An Automatic Compensation of External Disturbances for a High Sensitive Magnetic Sensor

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Abstract-The paper deals with an automatic method designed to compensate the external magnetic disturbances acting upon a high sensitive magnetic sensor mounted in an ac bridge configuration, whose influences upon the output voltage are comparable to those produced by the quantity to be measured. The method is particularly applied for sensors whose characteristic is non-linear and which cannot be compensated using the classical method of supplying the bridge with a constant current source.

I. Introduction

Magnetic sensors are widely utilized in industrial processes for measuring various quantities by intermediate of magnetic field, namely: current, speed, proximity, distance, position, vibrations, force, speed, non-destructive testing, concentration of ions in water, etc. [1-5]. Some effects on the basis of which the energy of the quantity to be measured is converted into an electrical one through magnetic parameters are: Hall effect, direct and inverse Wiedemann effect, Matteucci effect, magnetoresistivity, electromagnetic induction, magnetostrictivity, magnetoimpedance and magnetoinductance, stressimpedance etc. We can remind here the classical current transducers based on the Hall effect, field, pressure, current transducers based on magnetoresistance sensitive elements, displacement, proximity or speed transducer based on electromagnetic induction or, more recent, current, force, angle, displacement and tilt transducers based on the Giant Magnetoimpedance (GMI) effect occurring in magnetic amorphous wires [6-10]. Fundamentally, the operation principle of GMI sensors is based on parametric modification of the sensor impedance that is subjected to an external field or mechanical stress. In many cases, the unwanted influences might have larger effect upon the sensor impedance variation than that of the quantity to be measured itself. Usually, the first signal processing circuit employed for converting the impedance variation into an electrical signal (out of sensors providing directly an output voltage) is the ac bridge working in unbalancing regime. The unbalance voltage provided by the bridge is generally non-linearly related to the measurand but also to the inherent external influences. Unlike the Wheatstone bridge, in which the external unwanted influences are cancelled by supplying the bridge with a constant current [11], in the case of ac bridges, the non-linear dependences of both the sensor module and phase impedance with the input quantity drastically decay the method's efficiency, even if the bridge comprises a pair of "witness sensors" employed for tracking the disturbance variations. Several other methods involving either passive circuits or more complex digital methods of compensation have been reported [12-15]. In the paper we propose a new method for compensating the large influences of terrestrial magnetic field upon a high sensitive GMI sensor mounted in an ac bridge working as primary signal conditioning block for a 2-axis tilt transducer. We do not deal in the paper with the tilt sensor construction and performance itself, but only with the compensation technique, which was the most troubling problem encountered in this approach.

II. Short presentation of the problem

A. About magnetic amorphous wires and their magnetoimpedance effect

Among all magnetic sensors, maybe the most sensitive ones are the magnetic amorphous wires (MAW). Basically, these devices are thin wires having a diameter of maximum 120 μm, made of metallic alloys mixed with Si and B in different proportions [16]. Owing to their special structure sketched as an inner core having a single magnetic domain aligned along the wire axis, surrounded by an outer shell exhibiting circular domains, the GMI effect occurs when a MAW is subjected to an ac current i_{ac} of a certain frequency flowing through it [17-19]. GMI consists in sudden variations of the wire impedance caused by particular influences, namely external magnetic fields or mechanical axial or circular stresses. For frequencies above 1 MHz, the sensitivity of

such device with respect to the above quantities, relative to the lowest value in the nominal range, exceeds sometimes 120 %. This is a very high value comparing to other magnetic devices, for which the sensitivity does not exceed in some cases 20 %. This sensitivity confers to the transducer a very good signal to noise ratio and reproducibility, but, on the other hand, it is prone to reduce significantly the accuracy when such a quantity is seen as a disturbance factor. For instance, if $Z(H,F)$ is a function of H – axial magnetic field and Γ – axial tensile stress, then:

$$\left.\frac{\Delta Z}{Z_0}\right|_{H,\Gamma} \times 100 > 120\ \% \tag{1}$$

where ΔZ is the impedance span relative to a certain variation of H or Γ and Z_0 is the reference, usually taken in absence of any external influence.

