A Novel Current Sensor Using Magnetostrictive Amorphous Wires

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Abstract-The current sensor presented in the paper is built around a relatively new category of materials expressed by magnetic amorphous wires. Its operating principle is based on the Matteucci effect occurring in amorphous wires showing high level of magnetostriction. The wire is wound around the conductor through which the current to be measured flows. Under certain conditions, at the ends of the wire sharp voltage pulses appear whose amplitude depends on the intensity of the circumferential magnetic field generated on the conductor surface and, implicitly, on the current intensity.

I. Introduction

The magnetic amorphous wires (MAW) (magnetic glasses) are produced by the so called "in-rotating-water quenching-method", in which the melted metal is loaded into a quartz nozzle, and then ejected under pressure through the orifice of quartz nozzle into a rotating water layer [1]. Due to the rapid quenching rate, the crystallization of the material is no more possible, thus resulting strong residual internal stresses as well as high magnetostriction (the saturation magnetostriction constant is $\lambda_S=30\cdot10^{-6}$). A kind of composition which exhibits very stable properties is of the form $(Fe, Co, Ni)_x\ Si_y\ B_z$, where the transition metal content is in the range 70-80% and the Si and B contents are in the range 10-20%. The internal stresses, frozen-in during the fabrication process, couple with the magnetostriction constant, λ_S, giving rise to distributed magnetoelastic anisotropy which play a decisive role in determining the domain magnetisation directions. The existence of two main regions is accepted for wires with large and positive λ_S: a central core where the magnetization lies in the axial direction and a shell with domains whose magnetization is radially oriented. The volume ratio of the core to the whole wire was estimated to be about 0.5 [2,3].

Several interesting effects arise from their complex internal structure, among which the Large Barkhausen Effect (LBE) is the most important [4]. According to it, sharp voltage pulses appear at the ends of a coil wound around a MAW, when this is subject to a low alternating field axially oriented with respect to the wire axis. This is due to a mechanism of magnetic reversal into the inner core [2], which starts from the depinning of the closure domain walls in one end of the wire, followed by the propagation of a large wall to the other end. So, a sudden 180º reversal occurs in the main inner core domain, thus inducing the sharp pulses in the coil. The wall propagation velocity directly depends on the magnetic field intensity and on the wall mobility. The Matteucci effect (ME) [4] is a variant of LBE, being a consequence of the helical magnetic anisotropy induced in the wire core by a mechanical torsion or by various thermal treatments applied to the wire in certain conditions. This effect consists of sharp voltage pulses generation at the ends of a torsioned MAW magnetized with an alternate magnetic field oriented parallel to its axis. The amplitude of these pulses depends on several parameters such as: torsional degree, magnetic field intensity and frequency, wire length and diameter, alloy composition, axial tensile stress and temperature.

These effects, combined with other magnetic, electrical and mechanical properties made the MAWs very attractive in construction of a new generation of sensors spread in a large area of application such as automobile and robot industries, power motor drives, electric power systems, industrial and laboratory instrumentation [5,6].

In the paper we present a novel idea based on a special arrangement of a MAW for a sensor designed to measure the alternative current flowing through a conductor.

II. Experimental set-up

The main idea in our approach is to measure the pulses amplitude across the ends of a torsioned MAW, created by a circular magnetic field produced by a current flowing through a conductor, using the ME. In order to obtain the ME, the wire must be subject to an axial alternate magnetic field. This is the field having circumferential orientation created around a conductor through which an alternative current passes. Our wire is wound around a cylindrical conductor, thus creating the axial orientation with respect to the field and, in the same time, having the possibility of modifying its length according to the study needs (fig. 1). In the winding process of the coil, the MAW is torsioned a number of times and then it is stiffed at its ends. We used in our experiments high magnetostrictive amorphous wires (λ_s = $30 \cdot 10^{-6}$, where λ_s is the saturation magnetostriction), having the nominal composition $Fe_{77.5}Si_{7.5}B_{15}$. The

