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CHARACTERIZATION OF A MAGNETIC FIELD TRANSDUCER BASED ON THE GMI EFFECT

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Abstract: A magnetic field transducer based on the giant magnetoimpedance (GMI) effect has been developed by the Laboratory of Biometrology at PUC-Rio. It is aimed at biomedical applications, especially three-dimensional localization of needles accidentally inserted in the human body. This manuscript presents some new measurements that led to a better understanding of the prototype's behavior.

Keywords: magnetic transducer, giant magnetoimpedance, localization of magnetic foreign bodies in humans.

1. INTRODUCTION

The Laboratory of Biometrology at PUC-Rio has been researching and developing new magnetic field sensors for biomedical applications that present characteristics of being non-invasive and innocuous, and having a low cost of fabrication and operation [1, 2]. This manuscript presents a review of an already presented magnetic field to voltage transducer, which is based on the giant-magnetoimpedance effect (GMI) and uses an original coil-shaped geometry [3]. It also describes some recent measurements that helped to further characterize and optimize its behavior. Once the main application intended for the transducer is the localization of steel needles in human bodies, additional *in-vitro* measurements were performed to evaluate the transducer response produced by the magnetic field associated with this kind of object.

The technique for localization of steel needles in humans was first developed using a single-channel LTS-SQUID magnetometer for measuring the remanent magnetic field associated with this type of object [1-3]. This technique has already been successfully applied to six patients. Despite the success of the technique, the costs involved with LTS-SQUID operation (mainly due to the need of liquid Helium handling) make it prohibitive to be systematically applied on the whole health community. In order to identify a cheaper transducer that could be applied in such a technique, an investigation analyzing the characteristics of the most used magnetic transducers in the scientific community were performed. Table 1 presents the current resolution and estimated costs for these transducers and the estimated resolution and cost for the transducer developed in this research (GMI sensor). As it can be seen, the sensor's resolution is high and its cost is very low if compared with the other ones, justifying our effort in developing it.

Table 1. Magnetometers, resolution and price.

Sensor	Resolution (Tesla)	Cost
SQUID LTS	10^{-14}	US$ 100.000,00
Fluxgate	10^{-10}	US$ 5.000,00
Hall Effect Sensor	10^{-6}	US$ 2.000,00
GMI Sensor	10^{-10}	US$ 200,00

The following section presents a brief description of the GMI effect and section 3 shows a review of the developed transducer. Section 4 presents the characterization measurements and section 5 the *in-vitro* measurements performed with a straight needle. In the conclusion, improvements and solutions to the problems detected during this research are suggested.

2. GMI EFFECT

The GMI phenomenon consists on the drastic variation observed in the impedance of samples of soft ferromagnetic materials submitted to electrical current ac (I) when a tangential external dc magnetic field (H) is applied, as illustrated in Fig. 1.

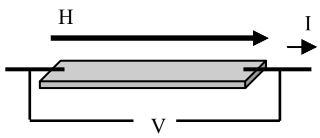

Fig. 1: Illustration of typical GMI measurement.

The GMI effect is actually a result of the skin depth dependency with the magnetic permeability, which varies not only with the external magnetic field that is applied to the sample, but also with the frequency and intensity of the current that passes through it.

The impedance (Z) can be obtained via Ohm's Law: $Z = V / I$. Despite the fact that the impedance is a complex value, the measurements were realized examining only its magnitude (|Z|).

3. MAGNETIC FIELD TRANSDUCER (B – V)

The sensor element was conceived as two identical GMI ribbons in a bridge configuration, with the ribbons in opposite arms, so as to increase the sensitivity. To reduce the influence of remote magnetic fields, both ribbons were configured as parallel coils over a ring [3], as shown in the picture of the partially complete prototype in Fig. 2. The ring has a radius of 2.5 cm, the ribbons around it have a length of 14.7 cm and there is a gap of 0.7 cm approximately, where the contacts are made.

