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USING THE GMI EFFECT FOR DETECTING SMALL ROTATIONAL MOVEMENTS

Cristian Fosalau [1], *Emil Vremera*[1], *Marinel Temneanu*[1], *Mihai Cretu*[1]

[1] Technical University "Gh.Asachi" of Iasi, Iasi, Romania, e-mail: cfosalau@ee.tuiasi.ro

Abstract: The paper goal is to describe the way in which the Giant Magnetoimpedance Effect (GMI) occurring in the magnetic amorphous wires can be utilized to detect small rotational movements. The operation principle is based on modification of the wire impedance under action of a torsional stress when an ac low current flows through it. The schematic overview of an angle sensor built around this effect, along with some experimental results obtained upon the functional model are presented in the paper. Analysis was performed on the sensor behavior under different frequencies and intensities of the current flowing through the wire as well as under different values of an axial dc magnetic field applied to the wire in order to control the angle span of the sensor.

Keywords: angle sensor, GMI effect, amorphous wires.

1. INTRODUCTION

The papers describes the operation principle, construction and performances of a new device aimed to detect and measure small rotational angles, whose operation is based on the GMI effect occurring in the magnetic amorphous wires (MAW) [1].

A large variety of products devoted to angle measurements are commercially available. Most of them are built for quite large ranges of operation, having excellent metrological qualities. Other attempts were made on the basis of magnetic phenomena [2] or using MAWs and Matteucci effect, as reported in [3,4]. Small angles are however difficult to measure due to the very high sensitivity requested for the sensor in the conditions of a low signal-to-noise ratio and also in the frame of very small dimensions requested by certain applications. The digital encoders, which are the most suitable for small angles measurements have, however, too large physical size when high resolution is requested for applications such as: rotational vibration detection on motor shafts, control of the yarns tightness, etc.

The MAWs are metallic glasses that are obtained by the so-called "in-rotating water spinning method" [5]. Their composition is based on a metal phase like Fe, Co, Ni, Cr, Mn, Cu, Nb, alloyed with Si and B in different proportions. The main feature of the MAWs is their non-crystalline structure, obtained as a consequence of the fast solidification of the alloy under the cold temperature of a water layer in which they are jetted. Accordingly, a very interesting and rather complicated magnetic domains structure arises that is dependent on the wire composition. With respect to their macroscopic properties, the MAWs are devised into two categories: those exhibiting high magnetostrictivity, based on the iron as a main transition metal and those having nearly zero magnetostrictivity, but with very high circular permeability. The latter ones are the subjects of the GMI effect that will be briefly described in the following section.

2. SHORT PRESENTATION OF THE GMI EFFECT

The non-magnetostrictive as-cast MAWs show a very interesting internal structure: an axially magnetized core surrounded by a circumferentially magnetized shell, as shown in fig. 1 [1].

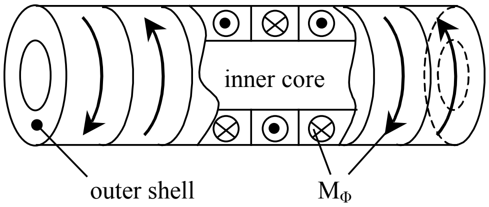

Fig. 1. The internal structure of a non-magnetostrictive MAW: an inner core surrounded by an outer shell in which the magnetic domains are circumferential.

The outer shell exhibits a circumferential anisotropy in terms of opposite magnetization M_Φ in adjacent magnetic domains.

In fig.2, the principle of the GMI effect is presented. When an ac current i_{ac} passes through this wire, it produces into the outer shell a circumferential magnetic field, H_Φ, whose intensity radially decreases to zero, from the surface to the wire axis. The flux variation created by this field in the circular magnetic domains of the shell produces, by electromagnetical induction, a voltage drop e_L between the ends of the wire, which is very sensitive to axial and torsional mechanical stresses and also to axially oriented magnetic field applied to the wire [6]. Therefore, this phenomenon is equivalent to modification of the wire impedance with regards to the above factors, mainly due to the dependence of the circular magnetic permeability of the shell domains on these factors. This is known as the GMI effect.

