Modeling the GMI Effect in Amorphous Wires by Means of Electric Equivalent Circuits

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Abstract- An electric equivalent circuit for Co-based amorphous wires is studied in this paper. Its structure is based on some simple assumptions related to domain structure and the coupling between these domains but also on the presence of the specific relaxation mechanisms. Model parameters were identified using impedance spectroscopy techniques.

I. Introduction

Being one of the most promising magnetotransport phenomenons, the giant magnetoimpedance effect in amorphous wires and ribbons consist in a strong dependence of the sample impedance on an external magnetic field. A typical magnetic response of an AC voltage across a small sized Co-based sample is about 25%/Oe and 10%/Oe in the case of low frequency magneto-inductance and high frequency magnetoimpedance respectively [1]. This sensitivity explains the recent considerable interest for the applications in magnetic sensors [2], [3]. The electromagnetic origin of the MI effect has been attributed to the combination of the skin effect and the field dependence of the circumferential magnetic permeability associated with the circular motion of magnetic moments. Using impedance spectroscopy technique, this paper is investigating the influences of the external magnetic field on the parameters of a simple equivalent electric circuit proposed in [4].

II. Theoretical considerations

The equivalent circuit methodology consist in modelling the material's frequency response by means of an electric circuit with ideal passive components, usually associated with physical parameters of the material. An equivalent circuit founded to approximate with good accuracy the wire frequency behaviour has a series R_1 L_1 circuit connected to a parallel R_2 L_2 arrangement. R_1 accounts for the DC resistance, L_1 is related to the circumferential rotational permeability of the wire, L_2 and R_2 are associated with circumferential domain wall permeability and wall damping, respectively [4], [5]. For the proposed topology the expression of the complex impedance is:

$$Z^* = \left[R_1 + \frac{R_2 L_2^2}{R_2^2 + \omega^2 L_2^2}\omega^2\right] + j\omega\left[L_1 + \frac{R_2^2 L_2}{R_2^2 + \omega^2 L_2^2}\right] = R_s + j\omega L_s \tag{1}$$

Some approximations in low and high frequency have to be done in order to determine the values of the circuit elements. As we intend to evaluate the model behaviour for frequencies between 100 Hz and 300 kHz, and based on some previously reported results, the following equations can be used:

$$\begin{aligned} \omega = 100Hz &: Z^* = R_1 + j\omega(L_1 + L_2) \\ \omega = 300kHz &: Z^* = (R_1 + R_2) + j\omega L_1 \end{aligned} \tag{2}$$

The results obtained in model identification are further presented in this paper.

III. Experimental results

This paragraph is detailing both the experimental setup used to collect data and the results expressed in terms of models parameter variations over the analysed frequency spectrum for different DC currents and consequently, different values of axial magnetic field intensity.

A. Experimental setup

We used as-quenched amorphous wire of nominal composition $(Co_{94}Fe_6)_{72.5}B_{15}Si_{12.5}$, 125 μm diameter and 2,2 cm. length, prepared by the in-water-rotating technique. The sample was placed in a small PVC tube positioned inside a solenoidal coil , with the tube axis parallel to the axis of the solenoid. The

ensemble was mounted in a special sample holder with firm electrical contacts and impedance measurements were carried out by means of a system build with a Novocontrol analyser (Alpha type) controlled by a PC. All data were measured at room temperature with wire axis established at 90 degrees in respect with earth's field. The AC current through the amorphous wire was kept constant (10 mA) and the DC current flowing through the solenoid was varied in the range 0–1 A. For each of the DC current values complete spectroscopic measurements were done at frequencies from 100Hz to 300 kHz.
A schematic representation of the experimental setup is presented in Figure 1