In order to obtain a good linearity and a high sensitivity $|\Delta Z|/\Delta H$, the ribbons are biased by an external polarization field, so that the low intensity field to be measured works as a modulating signal [3]. Therefore, an external ring to protect the ribbons and a toroid with 125 coils were added, in order to generate this longitudinal quiescent field (see Fig. 3). For the polarization field adopted ($H_0 = 0.3$ Oe), the sensor element presents a sensitivity of $|\Delta Z|/\Delta H \approx 3\Omega$/Oe (0.04 Ω/(A/m)).

The dedicated electronic circuit consists in an alternating current supply with 10 mA peak and 1 MHz frequency that feeds both ribbons in a bridge configuration. The output voltage of the bridge is then fully rectified and amplified, generating a voltage in the circuit's output that is proportional to the variation of the magnetic field being measured around the polarization field.

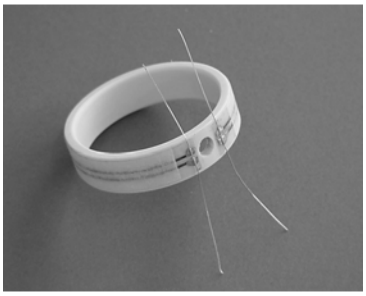

Fig. 2: The partially complete prototype of the magnetic field transducer.

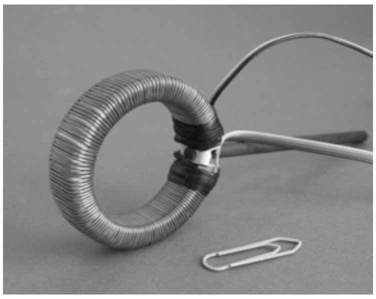

Fig. 3: The complete prototype of the sensor element of the transducer.

The total gain of the circuit can be adjusted up to the maximum value of 1000. The circuit sensitivity was simulated in a SPICE program and estimated as $\Delta V/\Delta|Z| \approx 4$ V/Ω, with a good linearity ($\varepsilon_{max} < 0.7\%$ in relation to the nominal sensitivity).

By combining the sensor element sensitivity with the circuit sensitivity, it is possible to estimate the overall transducer sensitivity as 12 V/Oe (0.15 V/(A/m)). This estimated sensitivity can be considered high if compared to a typical Hall effect sensor (1 V/Oe), and is already comparable to a fluxgate sensor, which has a sensitivity of 5 V/Oe in its least sensitive scale.

4. CHARACTERIZATION MEASUREMENTS

Some measurements were performed in order to analyze the transducer behavior in relation to some parameters and, when possible, to optimize its response. The most important results obtained in such measurements are presented in the following sections.

4.1. Variation of the transducer output signal with the current frequency

The first measurement was made varying the frequency of the current that flows in the ribbons composing the sensor element. Fig. 4 shows the transducer output signal as a function of the external magnetic field for frequencies varying from 400 kHz to 1 MHz, in accordance with the electronic constraints.

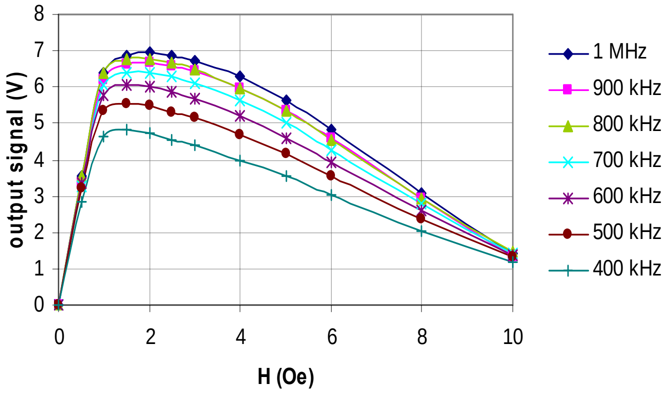

Fig. 4: Transducer output signal as a function of the toroid magnetic field (H) for different current frequencies of the element sensor ribbons.

It can be noticed that the signal magnitude rises as the frequency rises, but this behavior becomes softer for higher frequencies. This suggests that, at 1 MHz, the output is near the maximum magnitude that can be achieved. Therefore, all further measurements were made at 1 MHz.