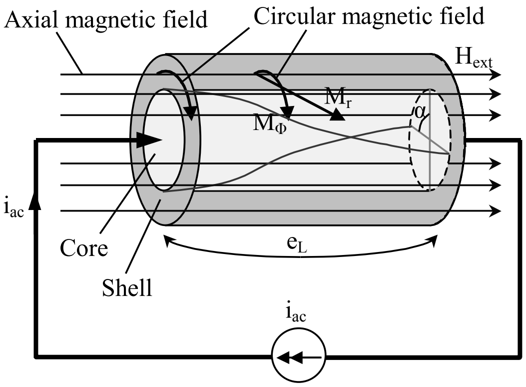

Fig.2. Principle of the giant magnetoimpedance effect

If the frequency of i_{ac} current passing through the wire is high (commonly more than 100 kHz), the skin effect also occurs onto the wire, which depends on changes of the circumferential permeability upon the external axial magnetic field applied. Therefore, both components of the impedance are changing with frequency and also with torsion.

3. SENSOR STRUCTURE AND OPERATION

The schematic view of the proposed sensor is presented in fig. 3. It consists of two circular metallic magnetic plates sustained by a magnetic ring case that has coaxially mounted the MAW whose ends are glued to the plates centers. We have utilized as-cast Co-based amorphous wires having the composition $(Fe_{0.06}Co_{0.94})_{72.5}Si_{12.5}B_{15}$, supplied by Unitika Ltd. The wire diameter was 125 μm. Around the ring case, a bias coil is mounted in order to produce an additional dc bias magnetic field H_x, in order to increase the sensitivity and linearity of the sensor.

The bias coil is fed with a dc current i_{bias}, which produces the axial magnetic field to the wire. This field acts upon the circular magnetization direction and thus on the circular permeability, μ_Φ, which is directly responsible with the impedance change. Accordingly, the circular differential permeability decreases with increasing H_x due to the inclination of the resultant magnetization vector M_r (see fig. 2) from the circumferential direction towards the wire axis. On the other hand, the wire is supplied with an ac driving current, i_{ac}, supplied by the electronic conditioning circuitry of the transducer. As soon as the plates move around the sensor axis relatively to each other with an angle α, the wire is torsioned and a helicoidal stress is induced in the wire structure, also producing an alter of the circular resultant magnetization vector into the wire shell. So, the effect is a change of the wire impedance in two cases: i) if the frequency is low, the reactive part of the impedance predominates with important variation of the wire inductance (also known as the magntoinductive effect) and ii) if the frequency goes to high, the skin effect occurs and the active component of the impedance becomes important.

For any frequency, the impedance is defined as [7]:

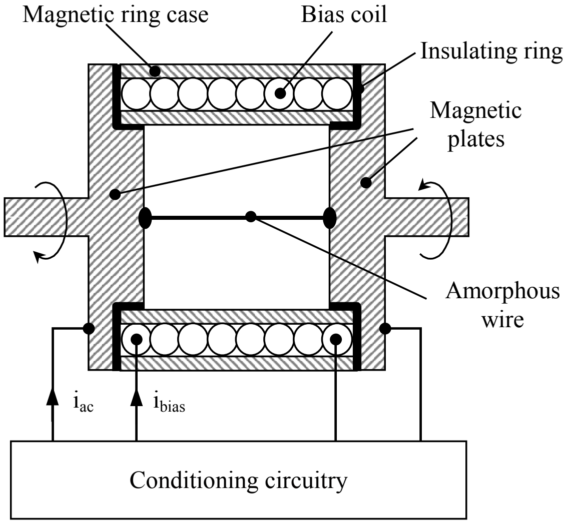

Fig. 3. Schematic view of the sensor for measuring small rotational movements using magnetic amorphous wires

$$Z = R_{dc} kr \frac{J_0(kr)}{2J_1(kr)}, \quad k = \frac{1+j}{\delta} \tag{1}$$

where R_{dc} is the wire resistance in dc current, J_0 and J_1 are Bessel functions, r is the wire radius and δ is the skin depth, which is given by the following formula:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_\Phi(H_x\xi,\sigma)}} \tag{2}$$

The two components of Z, can be expressed as [8]:

$$\underline{Z} = R_{dc} + j\omega L, \quad L = \frac{l\mu_\Phi(H_x,\xi,\sigma)}{8\pi} \tag{3}$$

for $f \leq 100$ kHz or

$$\underline{Z} = \frac{r}{2\sqrt{2\rho}} R_{dc}(1+j)\sqrt{\omega\mu_\Phi(H_x,\xi,\sigma)} \tag{4}$$

for $f > 100$ kHz.

In the above equations, ω is the current pulsation, l the wire length, μ_Φ the circular permeability depending on the axial bias dc field, H_x, wire torsion, ξ, and axial tensile stress, σ, and ρ is the resistivity.