B. Problem encountered

We developed in the laboratory the functional model of a tilt sensor whose schematic principle of operation is shown in figure 1. The sensor consists of a body (B) of about 50 g which is suspended inside a fixed case by means of four identical orthogonally mounted magnetic amorphous wires, referred here as active wires Aw1 to Aw4 and situated in the same γ plan. The weight of the body, which is mounted in the centre of the system, acts on the four wires with axial tensile stresses produced by the forces Γ_1 to Γ_4 which, in turn, depend on the two tilt angles, pitch (α) and roll (β). According to GMI effect, the impedances of the four active wires will also depend on the forces Γ_1 to Γ_4 and hence on the tilt angles [20]. Knowing the relationship which links the sensors impedance values to the tilt angles by intermediate of stresses Γ, one can compute finally the angles α and β. The major problem encountered in our approach is the large influence of the terrestrial magnetic field and of other unwanted fields upon the active sensors Aw1 to Aw4. In some cases, these fields produce impedance variation of the same order of magnitude as the forces Γ, thus leading to unacceptable errors in angle measurements. In order to reduce these effects, we added a similar system composed of identical wires as above, but without the body hanging in the middle. We called these *witness wires* (Ww). The four witness wires, Ww1 to Ww4, are mounted parallel

Figure 1. Principle of operation of the tilt sensor

and very close to the active wires so that they be under the same field influence and so to undergo the same impedance variations caused by disturbances. Finally, two bridges have been created, each of them comprising two active wires and other two witnesses, as shown in figure 2. The bridges are fed by a constant current source I. By processing the signals provided by the bridges, δU_1 and δU_2, we have finally to solve an algebraic system from which the two angles are obtained:
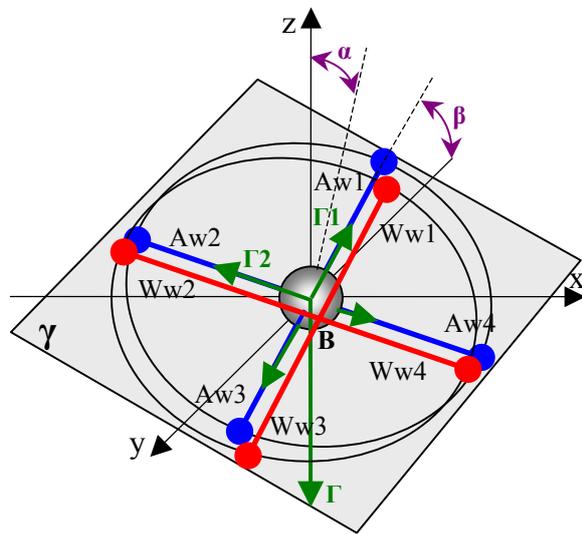
$$\begin{cases} \delta U_1 = f_1(\Gamma, H_d) = \varsigma_1(\alpha, \beta, \overline{H_t}) \\ \delta U_2 = f_2(\Gamma, H_d) = \varsigma_2(\alpha, \beta, \overline{H_t}) \end{cases} \tag{2}$$

Theoretically, in the ideal case in which the 8 sensors involved are identical and if the characteristic surface $Z_i(\Gamma, \overline{H_d})$ is a perfect plane, the influence of the terrestrial magnetic field $\overline{H_t}$ should be null [11]. However, neither the sensors can be made perfectly identical, nor the characteristics are linear. In real cases, the influence of terrestrial field on the voltage outputs of the bridge becomes important, this implying large errors over the two tilt angles measurement. In the paper we present an automatic system designed to compensate the magnetic field influences. The effects of the sensor characteristics dispersion caused by the amorphous material inhomogeneity and by the intrinsic mechanical stresses induced during the sensors fabrication will be treated in other paper.
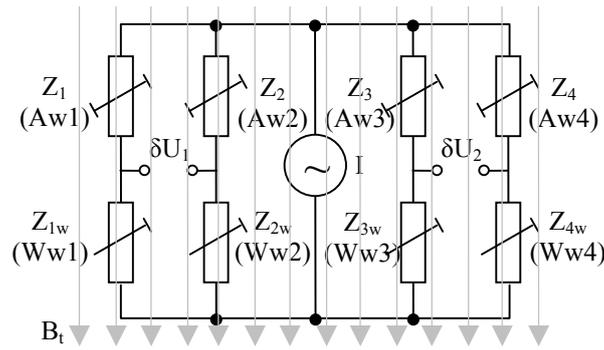
Figure 2. Configuration of the ac bridges