4.2. Hysteresis Effects

In order to observe the hysteresis effect of the transducer, measurements were carried out by varying the magnetic field produced by the toroid. Two curves were obtained, one beginning at the polarization field and increasing the field and other beginning at the same field but decreasing it. The result can be observed in Fig. 5.

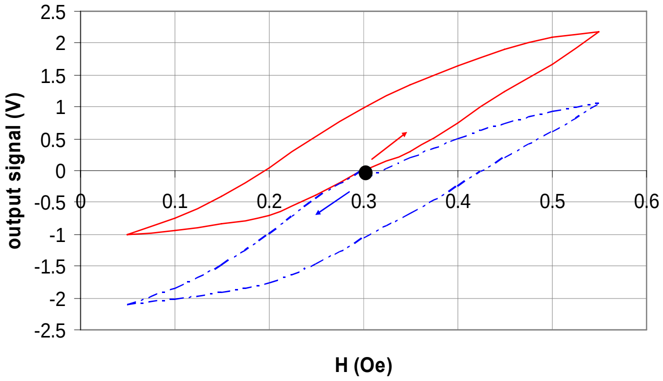

Fig. 5: Transducer hysteresis curves. Increasing field (solid line) and decreasing field (dashed line).

It can be concluded, with this measurement analysis that the transducer presents a strong hysteresis effect, which also depends on the history of the applied magnetic field.

4.3. Immunity to Uniform Fields

The third experiment consisted on verifying if the transducer was immune to uniform magnetic fields, as it was proposed in section 3. To this end, the sensor element was inserted in the middle of a Helmholtz pair and the magnetic field generated was varied. Two orientations were considered, with the sensor ring being initially parallel to the coils and then perpendicular to them. Fig. 6 presents the results.

By observing the curves, it can be noticed that, when the sensor ring is parallel to the Helmholtz coils (solid line), there is no significant variation on the transducer output signal with the field. This happens because with this orientation there is no magnetic field tangential to the ribbons. When the ring is perpendicular to the Helmholtz coils (dashed line), the transducer presents a good immunity to uniform fields until these fields reach the value of the polarization field. After this point, the output signal varies strongly with the field, clearly indicating that, the transducer leaves its linear range of operation.

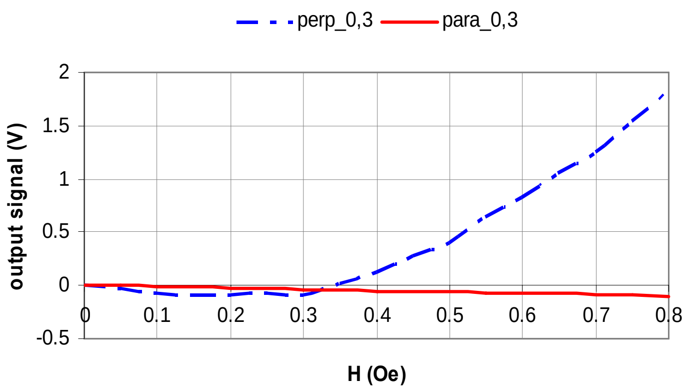

Fig. 6: Transducer output signal as a function of the magnetic field (H) produced by the Helmholtz coils. Sensor ring parallel to the Helmholtz coils (solid line) and sensor ring perpendicular to the Helmholtz coils (dashed line).

5. EXPERIMENTAL RESULTS

Since the main application intended for the transducer is the localization of needles in the human body, *in-vitro* measurements with a magnetized sewing needle of 4.5 cm length were performed. All experiments used 1 MHz / 10mA ribbon currents, a polarization field of 0.3 Oe and 2 cm liftoff between the sensor and the needle. Before the measurements were started the transducer output signal was reset to zero. Also, because the ribbons present a relaxation effect [6, 7], it was necessary to wait between consecutive measurements for the output signal to achieve equilibrium.

The first set of measurements presented here has considered a one-dimensional displacement between the transducer and the needle, i. e., the needle is moved above the transducer - which is fixed - in a straight line of 20 cm with steps of 0.5 cm. The next set of experiments was accomplished by moving the same needle in a plane of 15 cm x 15 cm, with steps of 1 cm.