The sensor has 8 mm in diameter and 12 mm in length. The bias coil has 250 turns of enameled copper wire of 0.1 mm. The magnetic ring case and plates ensure the magnetic shielding of the wire, since it is very sensitive to external magnetic fields.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

The sensor was tested considering the frequency and intensity of the i_{ac} current as well as the bias field intensity as parameters. The input quantity of the system was the torsional degree of the wire expressed in rad/m or in relative angles. As output, the wire impedance magnitude was considered. It was measured using a Hewlett Packard 4194A

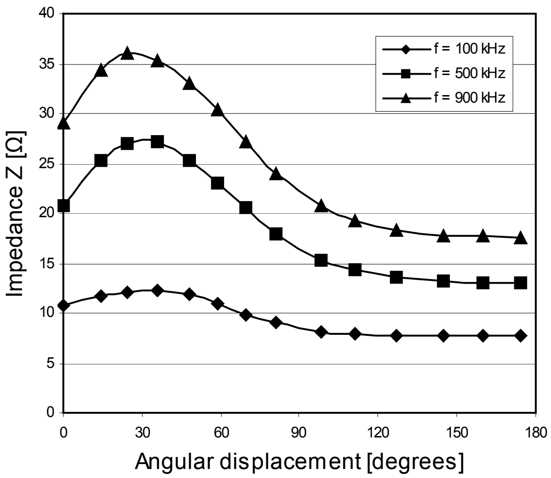

Fig. 4. Dependence of the wire impedance vs. angular displacement, for f = 100, 500 and 900 kHz, Hx = 0, i_{ac} = 2 mA.

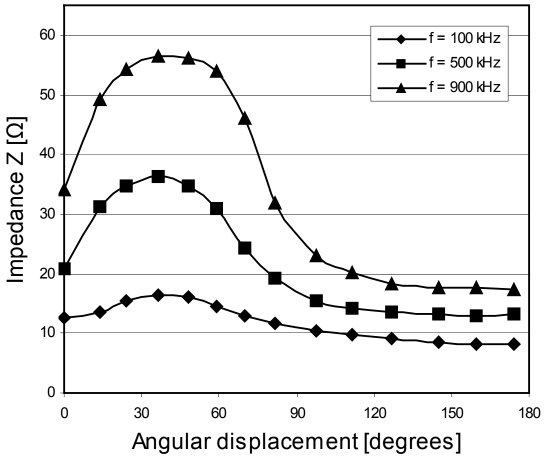

Fig. 5. Dependence of the wire impedance vs. angular displacement, for f = 100, 500 and 900 kHz, Hx = 0, i_{ac} = 10 mA.

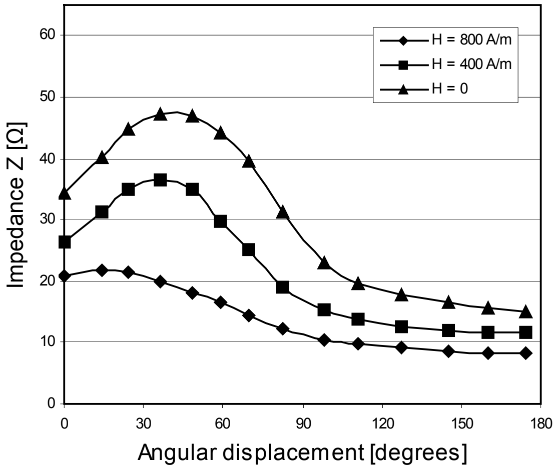

Fig. 6. Dependence of the wire impedance vs. angular displacement, for f = 900 kHz, Hx = 0, 400 and 800 A/m, i_{ac} = 6 mA.

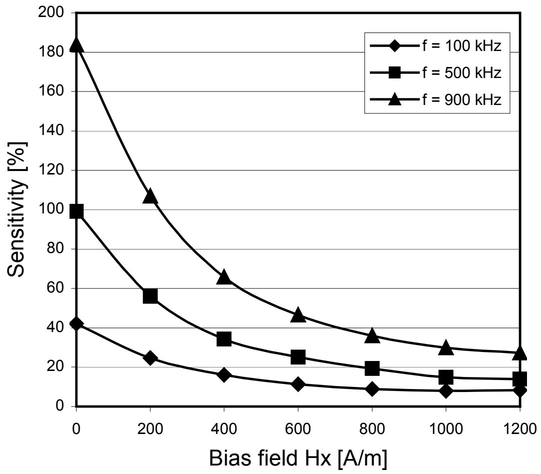

Fig. 7. Dependence of the sensor sensitivity vs. bias field, for f = 100, 500 and 900 kHz, i_{ac} = 6 mA, linearity = 1%.