C. Sensor characteristics

Figures 3 a) and b) present the family of characteristics $Z(\Gamma)|_{B=ct}$ and $Z(B)|_{\Gamma=ct}$ traced for a 50 mm long MAW of 120 µm diameter, having the composition $(Fe_{0.06}Co_{0.94})_{72.5}Si_{12.5}B_{15}$, kindly provided by the National Institute of Research & Development for Technical Physics Iasi, Romania. The characteristics have been traced at the frequency of 1 MHz using an automatic Agilent 4285A type bridge. All the measurements have been accomplished in a shielded case made of permalloy in order to avoid the influence of external fields. Γ denotes the axial tensile stress and B is an axial magnetic field applied to the wire by means of a coil, associated to the terrestrial magnetic induction. We considered as equivalent scheme of the sensor an ideal inductance L in series with a resistance R. Both L and R are modifying with parameters Γ and B. We considered in our study only one bridge (e.g. Aw1 – Aw2 – Ww1 – Ww2), since the other bridge has the same behavior with respect to our approach. We computed the errors of the output unbalance voltage δU_1 caused by a variation of B of 50 µT for different values of Γ. The error ε has been calculated by reporting the maximum span of δU_1 determined by the variation of B, to the value of δU_1 corresponding to the absence of any external field applied to the sensor. The span of variation of 50 µT for B is believed to be reasonable, since the terrestrial induction components at Iasi, Romania, varies between 19.37 µT$_{//}$ and 44,72 µT$_{\perp}$. The error values are shown in Table 1.
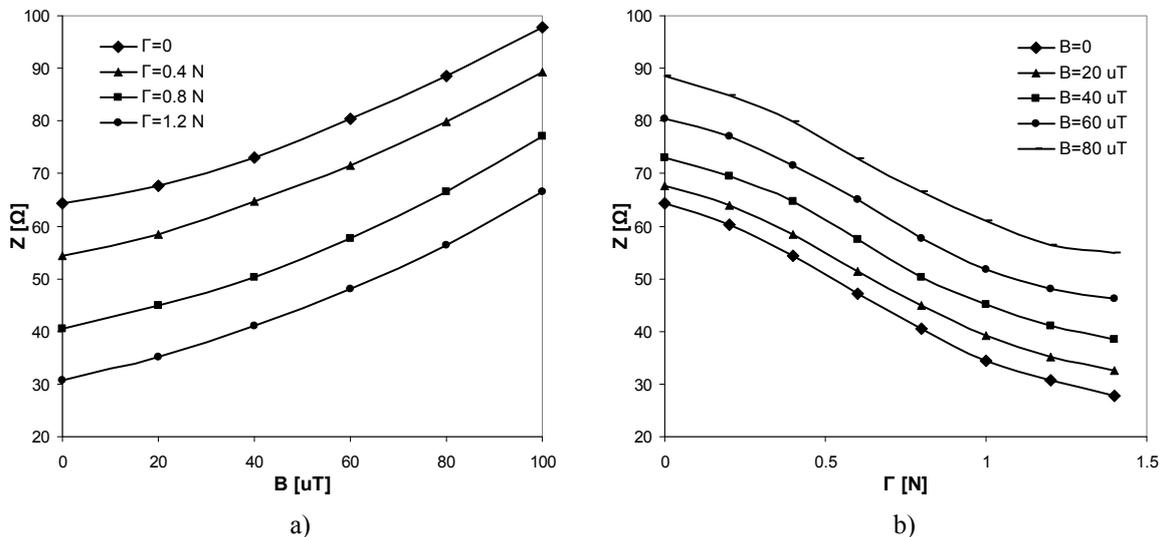

Figure 3. Family of characteristics for the MAW sensor employed in the tilt transducer construction

Table 1. Error caused by a variation of terrestrial field of 50 µT for different values of axial tensile stress Γ

	$\Gamma = 0.1$ N	$\Gamma = 0.2$ N	$\Gamma = 0.3$ N	$\Gamma = 0.4$ N	$\Gamma = 0.5$ N
ε [%]	5.4756	5.4584	5.4120	5.3637	5.2864

