Instrumentation Set-up for Characterisation of the Sensors Based on Amorphous Wires

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Abstract- High sensitivity, quick response, small size, non-contact sense and low-power requirement, make amorphous wires attractive for sensors and micro-sensors realization. Negative factors accompany magneto-impedance sensors based on amorphous wires. They must be compensated for an efficient use of the devices and therefore the behavior of the sensing element must be well characterized. The paper highlights most important characteristics of amorphous wires and proposes an instrumentation set-up based on vector-voltmeter analyzer useful for carrying out their measurement.

I. Introduction

It was found that the amorphous ferromagnetic wires such as FeCoSiB and CoSiB exhibit remarkable changes of their impedance beyond 10 MHz when an external magnetic field is applied [1]. This phenomenon has been called Magneto Impedance (MI) effect, being used for building highly sensitive magnetic field sensors. However, parasitical phenomena accompany the MI effect. Non-linear transfer characteristic, low saturation field, high level of noise and of pick-up signals, earth magnetic field, temperature, stress, torsion are the noticeable ones. For many of them, the cancellation of their effect can be carried out with a good design of the sensing element, but this requires a thorough characterization of the sensors based on amorphous wires.

II. Magneto –Impedance concept

When an external magnetic field is applied, the impedance Z exhibited by an amorphous wire may be expressed as follow [2]:

$$Z = R_{dc} + j\omega L \text{ without skin effect or } Z = \left(a/\sqrt{2\rho}\right)R_{dc}(1+j)\sqrt{\omega \cdot \mu(H_{ex})} \text{ for strong skin effect} \qquad (1)$$

where R_{dc} is the dc resistance, ρ is the resistivity, ω is the angular frequency of the ac current, and μ the circumferential maximum differential permeability. The inductive component of the impedance has a dependence on an external magnetic field H_{ex} through skin effect. The range of the maximum sensitivity is shifted towards 100 MHz for very thick films. The research on the MI effect in thin wires consists in determining the correlation of the magnetic properties to the impedance responses and in realizing a measurement set-up with which measurements of complex quantities will be efficiently and accurately done. Due to high parasitic factors, MI sensors need a differential configuration, an electric dc bias or a magnetic field bias, a pulse shape interrogation signal and peak or synchronous detection. In order to cancel the temperature dependence of the detecting element characteristics and to operate with high resolution, a full bridge configuration consisting of two detecting elements and two resistances was required [3]. The bridge output ac-voltage, caused by the unbalance, is fed to a synchronous rectifier circuit that extracts only the inductance component from the total impedance of the detecting element. Consequently, the output from the synchronous rectifier circuit provides the detecting signal corresponding to the external magnetic field. The electrical schemes of Fig. 1 show how the instrumentation set-up for MI measurement in amorphous wires and for detection of the related effects was implemented in our approach. An alternating current is supplied with dc-biased to the amorphous wire, whereby a voltage is produced between its P1-P2 leads, Fig. 1.a). As the voltage amplitude varies asymmetrically with the externally applied magnetic field, a pair of such MI elements is needed to obtain a field sensor having a linear characteristic.

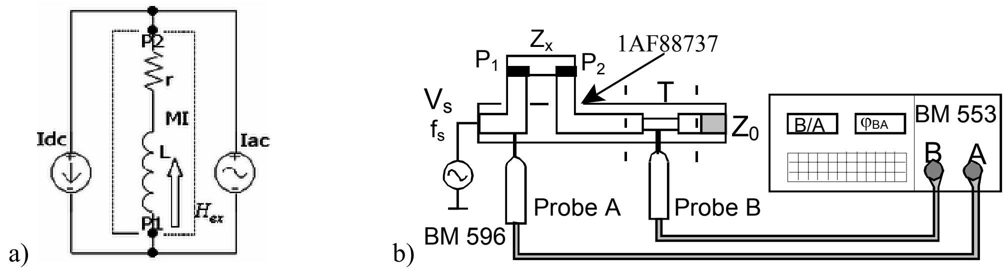

Figure 1. Magneto impedance (MI) simplified test circuit

III. Instrumentation set-up based on Vector Analyzer

We propose an investigation method based on Vector Network Analyzer also used by other researchers. In [4] for example, a high performance instrumentation set-up based on Network Analyzer is described, suitable both for MI measurements versus frequency and for MI measurements versus field intensity. The explored frequency range is from 10 MHz to 500 MHz, while the external magnetic field is between -15 mT and 15 mT. An alternative method is also presented in [5] for evaluating the magnetic response of soft magnetic systems from 1 MHz to 6 GHz.