5.1. One-dimensional measurements

To evaluate the transducer repeatability, three 1D measurements were taken under the same conditions. The results are presented in Fig. 7.

Observing the curves, it is possible to notice that the transducer presents good repeatability. One also can note that the signals are very asymmetric, probably because of the asymmetric shape of the needle and due to hysteresis effects. Moreover, it is possible to verify that there is a peak around the position of 8 cm that appears in all curves, which is believed to be an indicative of the effect of the needle's hole.

In order to assess the transducer reproducibility, another measurement was made by changing the initial position of the needle. First, the needle was moved from 0 cm to 20 cm, and then it was moved from 20 cm to 0 cm. Fig. 8 shows the results.

This experiment indicates a good reproducibility and the small variation between the curves can be justified by the hysteresis effect. The needle asymmetric shape produces fields of different intensities in each needle end. Consequently, when the initial position is changed, the hysteresis curve, through which the transducer is traveling (see Fig.5), is also changed.

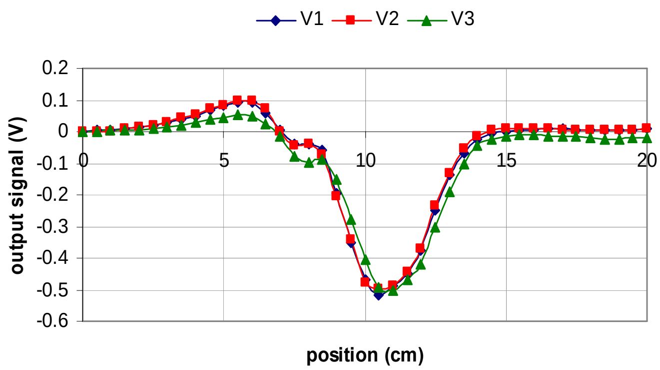

Fig. 7: Transducer output signal as function of the needle position for three different measurements taken under same conditions.

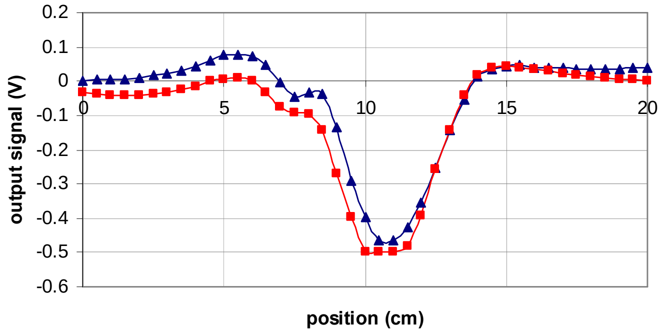

Fig. 8: Transducer output signal as a function of the needle position for the needle moving from 0 cm to 20 cm (squares) and from 20 cm to 0 cm (triangles).

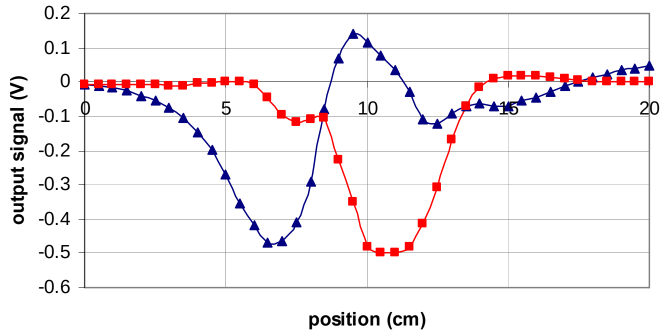

Fig. 9: Transducer output signal as a function of the needle position for the poles at 0° (squares) and at 180° (triangles).