In figure 4 the dependences of the modulus M and phase φ of the unbalancing voltage δU_1 as a function of the field B are given.
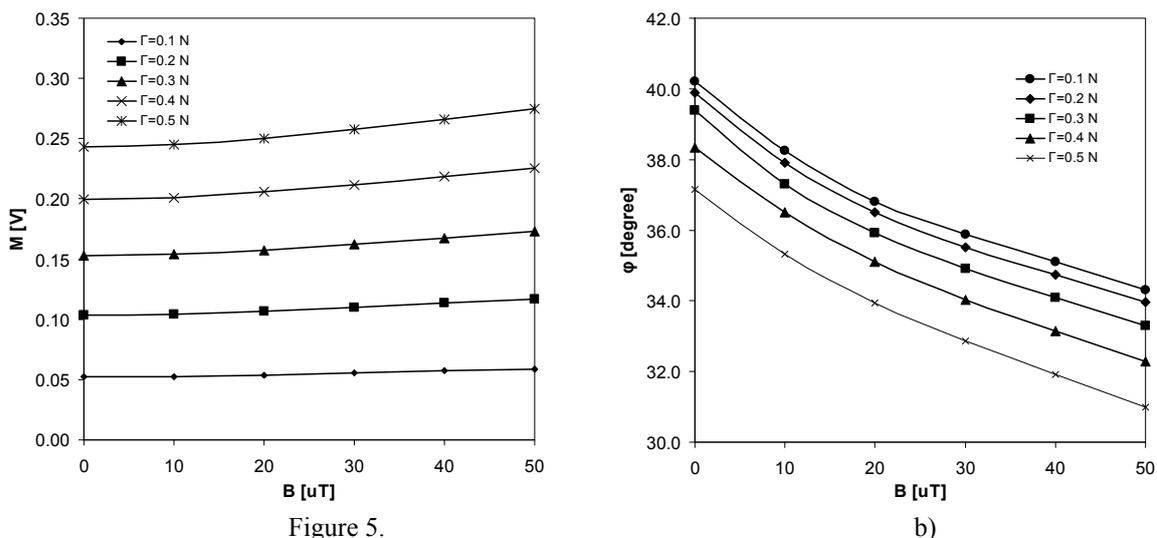
Figure 5.   b)

Figure 4. Representation of a) modulus M and b) phase φ of δU_1 vs. B for different values of stress Γ

III. Presentation of the method

In order to diminish the influence errors calculated in Table 1, we started from the idea to compensate the increasing of δU_1 modulus by decreasing the signal phase so that to correct the characteristic $M|_{\delta U1}(\Gamma)$. In figure 5, the block diagram of the compensation system is depicted.
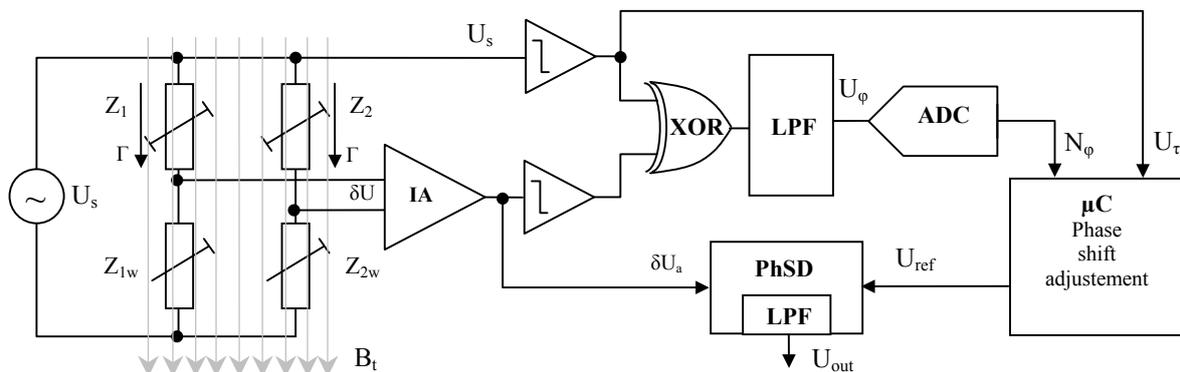

Figure 5. Block diagram of the compensation system: IA – Instrumentation Amplifier, LPF – Low Pass Filter, ADC – Analog to Digital Converter, PhSD – Phase Sensitive Detector, μC – microcontroller