Our system is designed for measurements of MI-sensors from 1 MHz to 100 MHz. In this set-up, the Network Analyzer works as vector voltmeter. The sensor under test is connected through an adapter having several features, e.g., a floating input, distinct ways for dc and RF-currents, independent current settling through sensor arm and asymmetric output. Fig. 2 shows details of the instrumentation set-up.

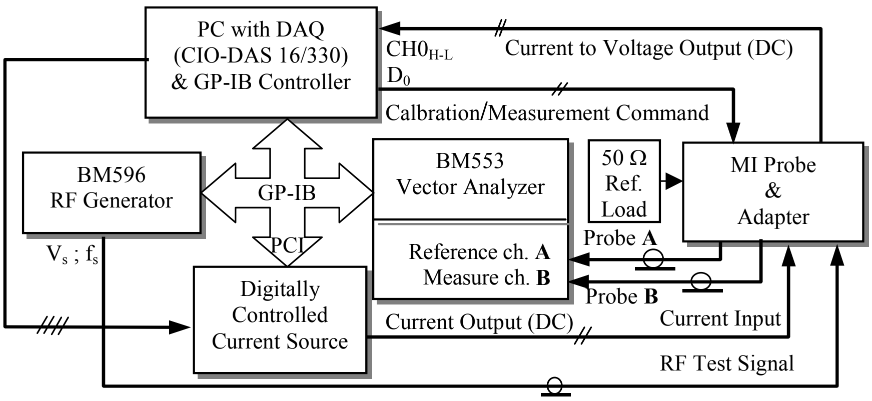

Figure 2. Instrumentation set-up for MI measurements

The PC is endowed with some necessary internal extensions such as a data acquisition board (DAQ), a GP-IB controller and a digitally controlled current source (DCCS). Along the other GP-IB instruments, RF Generator and Vector Analyzer, it implements a virtual instrument under Visual Basic program. Since an executable program was obtained, the use of this virtual instrument becomes simple, easy and convenient. The output of the DCCS together with a differential analog input DAQ channel and the coil for H_{ex} generating, allow to be performed magnetic field dependent measurements for the MI. The Vector Analyzer, having two identical input channels measuring in a very large frequency bandwidth and dynamic range, simultaneous measures two voltages and their phase angle. One of the two Vector Analyzer channels is utilized to measure the RF current, whilst the other one is used to assess the MI voltage drop. From the Vector Voltmeter working equation in a measuring configuration like that in Fig. 1.b):

$$\frac{\underline{V}_A - \underline{V}_B}{\underline{Z}_x} = \frac{\underline{V}_B}{\underline{Z}_0} \quad \Rightarrow \underline{Z}_x(\underline{Z}_0 = R_0) = R_x + j\,X_x = R_0\left(\frac{\cos\varphi_{BA}}{V_B/V_A} - 1\right) - j\,R_0\frac{\sin\varphi_{BA}}{V_B/V_A} \qquad (2)$$

will result the components of the MI:

$$R = R_0\left(\frac{\cos\varphi_{BA}}{V_B/V_A} - 1\right)\ \text{(a)};\quad L = R_0\frac{\sin\varphi_{BA}}{V_B/V_A}\cdot\frac{1}{2\pi f}\ \text{(b)} \qquad (3)$$

These two last equations will also allow computing of the sensitivity coefficients for uncertainty budged estimation [6]. Because there are some differences between the two channels of the Vector Analyzer, a calibration measurement step is needed for every measured point. A reed relay was used for short-circuiting the MI. The command for this relay is done with digital out of the DAQ, line D_0. The obtained value for the voltage ratio, V_B/V_A, and for the phase angle, φ_{BA}, are memorized and then used for performing relative measurements. In this manner, the non-balance between channels and some parasitic components is rejected.

