A New Current Sensor Based on Giant Magnetoimpedance Effect

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Abstract-The paper presents a new current sensor whose operation principle is based on the Giant Magnetoimpedance Effect (GME) occurring in non-magnetostrictive magnetic amorphous wires (MAW). This effect consists in sudden variations of the voltage drop picked-up from the ends of an amorphous wire when a high frequency current flows through it and it is subjected to an external axial magnetic field. The wire is mounted around a cylindrical conductor, through which the measured current flows, thus creating the necessary axial field to which the sensor is sensitive. Construction, operation principle and characteristics of the sensor along with details related to its performances are presented.

I. Introduction

The magnetic amorphous wires are categorized as magnetic glasses, being produced by the so-called "in-rotating-water-quenching-method" [1]. They are used in various applications as magnetic sensors and micro-magnetic devices [2]. In order to measure the current, in industrial applications usually shunts and Hall-effect sensors are utilized. The first are more often employed for measuring dc currents in low and medium ranges, but their serious drawbacks related to galvanic contact, large dimensions and low precision restrict their application. The latter have wider applications due to their precision, small dimensions and rather large bandwidth, but they need strong magnetic field, the output signal is very weak and they need special error-compensation circuits for large temperature variations. Several attempts were made for developing new current sensors using the MAWs. Thus, in [3] and [4] a sensor for large values of current (hundreds of ampere) using a multivibrator bridge circuit is described. This sensor has very small dimensions, but is strongly influenced by its position with respect to the magnetic field created by the measured current. Other approach is presented in [5], where a small MAW is placed in a magnetic circuit through which the flux created by the measured current along with a feedback coil flows. The voltage across the ends of the wire is simply picked-up, rectified, detected and then measured. Its magnitude is approximately proportional to the current. Both the above methods use the GME.

A device based on the Matteucci Effect (ME) occurring in magnetostrictive MAWs is described in [6]. There, the twisted MAW is wound around a conductor a number of turns. According to ME, sharp pulses are generated between the ends of the MAW when it is placed in the ac magnetic field produced by the measured current. Their magnitude depends on several factors and is proportional to the field intensity and hence to the current value.

In the present paper we describe the construction, operation principle and characteristics of a new current sensor based on the GME occurring in Co-based MAWs exhibiting very low magnetostrictivity. Their exact composition is $(Fe_{0.06}Co_{0.94})_{72.5}Si_{12.5}B_{15}$. We have used wires with diameter of 120 μm, and different length, being kindly supplied by Unitika Ltd. from Japan.

II. The Giant Magnetoimpedance Effect

The non-magnetostrictive MAW shows very interesting internal structure: an axially magnetized core surrounded by a circumferentially magnetized shell [7]. 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 electromagnetic induction, a voltage drop e_L between the ends of the wire that is very sensitive to any axially oriented magnetic field applied to the wire, H_{ext}. (see figure 1). Therefore, this phenomenon is equivalent to the modification of the wire impedance, mainly ascribed to the dependence of the circular permeability on the axial field applied. This is known as *Giant Magntoimpedance Effect.* If the current frequency is high, both the active and reactive parts of the impedance are modified with the field owing to the skin effect that occurs in the wire, which also depends on the frequency and on the circumferential permeability. Then, the

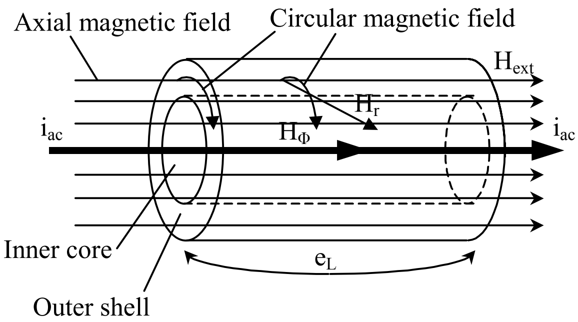


Figure 1. Model for illustration of GMI

impedance is defined for any frequency as [8]:

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

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:

$$\delta = \sqrt{\frac{2\rho}{\omega \mu_\Phi (f, H_{ext})}} \tag{2}$$

In the case of a strong skin effect, the above expression can be reduced to:

$$|Z| = \sqrt{\frac{R_{dc} l \omega |\mu_\Phi (f, H_{ext})|}{4\pi}} \tag{3}$$

where l is the wire length and $|\mu_\Phi|$ is the absolute value of the circumferential permeability that depends on the frequency and the external field.