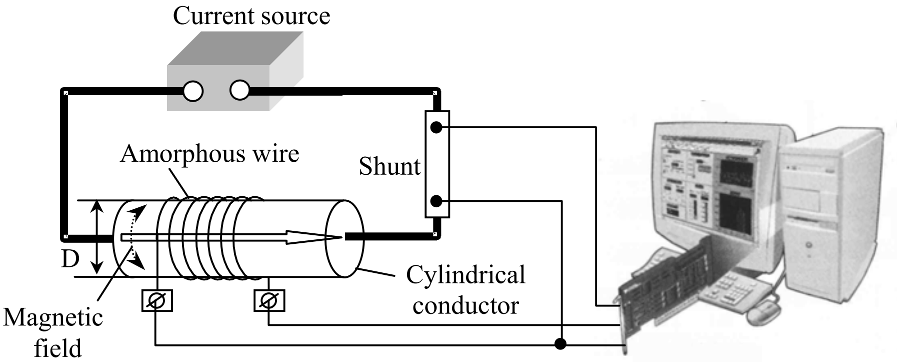

Figure 1. Experimental set-up for the study of sensor characteristics

average diameter of the wire is 125 µm. It was generously supplied by the Unitika Corporation. The cylindrical conductor is supplied by a current source having the possibility of fixing the current value every ampere. In this experimental set-up, the Matteucci pulses picked-up from the ends of the wire are acquired using a National Instruments' PCI-6111 12 bits data acquisition board with a maximum sampling rate of 5 Msamples/s. It allows better than 0,1 % FS accuracy in the peak detection process. The electrical shunt is a laboratory one, having 0,1 % accuracy.

Fig. 2 shows the qualitative shape of the detected Matteucci pulses compared with the current shape acquired from the electric shunt. In this example, the waveforms were recorded for the following parameters: wire length l_{MAW} = 30 cm, conductor diameter D = 10 mm, current value I = 30 A, torsional degree ζ = 20π rad/m. The wire was in the as-cast form and the helical anisotropy was obtained by mechanical torsion. In such conditions, the amplitude of the pulse was about 150 mV and the width 45 µs. In the next section, we shall study the behaviour of the device under the influence of several parameters like: cylindrical conductor diameter (D), wire length (l_{MAW}), torsional degree (ζ) and current frequency (f). The influence of the temperature θ will be also discussed. The study was performed with the aim of observing the behaviour of the sensor in terms of sensitivity, accuracy, stability and linearity.

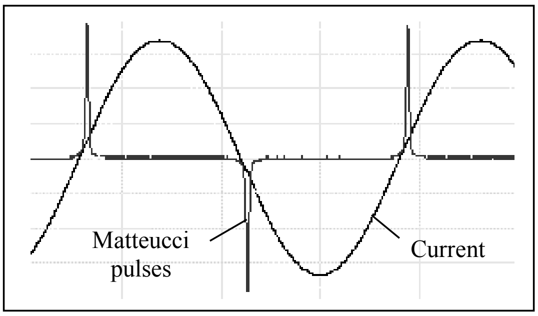

Figure 2. Waveform of Matteucci pulses for l_{MAW} = 30 cm, D = 10 mm, I = 30 A, ζ = 20π rad/m

III. Results

A. Experimental conditions

In order to trace the sensor characteristics, the peak values of the Matteucci pulses were measured taking the currents flowing through the cylindrical conductor as variable. The peak value was calculated by averaging the maximums of 16 successive pulse acquisitions using the DAQ card. There were performed the following sets of measurements: two values of the conductor diameter (10 mm and 6 mm), three values of the wire length (5 cm, 30 cm and 45 cm), and three values for the wire torsion (5π, 15π, and 25π rad/m). The current shape was sinusoidal, with a Total Harmonic Distortion (THD) of 0.2 %, and squarewave. Its frequency span ranged between 50 Hz and 1 kHz. The experiments were made at two ambient temperature values: 20 ºC and 70 ºC. The second temperature was obtained by introducing the sensor inside an electric oven whose temperature control accuracy was better than ± 2%. The wires were tested in the as-cast form.