IV. Practical measurements and results

The measurements were performed on a sensor designed for non-contact current measurement. It is based on a non-magnetostrictive magnetic amorphous wire provided by Unitika Ltd. It was obtained by "in-rotating-water quenching-method", having the composition $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{15}$ and the dimensions of 120 μm diameter and 20 mm length. The amorphous wire was axially mounted inside the electric current coil. This coil has five turns and a diameter smaller than its 6.3 mm length. After converting to voltage, the current who creates the magnetic field is measured with a differential input channel of DAQ. Data packages are carried out in two different ways: at constant RF test current by varying the frequency of the test signal, and at constant RF test frequency by varying magnetic field intensity through the current. Every data set is obtained by digitally filtering for a good rejection of the perturbations. Moreover, ten consecutive filtered measurements are performed for every measured point. The mean of these values represents, in this manner, a good result and allows associated uncertainty computation for wanted quantities: R, L and Z, respectively $u(R)$, $u(L)$ and $u(Z)$. Two representative cases selected in the above-mentioned situations are illustrated in the next tables. Associated uncertainties for wanted quantities are computed for coverage factor k = 2. These uncertainties include those resulting from voltage modulus ratio and phase, $u(V_B/V_A)$ and $u(\varphi_{BA})$ respectively, like type A uncertainties, and those resulting from $1/N$ terms like type B uncertainties [6].

Table 1. *Results at 1 mA and 1 MHz RF test signal for various magnetic field strengths, H*

I [A]	0	0.1	0.2	0.4	0.8	1.6	3.2	6.4	Obs.
H [Oe]	0	1	2	4	8	16	32	64	
V_B/V_A	0.9201	0.9368	0.9343	0.8589	0.8297	0.846	0.8626	0.8715	
$u(V_B/V_A)$	0.0057	0.0107	0.0070	0.0126	0.0070	0.0147	0.0120	0.0120	k=1
φ_{BA} [o]	-1.89	-1.06	-2.48	-4.39	-5.9	-5.72	-5.03	-3.62	
$u(\varphi_{BA})$ [rad]	0.0011	0.0022	0.0012	0.0025	0.0016	0.0029	0.0020	0.0028	k=1
R [Ω]	4.31	3.36	3.47	8.04	9.94	8.81	7.74	7.26	
$u(R)$ [Ω]	0.668	1.216	0.799	1.710	1.009	2.046	1.603	1.576	k=2
L [μH]	0.29	0.16	0.37	0.71	0.99	0.94	0.81	0.58	
$u(L)$ [μH]	0.020	0.037	0.021	0.051	0.035	0.063	0.042	0.053	k=2
Z [Ω]	4.67	3.51	4.17	9.20	11.72	10.60	9.26	8.11	
$u(Z)$ [Ω]	0.619	1.169	0.668	1.503	0.864	1.715	1.348	1.418	k=2

Table 2. *Results at 1 mA RF test signal, without magnetic field*

f [MHz]	1	2	4	8	16	32	64	128	Obs.
V_B/V_A	0.920	0.917	0.910	0.901	0.888	0.872	0.847	0.817	
$u(V_B/V_A)$	0.0057	0.0099	0.0191	0.0156	0.0065	0.0072	0.0057	0.0072	k=1
φ_{BA} [o]	-1.89	-1.780	-1.870	-2.400	-2.700	-3.130	-3.620	-3.290	
$u(\varphi_{BA})$ [rad]	0.0011	0.0018	0.0040	0.0033	0.0004	0.0013	0.0012	0.0010	k=1
R [Ω]	4.31	4.53	4.95	5.46	6.26	7.28	8.91	11.07	
$u(R)$ [Ω]	0.668	1.175	2.313	1.925	0.827	0.949	0.788	1.079	K=2
L [μH]	0.285	0.135	0.071	0.046	0.026	0.016	0.009	0.004	
$u(L)$ [μH]	0.0196	0.0156	0.0177	0.0074	0.0006	0.0008	0.0004	0.0002	K=2
Z [Ω]	4.67	4.84	5.26	5.93	6.80	7.93	9.66	11.61	
$u(Z)$ [Ω]	0.619	1.103	2.179	1.777	0.762	0.873	0.729	1.029	K=2