III. Sensor construction

In figure 2, an intuitive diagram of the sensor is depicted whilst in figure 3 the experimental arrangement for tracing its characteristics and assessing its performances is shown. The sensor is composed by a cylindrical conductor with diameter a made by copper, around which a MAW exhibiting nearly zero magnetostrictivity (λ_S = $0.6 \cdot 10^{-7}$) is wound. The MAW composition is $(Fe_{0.06}Co_{0.94})_{72.5}Si_{12.5}B_{15}$. The measured current, I, flows through the cylindrical conductor, creating around it a circular magnetic field, H_c, whose intensity depends on the distance to the conductor axis, r, in accordance with:

$$H_c = \frac{I}{2\pi r} \tag{4}$$

As can be seen in figure 2, H_c is applied to the MAW as an axial field H_{ext} whose intensity is that of H_c at the conductor surface ($r \approx a$). On the other hand, the MAW is supplied with an ac current i_{ac} provided by a sinusoidal signal generator, that produces along with the field H_{ext} a change in the magnetization direction and magnitude of the wire shell (surface domains) and so, a variation of the wire overall impedance. This impedance variation is directly related to the field intensity and so to the current magnitude by intermediate of the circumferential permeability μ_Φ, according to

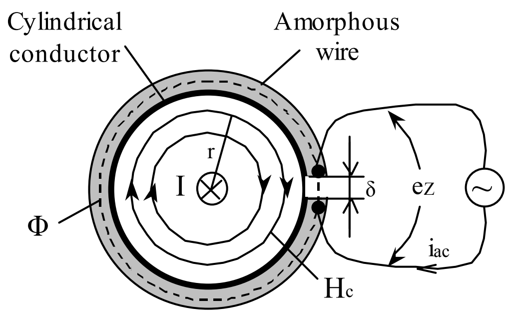


Figure 2. Cross-sectional view inside the sensor

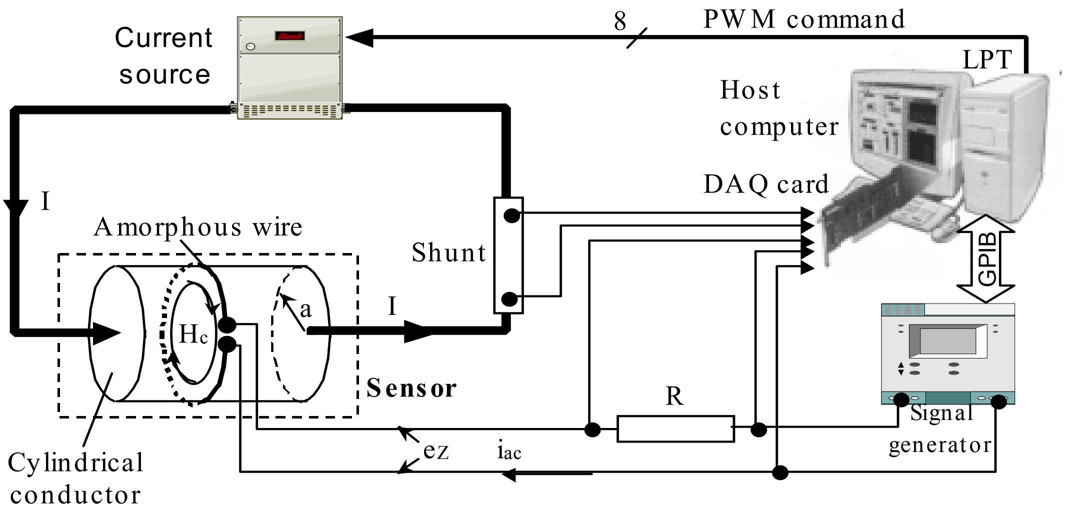


Figure 3. Experimental set-up for sensor characteristics tracing

(3). One obtains in this way a voltage drop, e_Z, expressed as:

$$e_Z = i_{ac} Z = f(\mu(H_{ext}, f), a, \delta) = f(I, f, a, \delta) \quad (5)$$

The gap δ between the ends of the wire also determines the sensor sensitivity and linear range through the reluctance introduced. The sensor is very sensitive to low magnetic fields and so to low currents.

