Application of Fiber Bragg Grating to Determine the Terfenol-D Magnetostriction Characteristics for Sensor Development

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Abstract—The magnetic bodies present deformation in the direction of the magnetic field and this phenomenon is called magnetostriction. Electric current sensors based on magnetostriction have been reported in several papers. In common these previous papers use fiber Bragg grating (FBG) to perform the direct measurement of strain caused by the magnetostrictive material. However, magnetostriction sensors present few disadvantages often neglected, such as the temperature dependence. In this paper a Terfenol-D rod (a giant magnetostrictive material-GMM) is used as well as two multiplexed FBGs for simultaneous strain and temperature measurement. One of them is encapsulated in an alumina tube and it is subjected to temperature variation. The first result presents unipolar characteristics of Terfenol-D magnetostriction. Other experiments determine the Terfenol-D response for different temperatures. The Terfenol-D sensitivity increases when the temperature increases, however the saturation of the material occurs for small field values. The issues presented in this paper must be taken into account on the development of magnetostrictive sensors.

Index Terms—Current sensor, fiber Bragg gratings, magnetostriction, Terfenol-D

I. INTRODUCTION

Magnetostriction is defined as the phenomenon where a magnetic body shrinks or expands in the direction of the magnetization as a function of an applied magnetic field. The magnetic sample shrinks (negative magnetostriction) or expands (positive magnetostriction) in the direction of magnetization. Thus, magnetostrictive materials convert magnetic energy into mechanical energy, and the inverse is also true; that is, when the material suffers an external induced strain its magnetic state is changed[1].

The principal magnetostrictive effects observed experimentally are: the Joule effect, the volume effect and the Wiedemann effect. The Joule effect is an extension or a contraction in the same direction as the magnetic field or in some other direction. The volume effect, or volumetric expansion, is a very weak effect and generally is neglected. The Wiedemann effect is a shear strain response to
the magnetic field, analogous to the tensile or compressive strain produced in the Joule effect[1],[2].

Magnetostriction measurement techniques can be broadly classified as either direct or indirect, depending on whether the strain is measured directly or the magnetostriction is deduced from a measurement of some other property dependent upon strain. Direct methods enable the magnetostrictive strain to be measured as a function of the applied field, whereas indirect methods are suitable only for measuring the magnetostriction saturation. Indirect measurements are those in which a change in a magnetic property as a result of stress is measured, and the magnetostriction is deduced from theoretical models[3].

There are cases where magnetostriction is undesirable since it may introduce additional power losses, like in electrical machines and transformers or increased levels of noise in inductive or magneto-transport sensors[4]. However, the magnetostriction presents an application in the sensors field, particularly electric current sensor and magnetic field sensors. Electric current sensor was presented in previous papers [5]–[8] where different arrangements were used in order to improve the magnetostriction response. The commercial magnetostrictive material Terfenol-D is the most commonly used in actuation applications. Terfenol-D is used due to a high conversion energy density, a large force and a fast response can be achieved over a broad frequency bandwidth. The Terfenol-D is composed by iron, terbium, and dysprosium (a giant magnetostrictive material-GMM). Terfenol-D magnetostriction characteristics are a unipolar phenomenon, a positive strain is produced in the presence of positive or negative magnetic fields. In addition, the strain output is non-linear and approximately proportional to the square of the magnetic field[4].

In common some of the previous papers published in the literature use a fiber Bragg grating (FBG) to determine the strain of the magnetostrictive material by a direct measurement technique. The FBG has numerous advantages for this application, including small size, insensitivity to optical source intensity fluctuations and to electromagnetic interference, good noise-signal rate and multiplexing potential[9], [10].

However, the magnetostrictive material presents a few disadvantages which complicate its use as a sensor. The disadvantages which can be mentioned are the temperature dependence of the magnetostriction, the nonlinear response and the hysteresis characteristics of ferromagnetic materials. One disadvantage which are not mentioned in the literature and are related to magnetostrictive sensors is its temperature dependence[7]. In [5] a mechanical compression load is applied in the Terfenol-D in order to minimize disadvantages of temperature dependence. The mechanical load modify the magnetostriction response.

In this paper some characteristics of a magnetostrictive materials using FBG to determine the strain of the material are presented. The objective is to present the features that are usually neglected when the Terfenol-D is used for the development of current and magnetic field sensors. The features analyzed are the temperature dependence of the magnetostriction and hysteresis.
II. MATERIALS AND METHODS

A. Fiber Bragg Gratings

Among the fiber-optic sensors used in more recent years, there are those based on the properties of fiber Bragg gratings. An FBG is formed by a periodic modulation of the refractive index in the longitudinal direction in the fiber core. The existence of this modulation causes the reflection with a narrow frequency band of the light beam propagated therein. The reflected narrow frequency band is centered on a particular wavelength, known as the Bragg wavelength $\lambda_B$. The Bragg wavelength depends, among other parameters, of the spatial step of the modulation index. This makes it possible to obtain reflections in different bands and different gratings can be recorded on the same fiber, allowing the wavelength multiplexing. Figure 1 illustrates three multiplexed FBG wavelength spectra.