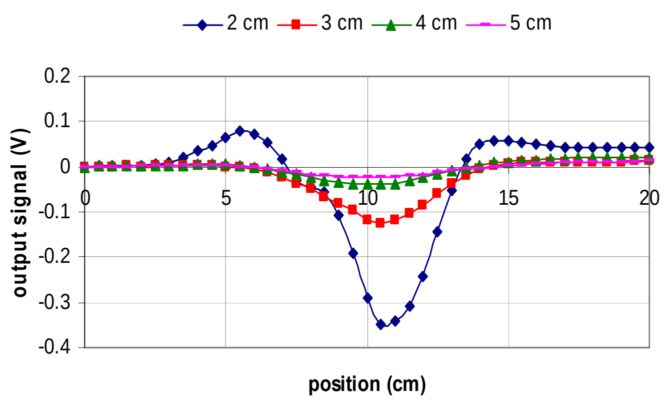

Fig. 10: Transducer output signal as a function of the needle position for a distance of 2 cm (♦), 3 cm (▪), 4 cm (▲) and 5 cm (-) between the sensor and the needle.

The next measurements were carried out to investigate the influence of the direction of the needle poles. At first, the signal produced by the motion of the needle in a certain orientation was taken and then the needle was rotated by 180°. It is important to notice that, when the poles are inverted, so is the field to be detected by the transducer. The results are presented in Fig. 9.

If it is considered that the signals are rotated by 180° from each other, it can be said that they are quite similar, except by the negative peak in the triangles curve located around 7 cm. These different responses to fields of different polarities suggest that, apart from hysteretic effects, the transducer is leaving its linear range of operation.

The last set of straight line experiments examined the dependency of the transducer output signal with the liftoff *h* between the sensor and the needle, varying it from 2 cm to 5 cm. The results can be observed in Fig. 10. By analyzing the variation of the amplitude with the distance, one can verify that it varies approximately with $1/h^2$, in agreement with theory.

5.2. *Two-dimensional measurements*

The 2D measurements were performed to obtain a map of the voltage associated with the magnetic field of the needle. Fig. 11 shows the voltage map, where the gray levels represent the voltage intensity in each point.

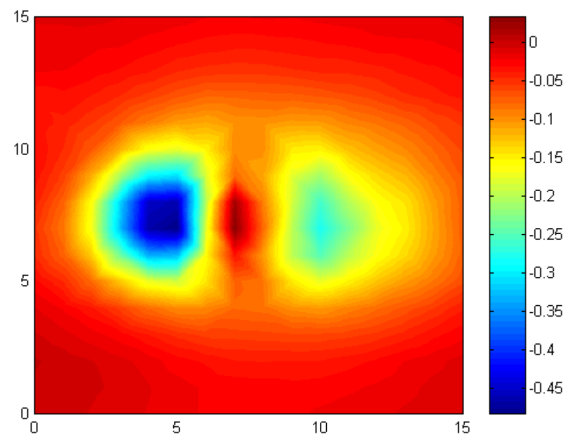

Fig. 11: Map of the transducer output signal for the magnetic field generated by a needle.

The result presents an asymmetric shape, as it was observed on the one dimensional measurements. Once more, it can be justified by the needle's asymmetric shape and by the hysteresis effects of the GMI ribbons. When the first extremity of the needle, which corresponds to a pole, runs closer to the sensor, the ribbons get magnetized, so that the transducer response to the other needle pole is different to the first one.

6. DISCUSSION AND CONCLUSIONS

The measurements indicate that the developed transducer presents a strong hysteresis effect and, under strong external fields, it leaves its linear range of operation, failing to be immune to uniform fields. These problems hinder the main intended application of the transducer, i. e., the localization of magnetic foreign bodies in humans. Therefore, transducer improvements are necessary to solve these inconveniences.

In order to reduce the influence of strong uniform fields on the output signal, the gap between the ribbons ends could be reduced. Special annealing treatments [8], to which the ribbons can be submitted, could be used to reduce the hysteresis effect and to improve the ribbon sensitivity. Besides, one could use new GMI ribbons with better characteristics, such as improved sensitivity of the impedance with the magnetic field, particularly at higher polarization fields (so that a better immunity to uniform fields would be guaranteed), stronger transversal magnetic anisotropy (in order to detect only tangential magnetic fields [7]) and higher homogeneity (so that its response would be the same along all its length).

Despite these issues, the measurements with the needle confirmed the high sensitivity of the transducer and it is believed that even without the proposed improvements, for less rigorous and non-biomedical experiments, like non-destructive testing, the transducer already presents satisfactory characteristics, and has the advantage of reduced fabrication and operation costs.

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