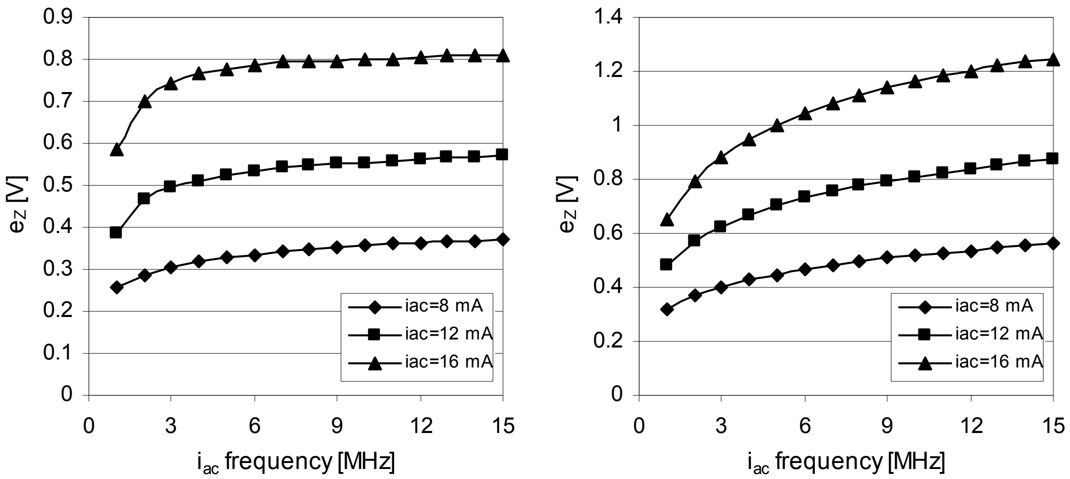
A host computer, which drives the whole system, acquires by means of a digital acquisition card type PCI-MIO-16E-4, the signal picked-up from the ends of the MAW, e_Z, the voltage drop on the resistor R, proportional to i_{ac} , and the signal proportional to the current I picked-up from a precise shunt. The computer also drives the signal generator type Tektronix AFG310 by means of the GPIB interface with which the generator is endowed and the current source through the parallel port. The current source is actually a power pulse width modulation (PWM) generator supplied by the host computer with an 8 bits digital word that expresses the value of the PWM signal. The supplied current magnitude is proportional with this digital word. I may be a dc or an ac current whose magnitude is set by the computer according to the testing algorithm. The system is able to fully automatically trace the sensor characteristics. The entire process is supervised by a virtual instrument built in LabVIEW, concerned on the tasks required for acquiring, processing, storing and displaying the sensor information. Consequently, its productivity of data processing allowed us to analyze a large amount of influence factors upon the sensor behavior.

IV. Experimental results

All the sensor characteristics were traced considering I as input quantity in the system and the voltage across the wire, e_Z, as output. The conditions of the experiment were: cylindrical conductor diameter 3 mm, I between 0 and 3 A direct current, f = 1 to 15 MHz, δ = 0.1; 0.5; and 0.8 mm. In figures 4 a) and b), the dependence of e_Z on the frequency of the current i_{ac} flowing through the wire is presented, traced for three different values of i_{ac} and for the extremities of the sensor range, I = 0 and I = 3 A dc. As can be observed from these figures, for no current applied, the frequency influence upon the measured output is very weak from 3-15 MHz, so the frequency does not affect anymore the GME occurring in the wire. For I = 3 A, this influence becomes stronger mainly for higher values of the ac current through the wire.

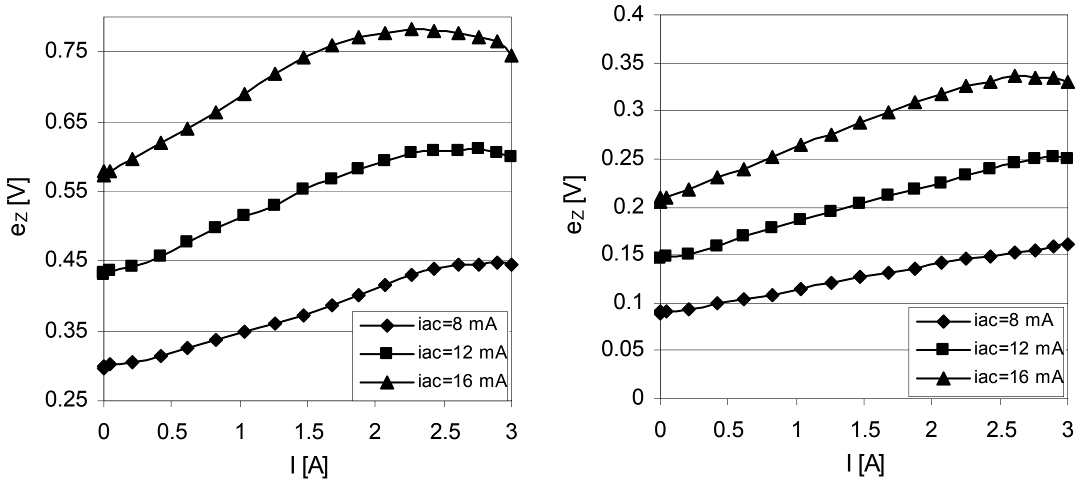
In figures 5 a) and b), the output characteristics of the sensor are traced, i.e. the dependence of e_Z upon the current I for the same three previous values of i_{ac} and for two different gaps, δ = 0.1 mm and δ = 0.5 mm. One observes that the linearity severely decays for higher values of i_{ac} and for low δ due to wire shell saturation. However, this parameter can be improved by increasing the gap so that the magnetic circuit becomes linear, but the sensor sensitivity decays, as can be seen in figure 5 b). A better linearity implies also the signal to noise ration decrease, since the output voltage is rather noisy, and the signal magnitude decreased with 50-70 %.