The dependence of the measured quantities on frequency, shown in Fig. 3 a) and b), reveals that they are almost independent of RF test current, this being between 1 and 8 mA. The associated error bars, represented for 1-mA curves, prove this supposition. Although the independence of the test RF current intensity was proved, a voltage closely of 50 mV on R_0 = 50 Ω reference load was permanently adjusted, voltage measured with Vector Analyzer B probe. This means a RF current of 1 mA through MI at all test frequencies. The next pair of graphs represents the MI components variation under magnetic field influence for all test frequencies. The magnetic field strength is directly related from the current. Its values for the sensor coil, expressed in Oe in Table 1, are ten times greater then the values of the current. For the highest MI components curves, the error bars depict the accuracy of the results. Lower values of the inductance at upper limit of the frequency may be the result of the capacitive reactance, not yet corrected in this stage of the experiment. This new measurement step supposes other two data sets taken with amorphous wire disconnected successively from mounting point P1 respectively P2, followed by a similar procedure for data computation. The expected result is an increasing of the inductance value and of the afferent uncertainty.

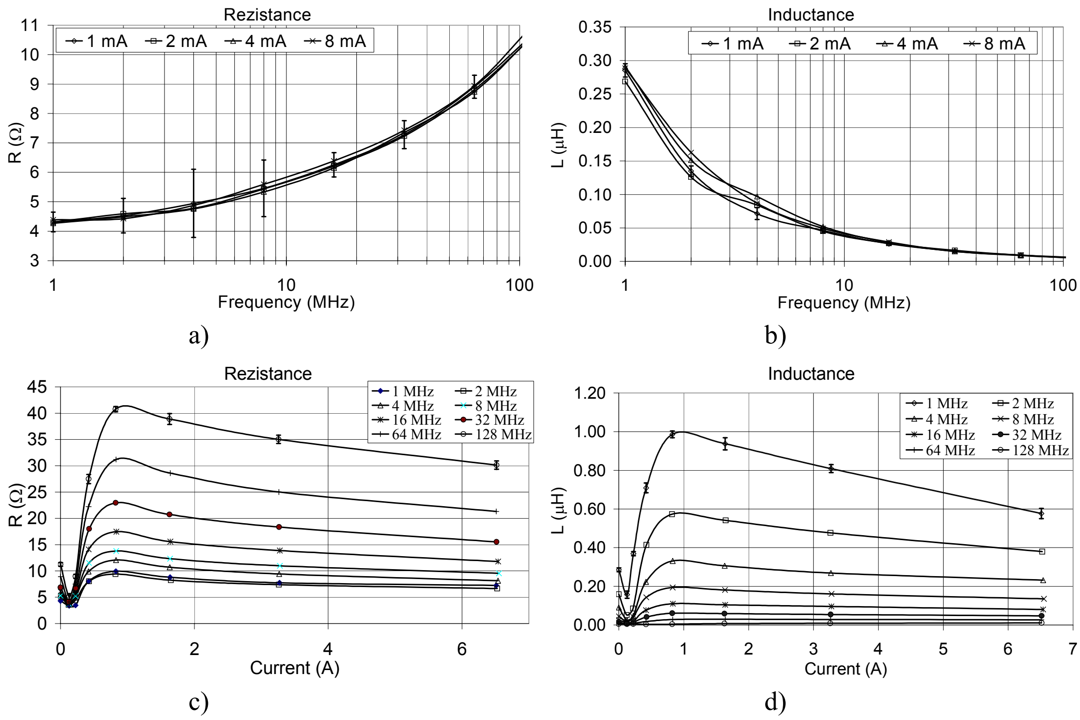

Figure 3. Diagrams of the computed results: a) Rezistance *vs.* frequency; b) Inductance *vs.* frequency; c) Rezistance *vs.* current; d) Inductance *vs.* current.

V. Conclusions

A Vector Analyzer is used as the heart of an automated measurement system dedicated to measure properties of the amorphous wires. The result provided by this system is an efficient characterization of the sensing component through accepted quality parameters. Measurements and related uncertainties show the great possibilities of the virtual instrument build around of the Vector Analyzer. With a refinement of the presented set-up, it is possible to analyze higher frequencies with accuracy improvements at the real sensor working frequency.

Acknowledgments

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