B. Influence of the cylindrical conductor diameter

In figure 3, the graphical dependence of the pulses peak value (PPV) with respect to the variable current *I* for two cylindrical conductor diameters (D = 10 mm and D = 6 mm) and for fixed l_{MAW}, ζ, f and θ was traced. As it can be observed from this figure, as the diameter decreases, the sensor sensitivity increases along with important linearity decay. It can be explained by the larger magnetic field dispersion around the conductor and by non-uniform field distribution inside the wound. A better sensitivity is expected as the diameter becomes even smaller, but some technical difficulties could arise with this respect, as the wire, which is rather breakable, could crack in the winding process.

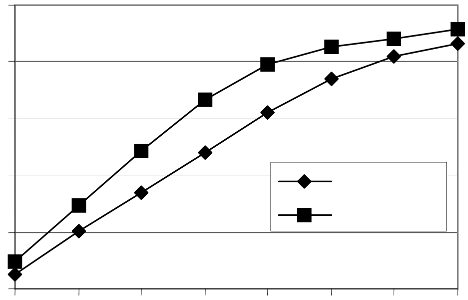

Figure 3. Sensor characteristic for $\zeta = 20\pi$ rad/m, l_{MAW} = 30 cm, f = 50 Hz, θ = 20 ºC

C. Influence of the current frequency

The sensor was tested considering two shapes of the current flowing through the circuit: sinusoidal and squarewave. The sensitivity of the device with respect to the sinusoidal current frequency, when the frequency varies between 50 Hz and 1 kHz is shown in figure 4. According to this figure, the sensor sensitivity increases with frequency because the greater frequency is, the more sudden is the field passing across the wire critical field H^* and hence the faster is the flux variance in this region, finally conducting to sharp pulses with higher amplitude. This phenomenon occurs till a certain frequency (about 700 Hz in these experiment conditions), when the internal losses into the wire cause diminishing the magnetoelastic energy, this contributing to pulse amplitude fall along with pulse width enlarging. The sensitivity of the device with frequency can be seen as a drawback which reduces its accuracy when high-distorted currents have to be measured.

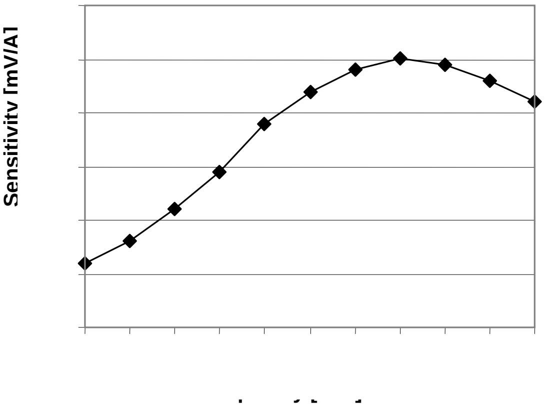

Figure 4. Sensor sensitivity vs. frequency for sinusoidal current ($\zeta = 20\pi$ rad/m, l_{MAW} = 30 cm, D = 10 mm, θ = 20 ºC)

When the current goes to a squared shape, the things become completely different. In this case, the passing speed of the magnetic field across H^* is higher than in the sinusoidal case (this is due to the bandwidth of squarewave signals which is theoretically infinite), and the sensitivity goes also higher. The figure 5, which presents the same characteristic as in figure 4, but traced for squared currents, demonstrates this supposition. Moreover, the sensitivity remains practical constant up to 600 Hz. Above this value, the sensitivity dramatically decreases, probably caused by two aspects: i) the loss of magnetoelastic energy with frequency inside the wire and ii) the low-pass filter effect of the coil.