There were performed also experiments with various degrees of torsion, ξ, for the MAW. The



a) b)

Figure 4. Dependence of the output voltage e_Z on the i_{ac} frequency for different values of i_{ac} when a) I = 0 and b) I = 3 A.



a) b)

Figure 5. Dependence of the output voltage e_Z on the measured current I for different values of i_{ac} and f = 4 MHz when a) δ = 0.1 mm and b) δ = 0.5 mm.

torsion stresses were "frozen" in the MAW by current annealing under stress with a 440 mA dc current passing through the wire for 5 minutes. There were chosen two values, $\xi = \pi$ rad/m and $\xi = 2\pi$ rad/m. By torsioning the wire, a helically induced anisotropy occurs that affects both the real and imaginary parts of the circumferential permeability, μ_Φ [9]. Accordingly, torsioning the wire is equivalent with adding a dc component to i_{ac}, which corresponds to translating the characteristics to the left or to the right, according to the torsion sense. Such a characteristic looks like in figure 6. Therefore there is no improvement with this action except the sensor range translation to higher current values.

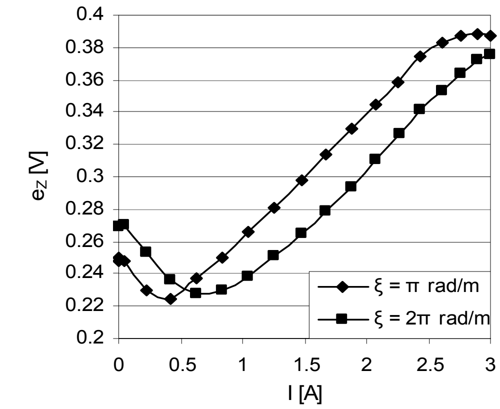


Figure 6. Transfer characteristic for two different values of torsion degree, ξ

V. Conclusions

As a result of our experiments regarding the sensor behavior under various conditions and factors of influence, we found the following performances obtained after optimizing the characteristics: sensitivity 80 mV/A, linearity under 1 %, signal to noise ratio 45 dB, temperature coefficient 0.1 %/ºC, accuracy 1.2 % of FS. The experimented range was 0 – 3 A dc, but it can be modified from constructive considerations. Other tasks for future work are more turns of the MAW wound around the conductor, study of the sensor behavior in ac current, and the MAW placed linearly inside a 2 – 5 turns coil fed by the measuring current.

Our sensor can be an alternative to commercial Hall effect sensors, taking advantage from its very small dimensions, low price and comparable performances.

Acknowledgments

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References

[1] I.Ogasawara and S.Ueno, Preparation and properties of amorphous wires", *IEEE Trans. Magn.,* vol. 31, pp. 1219-1223, Mar. 1995.

[2] P.T. Squire, D.Atkinson, M.R.J. Gibbs, and S. Atalay, "Amorphous wires and their applications," *J. Magnetism Magn. Mater.,* vol. 132, pp.10-21, 1994.

[3] Y. Kashiwagi, T. Kondo and K. Mitsui, "300 A Current Sensor Using Amorphous Wire Core", *IEEE Trans. on Magn,* vol. 26, no. 5, pp. 1566-1568, Sept. 1990.

[4] K. Inada, K. Mohri and K. Inuzuka, "Quick Response Large Current Sensor Using Amorphous MI Element Resonant Multivibrator", *IEEE Trans. Magn.,* vol. 30, 4623-4625, Nov. 1994.

[5] Y. Yoshida, A. Tayaoka, "Precise Current Sensor by means of Small-Angle Magnetization Rotation using Amorphous Wire and its Industrial Application", *IEEE Trans. Magn.,* vol. 29, pp. 3180-3182, Nov. 1993.

[6] C.Fosalau, C.Zet, M.Temneanu and M.Antoniu, "A Novel Current Sensor Using Magnetostrictive Amorphous Wires" *IMEKO-TC4 13th International Symposium on Measurements for Research and Industry Applications*, Athens, 29 September – 1st October 2004, pp. 21-25.

[7] L.V. Panina, K. Mohri, T. Uchiyama and M. Noda, "Giant Magneto-Impedance in Co-Rich Amorphous Wires and Films", *IEEE Trans. Magn.,* vol. 31, pp. 1249-1260, March 1995.

[8] K. Mohri, et al, "Magneto-Impedance Element", *IEEE Trans. Magn.,* vol. 31, pp. 2455-2466, July 1995.

[9] I. Betancourt and R. Valenzuela, "The Effect of Torsion Stress on the Cicumferential Permeability of CoFeBSi Amorphous Wires", *IEEE Trans. Magn.,* vol. 39, pp. 3097-3099, Sept. 2003..