magnetostrictive material with a magnetostriction constant of 0.2 ppm [18]. This alloy containing Fe, Cu, Nb, B and Si (Vitroperm$^{®}$ 800) was provided by Vacuumschmelze. The magnetic properties of the material were determined by Vibrating Sample Magnetometry (LakeShore 7300) and magnetooptical Kerr effect (MOKE) measurements under applied stress (laboratory setup). For the

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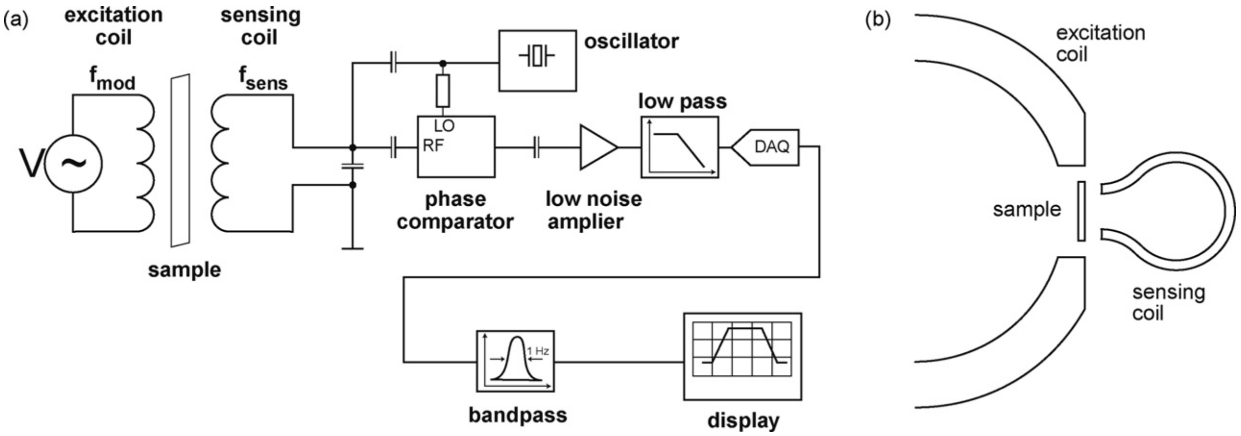

Fig. 1. (a) The phase comparator in the electronic circuit detects a phase shift between the signal from the oscillator and the output signal from the LC-circuit when a ferromagnetic material is placed in proximity of the sensing coil or when the permeability of this material changes due to strain. (b) The strain direction is perpendicular to the paper plane and to the measurement direction.

MOKE measurements the samples were mechanically polished on a Struers Rotopol-V.

Tensile tests were performed on a Zwick Z0.5. For both the MOKE measurements and the susceptibility measurements by frequency mixing, the sample was mounted using non-magnetic clamping jaws. The measurement principle of the latter and the readout electronics are described in the following subsections.

2.1. Methods

The non-linear characteristic of the *B*–*H* dependence of magnetic materials allows to use the frequency mixing technique for magnetic measurements. Based on this technique, the magnetic material is exposed to a magnetic field which consists of two frequencies: a low frequency component, f_{mod}, of rather high magnitude which saturates the sample and a high frequency component, f_{sens}, with low magnitude. The periodic saturation of the sample at f_{mod} causes a modulation of the susceptibility, χ ($\chi = \partial M/\partial H$), since $\chi \approx 0$ in the saturated state and $\chi = \chi_{max}$ at zero crossings of the low frequency field. Hence, the frequency of the modulation is $2f_{mod}$. Depending on the shape of the magnetization curve, the susceptibility (as a function of the applied field and hence as a function of time) shows sharp peaks for soft magnetic materials and rather low and broad peaks for materials with a higher anisotropy field. The concept has been explained in more detail in [9]. Accordingly, Fast Fourier Transformation (FFT) of the susceptibility signal will lead in general to a slow decay in the harmonics of $2f_{mod}$ in case of soft magnetic materials whereas a rapid decay can be observed for materials with higher anisotropy field. The hysteretic behavior of ferromagnetic materials can be neglected because in case of time-dependent considerations hysteresis leads to a phase lag between the excitation field and susceptibility compared to non-hysteretic materials. The phase lag however does not affect the result of the FFT analysis. A great advantage of this measurement technique is selectivity. Only magnetic materials with a non-linear *B*–*H* dependence in the range of the excitation field $\mu_0 H_{mod}$ contribute to the measurement signal. Furthermore, modulation of the measurement signal and the consideration of harmonics of $2f_{mod}$ only, lead to a high signal-to-noise ratio.

The susceptibility of a sample can be measured when it is placed as core material of a sensing coil in an oscillating LC-circuit as shown in Fig. 1(a). In this case the LC-circuit is driven by an external oscillator at the measurement frequency f_{sens} (20.30 MHz). The resonance frequency f_{res} of the LC-circuit equals f_{sens} for $\chi = 0$. For $\chi > 0$, the inductivity *L* of the coil increases and f_{res} decreases with $f_{res} = 1/(2\pi\sqrt{LC})$. This leads to a phase difference between the oscillating circuit and the oscillator. This difference can be used as the measurement signal for the change in susceptibility.

2.2. Setup

The oscillating circuit consists of a small capacity and the sensing coil which results in a significant change of the resonant frequency by any change of the inductance of the sensing coil. The sensing coil is positioned close to the sample which is clamped in the tensile testing machine and is subjected to the excitation field which periodically saturates the material. The excitation field is generated by a common function generator and further amplified by a power amplifier. The LC-circuit is driven by an external oscillator at the resonant frequency of the circuit without any magnetic core material present. Fig. 1(a) shows that the output signal is generated by a phase comparator that detects the phase difference, φ, between the driving signal and the signal of the oscillating circuit. Tunable capacities were used to find a good adjustment between resonant frequency, amplitude and phase shift. Without a magnetic material present, φ is set to 90° to exploit the highest sensitivity region of the phase comparator. For $\chi > 0$, the corresponding change in φ leads to a change in voltage at the phase comparator.

As high frequencies such as $f_{sens} + nf_{mod}$ are not considered for data evaluation, a low pass filter and a low noise amplification are applied to the signal. Harmonics of f_{mod} are observed after FFT in a LabView program.

3. Results and discussion

3.1. Material properties

For the measurement of the magnetic properties at precise strain levels a MOKE measurement setup was used in combination with a tensile testing machine. In this experiment measurement and strain directions were perpendicular. The minimum applied strain was 0.5% in order to guarantee a perfectly flat surface of the mechanically polished sample due to the tensile force and to minimize movements of the sample in the magnetic field.

The magnetic properties under mechanical stress are shown in Fig. 2. The MOKE measurements were performed at strain levels of 0.5%, 1.0%, 1.5% and 2.0%. With increasing strain a continuous decrease in the slope at zero field of the magnetization curve is observed. Consequently, higher magnetic fields are required to