![Figure 1: Three FBG wavelength multiplexed in a single optical fiber. The spectrum of the broadband light source is reflected by each FBG and the wavelength detection system is used for peak measurement.](image)

The photo-elastic and thermo-optical effects of the silica glass, used in the production of the optical fibers, leads to changes in the characteristics of the FBG. The changes occur due to a mechanical stress or temperature variation in the region where the FBG is recorded. This makes the Bragg grating sensing elements for these quantities and can be easily incorporated into fiber-optic links.

Changes in the spatial period $\Lambda$ or the effective refractive index $n_{eff}$ of an FBG leads to a shift in the Bragg wavelength. The spectral shift considering these effects and thermal expansion of the material can be described in (1)[9], [10]:

$$
\Delta \lambda_B = 2 \left( \Lambda \frac{\partial n_{eff}}{\partial l} + n_{eff} \frac{\partial \Lambda}{\partial l} \right) \Delta l + 2 \left( \Lambda \frac{\partial n_{eff}}{\partial T} + n_{eff} \frac{\partial \Lambda}{\partial T} \right) \Delta T
$$

where $l$ is the length and $T$ the temperature of the FBG.

B. Experimental Setup

The Terfenol-D rod with dimensions of 40 mm x 5 mm x 5 mm is used for tests. For simultaneous measurements of temperature and strain two multiplexed FBGs are recorded in a photosensitive optical fiber. One FBG is directly glued to the Terfenol-D being subjected to the deformation suffered by it. In order to increase the strain sensitivity a 15 mm FBG length is recorded. The other FBG is placed in an alumina tube with a length of 30 mm and an inner diameter of 0.5 mm. Alumina has a
thermal expansion coefficient close to the silica. Due to this characteristic, it can be used for FBG encapsulation, reducing the strain due to thermal expansion. This tube is glued in the Terfenol-D. Thus, the FBG does not suffer mechanical deformation, presenting only temperature sensitivity and can be used for temperature compensation. So, the first term in (1) is canceled. Figure 2 shows the FBGs arrangement in the Terfenol-D rod.

Fig. 2 FBG arrangement in the Terfenol-D. The figure shows the front (left) and back (right) of the Terfenol-D rod. The FBG inside the alumina tube do not suffer strain deformation and is used for temperature compensation.

In Figure 3 the experimental setup is presented. To evaluate the sensor behavior due to a magnetic field a 1200 turns toroidal coil with a diameter of 40 mm and a length of 70 mm is used. The magnetic field is calculated as a function of the toroidal geometric characteristics and the applied current. Current values are measured by a Tektronix current probe TCP0030 and a Tektronix oscilloscope DPOse4043. The Terfenol-D rod is placed inside of the toroidal coil in the same direction of the magnetic field. The experimental setup allows a variation in the magnetic field from 0 to 2x10³ A/m.

With the current flowing, the length of the rod increases by a small amount ΔL. The strain ΔL/L is measured for a particular value of the applied field and in a specified direction with respect to the demagnetized state. Amorphous magnetic materials can be regarded as essentially uniaxial in their magnetic properties [1], [3]. In this case the strain is given by:

$$\frac{\Delta L}{L} = \frac{3\sigma_s}{2} \left( \cos^2 \theta_f - \cos^2 \theta_i \right)$$  \hspace{1cm} (2)

Where $\theta_f$, and $\theta_i$, are the final and initial angles between the magnetic domains and the applied field. $\sigma_s$ is a constant representing the material constant. This constant is obtained experimentally when the substance, initially in the hypothetical demagnetized state, is magnetized to saturation [1], [3]. The maximum strain occurs when all the magnetic moments rotate through 90°, and is given by:

$$\frac{\Delta L}{L} (\text{max}) = \frac{3\sigma_s}{2}$$  \hspace{1cm} (3)
In order to improve the magnetostriction the Terfenol-D rod is placed in the same direction of the magnetic field.

Fig. 3 Experimental setup. A magnetic field leads to a strain $\Delta L$. The FBG sensors are measured by a Bragg interrogator DI410. The oscilloscope and current probe are used to calculate the magnetic field.

The two FBG are temperature characterized using a circulating silicone oil bath with a digital temperature control, model Lauda Eco Gold RE 415G, with a precision of 0.02°C and a resolution of 0.01°C. The FBG is read by the optical sensing interrogator DI 410 manufactured by HBM with 1 pm resolution. In Figure 4 the curves corresponding to the Bragg wavelength shift of the two sensors are depicted as a function of temperature. The expanded uncertainty of the calibration system is 0.8°C.