In principle, the heart of the systems is a Phase Sensitive Detector (PhSD) which is employed here with two aims, namely: for converting the ac voltage δU picked up from the unbalanced bridge into a dc voltage concomitantly with removing the noise and as a regulating element driven by means of its reference voltage U_{ref}. After amplification with the instrumentation amplifier IA, the unbalance voltage δU, together with the supplying voltage provided by the source U_s are formatted into squared signals and then fed to a phase meter scheme. The resulting dc voltage, U_φ, which is proportional with the phase shift φ, is next converted into a digital word using an A/D converter and then applied to the DIO port of the microcontroller μC. As a matter of fact, ADC may be the analogue interface of the μC, here an Atmel device type AVR Atmega16. In addition, the μC is provided with the trigger signal U_τ used as phase reference. The task to be fulfilled by the μC is to build the reference driving signal U_{ref} by adjusting the initial phase shift Φ_0 according to the $\varphi(B)$ dependence and to correct the nonlinearity of the $\delta U(\Gamma)$ characteristic as well. The nonlinearity correction might be seen as an additional duty for the μC and is performed on the basis of a look-up table containing the characteristics parameters. The inclusion of the look-up table in the adjustment algorithm offers a large flexibility to the system and improves the calibration process, thus allowing the system to be utilized theoretically to compensate the unwanted

influences and non-linearity of any other kind of sensor. Besides, within the final tilt transducer, the µC is also utilized for performing the calculation of angles α and β according to (2). The output voltage provided by the system, after low-pass filtering, is given by:

$$U_{out} = \frac{2.8}{\pi} \delta U(\Gamma, B) \cos(\phi_0 + \varphi(B))$$ (3)

By properly adjusting Φ_0 and φ, one can reach a significant reduction of the field influence.

IV. Results

Figures 6 a) and b) display the corrected characteristics $U_{out}(\Gamma)$ and $U_{out}(B)$ by using the above presented system, whereas the corresponding influence errors are calculated in Table 2.
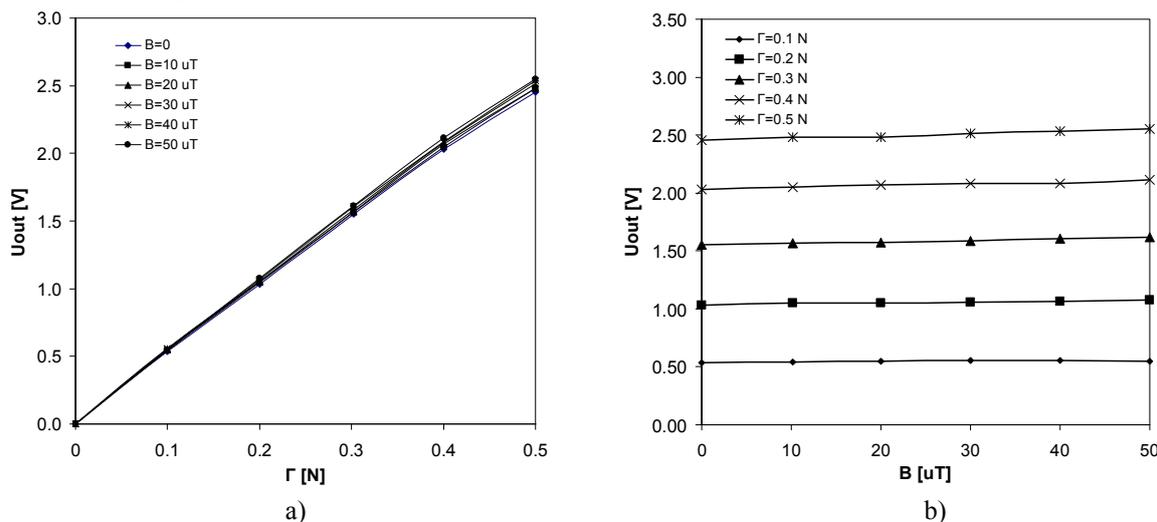

a)   b)

Figure 6. Corrected characteristics representing the dependence of the output voltage U_{out} on the a) axial tensile stress Γ and b) external magnetic field induction B

Table 2. Error obtained after correction calculated for a magnetic field span of 50 µT. Calculation has been made the same as for table 1.

	$\Gamma = 0.1$ N	$\Gamma = 0.2$ N	$\Gamma = 0.3$ N	$\Gamma = 0.4$ N	$\Gamma = 0.5$ N
ε [%]	0.9938	0.9608	0.9867	0.9613	0.9416

As noticed from the table 2, by referring to the values presented in Table 1, a reduction of over 5 times of the errors caused by external field influence upon the bridge sensors has been obtained. It should be noted that supplying the bridge with constant voltage increases the sensitivity of the method by increasing the slope of the dependence $\varphi(B)$ at the operating phase, Φ_0. Moreover, a constant U_s voltage allows obtaining an accuracy under 0.5 % for phase measurement. The phase control over the PhSD reference and implicitly over the voltage U_{out} is carried out by means of a series of parameters related to sensitivity, offset and drift, set when programming the microcontroller.