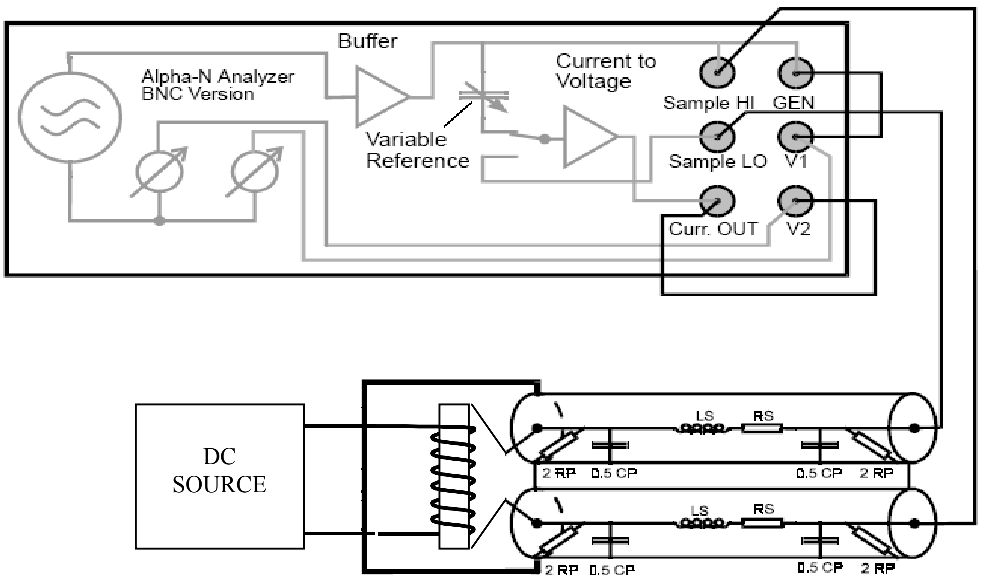

Figure 1. Schematic representation of the experimental setup

We used the recommended configuration [6] special attention being paid to the impedance compensation of the line from the analyser impedance inputs to the sample. The inductivities L_S and resistors R_S of the BNC lines contributing as a additional serial impedance to the measured one were taken into account using load short calibration and line compensation procedures. Because of the low value of the measured impedance, the R_P resistor has been considered large enough to be neglected. Also the capacitances C_P are requesting no compensation since they are eliminated by the virtual ground technique of the current input amplifier.

B. Results and discussions

Measured data were processed in order to emphasis the components of the complex impedance of the amorphous wire. Figure 2. shows the frequency dependencies of the equivalent serial inductance L_S and phase angle.

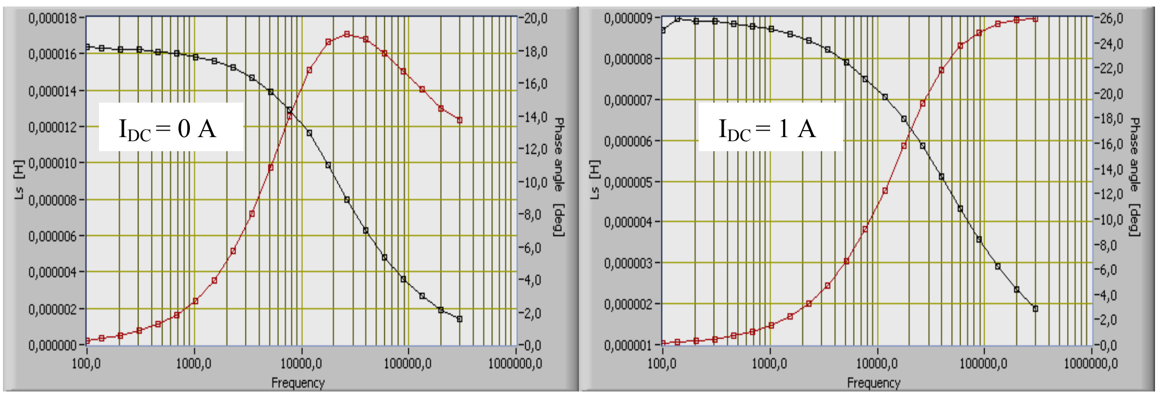

Figure 2. Frequency dependencies of the equivalent serial inductance and phase angle

It can be observed that the frequency behaviour show the features previously reported in other papers [4], [7], a relaxation domain being observed for both values of DC current flowing through the solenoidal coil. The equivalent serial inductance L_S usually associated with domain wall permeability decreases at high frequencies and the phase angle reveals a maximum at the relaxation frequency. A better illustration of the influences induced by the axial field over this specific behaviour is presented in Figure 3.