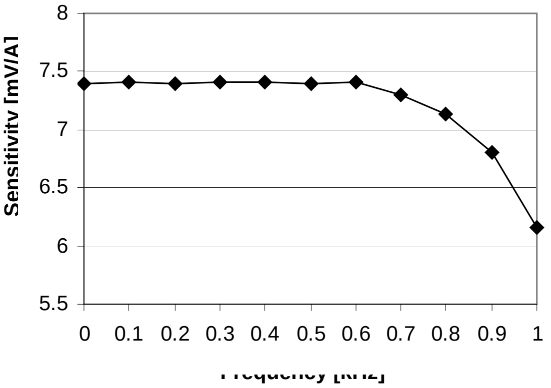

Figure 5. Sensor sensitivity vs. frequency for squarewave current ($\zeta = 20\pi$ rad/m, l_{MAW} = 30 cm, D = 10 mm, θ = 20 ºC)

D. Influence of the wire length

The wire length becomes important when it is smaller than a critical value, which usually depends on the wire diameter. For example, corresponding to the wire diameter of 125 μm, the critical length is approximately 7 cm. For wires whose length drops under 7 cm, strong reduction of the sensitivity and some output instability are expected.

In order to verify the above suppositions, we have tested three amorphous magnetic wire coils, each having 10 mm in diameter, but with different length of the wire: 5 cm, 30 cm and 45 cm. The experiments revealed in the 5 mm case an over three times sensitivity decay than that obtained with the 30 cm long wire. The signal instability was also measured, falling down to ± 1.25 σ of the average value, compared to ± 0.23 σ, found in the case of 10 mm.

This phenomenon can be explained as following: the usual theoretical model of an infinite MAW is represented by an inner core having axially oriented magnetic domains and an outer shell having the domains oriented radial, as stated in the first section. In reality, when the wire length is finite, conical closure domains exist at the ends of the wire, whose depths are related to the wire diameter. In the reversal process, the closure domain walls of one end propagate to the other end of the wire, producing a sudden 180º reversal in the magnetic domain orientation. When the wire becomes too short, the closure domains join and the reversal does not occur anymore. In this case, the Matteucci pulses split into two smaller parts, their width growth very much and they become unstable.

There are not significant differences between the performances of the device obtain in the case of 30 cm and 45 cm. It can therefore establish an optimal length a little above the critical length (10 cm for instance) for which the sensor performances are not affected.

E. Temperature influence

The temperature affects the internal stress distribution inside the MAW, contributing to material relaxation and diminishing the Barkhausen jumps. We have repeated the experiments at 20 ºC and 70 ºC. The characteristics PPV(I) presented in figure 3 for 20 ºC became more linear for 70 ºC, but the sensitivity decreased with 7 %. We have found the temperature coefficient of the sensor sensitivity as 0,15 %/ºC. The temperature influence was proved to be more significant for small degrees of the wire torsion, when the remanent internal stresses frozen-in during the fabrication process are preponderant.

F. Influence of the torsional degree of the wire

The wire torsion induces into the inner core structure a helical magnetic anisotropy whose tangential direction contributes to Matteucci effect. The more torsioned the wire is, the more accentuated the effect become. Qualitatively, as the torsion grows, the pulses amplitude also grows. We have not traced a significant characteristic for observing the linearity of this dependence, but we observed saturation in the PPV increase with the torsional degree beginning with 20π rad/m.

IV. Conclusions

The experimental model of the current sensor proposed in the paper reveals, at a glance, the following features: low price and constructive simplicity, robustness, good linearity and accuracy, low dependence of temperature. The study was made merely for drawing qualitative conclusions and to test the viability of the model for putting in evidence its possible advantages and drawbacks. Our team is now developing the prototype of the current transducer including also the signal conditioning circuitry. Based on the prototype, quantitative results will be reported in the next future.

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