V. Conclusions

Compensating the external influences upon high sensitive devices is a real challenge for designers, especially when the influences effects are comparable with those of the quantity to be measured. The paper described a new method for compensating the action of the terrestrial field upon a tilt sensor whose sensitive elements are high sensitive magnetic amorphous wires. The circuit uses as compensating parameter the phase shift of the reference voltage feeding a phase sensitive detector, provided by a microcontroller that converts the phase dependence of the output voltage of the bridge on the inductance of the terrestrial field, into the reference voltage. A reduction of over 5 times of the sensor error has been proven using the proposed method.

References

[1] John R. Brauer, *Magnetic actuators and sensors*, John Wiley & Sons Inc., New Jersey, 2006.
[2] W. Göpel, J. Hesse, J.N. Zemel, *Sensors in manufacturing*, Wiley-VCH, 2001.

[3]   Jon S. Wilson, *Sensor Technology Handbook*, Elsevier Inc., 2005.

[4]   A.Häberli, M. Schneider, P. Malcovati, R. Castagnetti, F. Maloberti, and H.Baltes, "2D magnetic microsensor with on-chip signal processing for contactless angle measurement", *IEEE Journal Solid-State Circuits* , vol. 31, pp. 1902-1907, 1996.

[5]   Keat G. Ong, Maggie Paulose and Craig A. Grimes, "A Wireless, Passive, Magnetically-soft Harmonic Sensor for Monitoring Sodium Hypochlorite Concentrations in Water", *Sensors*, vol. 3(1), pp. 11-18, 2003.

[6]   P. Ripka, "Current Sensors Using Magnetic Materials", *Journal of Optoelectronics and Advanced Materials* vol. 6, no. 2, pp. 587 – 592, 2004.

[7]   K. Inada, K. Mohri and K. Inuzuka, "Quick Response Large Current Sensor Using Amorphous MI Element Resonant Multivibrator", *IEEE Transactions on Magnetics,* vol. 30, pp. 4623-4625, 1994.

[8]   H. Chiriac, M. Tibu*, V. Dobrea, I. Murgulescu, "Thin Magnetic Amorphous Wires for GMI Sensor", *Journal of Optoelectronics and Advanced Materials* vol. 6, no. 2, pp. 647 – 650, 2004.

[9]   L. P. Shen, K. Mohri, T. Uchiyama, and Y. Honkura, "Sensitive Acceleration Sensor Using Amorphous Wire SI Element Combined with CMOS IC Multivibrator for Environmental Sensing", *IEEE Transactions on Magnetics* vol. 36, no. 5, 3667-3669, 2000.

[10] H. Chiriac, E.Hristoforou, Maria Neagu, Firuța Borza, "Force measurements using Fe-rich amorphous wire as magnetostrictive delay line", *Sensors & Actuators* vol. A91, pp. 223-225, 2001.

[11] Analog Devices, *Practical Design Techniques for Sensor Signal Conditioning*, Prentice Hall, 1999.

[12] D.R. Munoz et al., "Temperature compensation of Wheatstone bridge magnetoresistive sensors based on generalized impedance converter with input reference current" *Review of Scientific Instruments* 77, 105102, 2006.

[13] S. W. Arms, Ch. Townsend, "Temperature gradient compensation circuit", US Patent no. 5,914,593, 1999.

[14] A.D. Kurtz, "Compensated pressure transducer employing digital processing techniques, US Patent 4,192,005, 1980.

[15] Maxim Inc., "Sensor Temperature Compensation Using the Four DAC Signal Conditioning Architecture", Application note 1839, available on-line at www.maxim-ic.com/an1839

[16] I. Ogasawara and S. Ueno, "Preparation and Properties of Amorphous Wires", *IEEE Transactions on Magnetics* vol. 31, no. 2, pp. 1219-1223, 1995.

[17] L.V.Panina and K.Mohri, "Magneto-impedance Effect in Amorphous Wires", *Appl. Phys. Lett.*, vo1.65, pp. 1189-1191, 1994.

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

[19] K. Mohri, et al, "Magneto-Impedance Element", *IEEE Transactions on Magnetics*, vol. 31, pp. 2455-2466, 1995.

[20] J.N.Nderu, M. Nakamura, S.Murashige and A. Saito, "Effects of Tensile Stress on the Magnetization Properties of Co Based Amorphous Wires", *IEEE Transactions on Magnetics* vol. 31, no. 6, pp. 3140-3142, 1995.