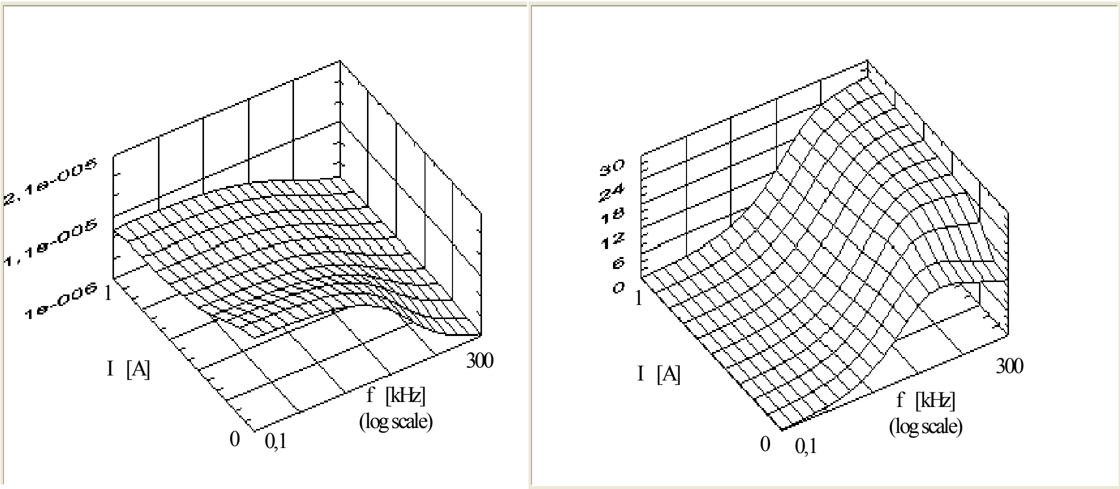

Figure 3. Equivalent serial inductance L_S and phase angle dependencies on frequency and DC current

There are represented the three dimensional surfaces of dependence for equivalent serial inductance and phase angle on frequency and I_{DC}.

Three important observations can be done:

- The general behaviour remains the same and therefore the axial field is to be considered only as an influence factor;
- For frequencies up to 20 kHz, where the skin effect is negligible, the serial inductance shows a decrease as the value of the DC current goes from 0 to 1A. This performance can be explained by the saturation effect occurring in high axial fields;
- The relaxation frequency is moving at higher frequencies (28 kHz for I_{DC}=0 and 300 kHz for I_{DC}=1A). This is essentially related to skin effects, the penetration depth being dependent on permeability which is lowered as the I_{DC} goes to 1A and we are approaching the saturation domain.

Basically there are two mechanism involved in this specific behaviour, the saturation effect and the skin effect. The shape of the characteristics is determined by their relative magnitude. In order to illustrate this, in Figure 4. are represented the dependencies of equivalent serial inductance L_S on I_{DC} for two frequency values, 100 Hz and 300 kHz. It is clear that once the skin effect is cancelled by the axial field (equally at high I_{DC}) the inductance is lowered by the increasing axial field, whatever frequency is considered. The saturation effect is stronger than the skin one. For low I_{DC} values and high frequency, the skin effect becomes important.

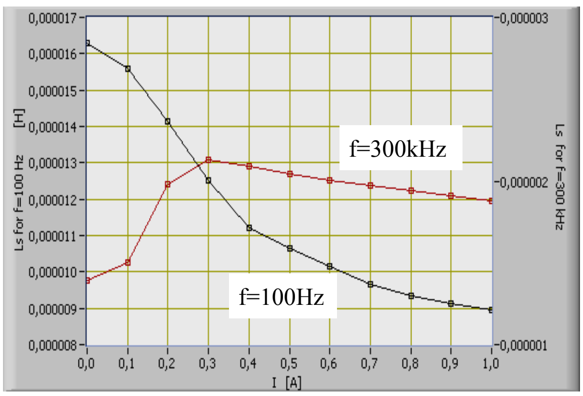

Figure 4. Equivalent serial inductance dependence on DC current flowing through the solenoid

Measured data have been processed according to (2) to identify the model parameters. The results are presented in Table 1.

Table 1. Model parameters for different DC current values

I [A]	0,000	0,100	0,200	0,300	0,400	0,500	0,600	0,700	0,800	0,900	1,000
L_1 [μH]	1,391	1,502	1,983	2,132	2,093	2,046	2,006	1,974	1,942	1,910	1,880
R_1 [Ω]	2,148	2,147	2,147	2,147	2,146	2,146	2,146	2,146	2,146	2,146	2,146
L_2 [μH]	14,91	14,08	12,17	10,39	9,135	8,600	8,136	7,672	7,387	7,228	7,085
R_2 [Ω]	8,567	8,579	8,026	6,990	6,482	6,148	5,853	5,623	5,436	5,295	5,152

The serial resistance R_1, computed from complex impedance's real part measured at 100Hz is in good accordance with previously reported results [4], [7]. It comprises not only the DC resistance of the amorphous wire but also the total contact resistance between the wire and the sample holder. As expected, low values were obtained for L_1, inductance associated with the rotational permeability of the wire. The parallel inductance L_2 is decreasing for large axial fields. Concurrently, the decreasing parallel resistance R_2 is confirming the strong coupling between the two mechanism discussed earlier in this paragraph.

IV. Conclusions

The magnetic behaviour of amorphous wires in terms of frequency dependence can be analysed using equivalent circuit methodology. Experimentally collected data reveal that the simple circuit topology proposed in [4] can be successfully used but model parameters must be adjusted in accordance with the relative magnitude between saturation and skin effects.

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