![Figure 4](image-url)

Figure 4 Temperature response for FBG in the alumina tube (Sensor 1) and FBG in the Terfenol-D (Sensor 2). Experimental data (marks) are connected by best-fit lines close.
III. RESULTS AND DISCUSSION

The first experiment is designed to determine the Terfenol-D response under positive and negative magnetic field. Figure 5 shows the Terfenol-D rod response that can be approximated to a quadratic function and the experimental points are obtained for a DC current. However, for sensing applications the Terfenol-D is inherently incapable of reproducing an AC waveform and sinusoidal input will result in a rectified output. Because of the material response that is proportional to the square of the magnetic field strength, the response is inherently nonlinear. These characteristics were explored in a previous paper, where it is possible to calculate the rms value of the current directly from the output of the sensor at 60 Hz[5]. However, for a direct measurement the FBG output must be filtered by a high-pass filter to avoid the FBG temperature sensitivity. The Bragg wavelength shift due to temperature has the same effect as the application of a DC current. Thus, when a high-pass filter is used the only measured Bragg wavelength shift is due to AC current. Therefore, it is not possible to measure DC current in the sensor presented in[5]. In industrial environments in most cases the measured current is AC and DC components occurs in specific situations such as short circuit. Under these conditions, the use of this sensor configuration is limited.

Fig. 5 Terfenol-D response due to positive and negative magnetic field.

Besides the non-linear response, the magnetostriction presents influence of the material stress and temperature. The stress states can change significantly the magnetic behavior of the materials [11]. When the material is subjected to a positive stress (compressed load) the magnetostriction has a lower sensitivity to the field variation [5]. On the other hand, the magnetostriction sensitivity increases when the temperature increases. This behavior is similar to a negative stress (tension load). Figure 6 presents the Terfenol-D rod behavior for different temperatures. The Terfenol-D sensitivity increases
when the temperature increases, however the saturation of the material happens for smaller magnetic field values.

The Terfenol-D magnetostriction presents a similar behavior at close temperature, such as at 75.5ºC and 78.7ºC. For these temperatures reaches the saturation region near to $8.5\times10^3$ A/m and after that start to behave differently from one another. Thus, errors are introduced when the sensor temperature change or when the sensor is in the saturation region, even for similar temperatures. During the transient load, as the induction motor starts, the measured current reaches values 10 times higher when compared to the current regime. In this situation, the sensor is operating at the saturation region. Moreover, the sensor must operate in aggressive environments subject to temperature variation. Such conditions represent a challenge to deploy these sensors in industrial plants.

![Terfenol-D response due to positive magnetic field at different temperatures.](image)

Another way to measure AC currents is by introducing a DC biasing field [6], [7]. DC biasing consists of applying a magnetic field from a DC current in the Terfenol-D. The DC bias field moves the operating bias point up the strain vs. magnetic field curve resulting in an output waveform whose polarity changes as the polarity of the input changes. The interest is reproducing a sinusoidal response in the Terfenol-D. However, the symmetric sinusoidal current result in a measured current asymmetrical due to non-linearity and the hysteresis of the Terfenol-D. For applications in power systems, involving currents in the order of $10^3$ A, the dc biasing value must be high sufficiently to ensure response bipolar condition, thereby increasing the complexity of the sensor.

Figure 7 shows the hysteresis for a positive magnetic field. The hysteresis presents another problem for measuring ac current. The sensor output presents a phase in order of 30º compared to measured current[7]. Generally, the measured current is used to compute the consumed (or generated) electric...
power. An error in the current phase leads to an error in the computed power. Therefore a processing signal method must be used to correct the effect of hysteresis[12]. However the method for compensating hysteresis causes delays in the measured current value. Thus, in a situation that requires real-time values such as the synchronism of power generators, this method cannot be used. In Figure 7, the Terfenol-D rod is in relaxed condition at the beginning of the experiment. When a magnetic field is applied and after removed the material presents a residual magnetism. Therefore, the hysteresis curve does not return to the starting point.

In this paper some characteristics of a magnetostrictive material (Terfenol-D) using FBG to determine the strain of the material is presented. The magnetostriction has some characteristics which limit its use as a current sensor. Besides the non-linear response, the magnetostriction presents influence on the stress condition and temperature. The stress states and temperature can change significantly the magnetic behavior of materials. The Terfenol-D magnetostriction increases when the temperature increases and the saturation of the material occurs for smaller field values. At similar temperatures magnetostriction has a similar behavior, such as 75.5 ºC and 78.7 ºC. In addition, the Terfenol-D presents a hysteresis as any ferromagnetic material. These characteristics must be taken into account in the development of magnetostrictive sensors.

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