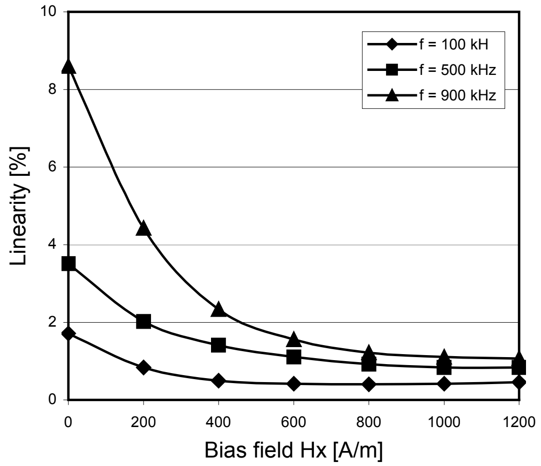

Fig. 8. Dependence of the sensor linearity vs. bias field, for f = 100, 500 and 900 kHz, Hx = 0, i_{ac} = 6 mA, angle span = 60°

impedance analyzer. Furthermore, this impedance is processed inside the sensor adapter in order to obtain a voltage output whose amplitude and/or frequency is proportional to the measured angle. The adapter structure is not the subject of the present paper. In the following figures, some families of characteristics were traced, depicting the dependence of the sensor impedance with respect to the torsional angle when i_{ac} frequency and intensity and bias field intensity were taken as parameters. The frequency span was chosen from 100 kHz to 900 kHz, just above the relative limit from which the GMI effect occurs, whilst the current varied between 2 and 10 mA in magnitude. The bias field was in the range of 0 to 1200 A/m. At a first glance, as can be observed from figures 4, 5 and 6, the impedance exhibits a maximum that depends, among other parameters, on the current flowing through the wire. This is caused by the remnant quenching torsional stress frozen-in during the fabrication process. In the output, this deviation can be corrected by zero-calibrating the transducer inside the conditioning circuitry. As the current increases, the maximum becomes more smoothed going through higher values.

In order to assess the sensor performances, we have calculated the global sensitivity expressed as:

$$S_g = \frac{Z_{\max} - Z_0}{Z_0} 100 = \frac{\Delta Z}{Z_0} 100 \qquad (5)$$

where Z_0 is an arbitrary reference value. We have chosen Z_0 as the minimum values of Z, for an angular displacement of 180º. In fig. 6 the sensor characteristics for 3 values of H_x were traced, while fig. 7 shows the dependence of S_g on the bias field value H_x with i_{ac} frequency as parameter. The characteristics clearly show the decay of global sensitivity with the field, explained in terms of increasing the inclination of M_r magnetization through the axial field direction along with decreasing of its circular component. This behavior is more significant for higher frequencies, for which the sensitivity gets to over 180 %. Another important parameter taken into consideration was the sensor linearity, calculated for a fixed angle span of 60º. As can be seen from fig. 8, the sensitivity decrease with the field is compensated by a corresponding augmentation of the linearity, more prominent also for higher frequencies. Table 1 presents the relationship between sensitivity, linearity and field value, considering the angle span required by the application as a global criterion.

Table 1. Relationship between field intensity, angle span and sensitivity for the linearity up to 1 %.

Hx [A/m]	Angle span [degrees]	Sensitivity [%]	Linearity [%]
0	14	186	< 1
200	34	116	< 1
400	50	82	< 1
600	61	60	< 1
800	68	47	< 1
1000	71	40	< 1
1200	72	35	< 1

It can be concluded that, if the application requires narrow angle spans for a linearity under 1 %, no field is required, allowing a sensitivity over 180 %. Conversely, if larger spans are needed, for the same linearity the bias field intensity must be increased, while the global sensitivity accordingly decreases to less than 35 %.

5. CONCLUSIONS

The GMI effect taking place in the low magnetostrictive magnetic amorphous wires can be used to detect smallrotational movements owing to the sensitivity of this effect to torsional actions upon the wire. If an additional constant axial magnetic field is added, the angle span for different sensitivities and linearities can be controlled, according to the application requirements. Increasing the field leads to lowering the sensitivity in conjunction with enlarging the input angle range. In certain conditions, the global sensitivity exceeds 180 % which means a very good signal to noise ratio for the output signal and, consequently, a better accuracy.

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