Detecting non-magnetic metallic foreign bodies by GMR sensors through the use of eddy currents

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Abstract: The location of non-magnetic foreign bodies in patients, such as firearm projectiles, for surgical removal purposes is a major challenge that leads to often unsuccessful hours-long extraction procedures. This paper presents the development of a new method to locate non-magnetic metallic foreign bodies through the generation of eddy currents by means of an external alternating magnetic field and the use of high sensitivity GMR sensors for detection. The developed electronic circuits are shown and simulation results are analyzed.

Keywords: foreign bodies, magnetometers, eddy currents, GMR, surgical removal.

1. INTRODUCTION

The Laboratory of Biometrology (LaBioMet) at PUC-Rio conducts research in the area of non-invasive clinical diagnosis, in particular involving the development of biomagnetic transducers [1, 2]. One of the research lines deals with the location of metallic foreign bodies using high sensitivity magnetic transducers [1-4].

The need for surgical removal of foreign bodies is very common in the medical practice. However, nowadays, the only widely available means of locating them are radiography, computed tomography and radioscopy procedures [2-4]. These methods are often ineffective, lasting several hours unsuccessfully, especially for small objects. In addition, all of the highlighted imaging techniques use ionizing radiation and so poses risks to patients and to the medical staff [2].

A study published in 2000 demonstrated that magnetic field maps can be used for locating magnetic foreign bodies. The proposed technique was applied in surgical procedures, reducing the time spent to successfully removing small metallic needles to around 10 minutes [2]. In these procedures, the magnetic fields were measured by a Superconducting Quantum Interference Device (SQUID).

SQUID sensors are currently the most sensitive magnetometers, showing extremely low noise levels. However, their operation requires cryogenic temperatures, usually supplied by liquid helium cooling. This introduces a high cost, making it difficult for SQUID equipment to be widely used, in particular for clinical use [2-4].

Furthermore, the detection of firearms projectiles presents a greater challenge, since they do not possess a remnant magnetic field. In that way, a theoretical technique for locating non-magnetic metallic foreign bodies was introduced in 2004. The proposed method involves the induction of eddy currents in metallic objects by a primary alternating magnetic field source. Then, these currents lead to the generation of a secondary magnetic field that can be measured by high sensitivity magnetic sensors [4-5].

The main objective of the current research is to design and develop a device capable of locating non-magnetic metallic foreign bodies for surgical removal. The device design was guided by some major project requirements: high sensitivity, low cost, safety, portability, ease of use and capacity to operate at room temperature [6]. Therefore, magnetometers based on giant magneto-resistance (GMR) were considered, rather than SQUIDs [6-9]. This work describes the main aspects of the design of the solenoid used as primary magnetic field source. It also presents the electronic circuit of the developed magnetic transducer, used to measure the secondary magnetic fields due to eddy currents.

A wide variety of GMR sensors are commercially available. The selected model was the NVE AA005-02, which presents a sensitivity of at least 0.45 mV/(V.Oe) = 5.65 μV/(V.A.m^{-1}), a linear operation range between 10 Oe and 70 Oe, and a bandwidth of about 1 MHz. These sensors are produced as integrated circuits (IC) in a SOIC8 package. Each IC has two GMR sensors disposed in a half bridge circuit configuration that provides a differential output, enhancing the quality of the readings.

The main limiting factor is the minimum noise level, which imposes the resolution of the sensor element. Characterization studies of the selected GMR sensors led to an estimated resolution of 43 μOe, or equivalently 4.3 nT.

2. PRIMARY MAGNETIC FIELD EMITTER

The parameters required for the solenoid, responsible for generating the primary magnetic field, are obtained by using a theoretical model for the eddy currents generated in a spherical projectile [4], associated with the characteristics of the chosen GMR sensor element.

Gradiometric configurations are usually employed in order to improve signal-to-noise ratio (SNR) of magnetic readings [2-4, 7, 9]. In such configurations, a differential reading is performed between two sensor elements positioned in line. Since magnetic fields are greatly attenuated with distance, one sensor element receives mostly the signal of interest, immersed in environmental magnetic field noise, while the other receives approximately only the environmental noise. Then, the differential reading minimizes the effect of environmental noise in measurement results. Figure 1 introduces a diagram of the proposed setup, for the detection of non-magnetic foreign bodies.

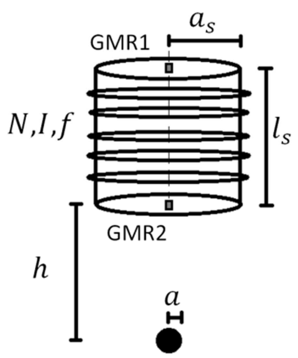

Figure 1. Diagram showing the solenoid with two GMR sensors in gradiometric configuration and the spherical foreign body.

The magnitude of the primary magnetic flux density B_0 generated by the solenoid is given by (1), where μ_0 is the vacuum magnetic permeability ($4\pi \cdot 10^{-7}$ H.m^{-1}), N is the number of turns, I is the amplitude of the applied current, h is the distance between the bottom of the solenoid and the foreign body, a_s is the solenoid radius and l_s its length.

$$B_0(h) = \frac{\mu_0 \cdot N \cdot I}{2 \cdot l_s} \cdot \left[\frac{l_s + h}{\sqrt{a_s^2 + (l_s + h)^2}} - \frac{h}{\sqrt{a_s^2 + h^2}} \right] \quad (1)$$

The magnetic flux density generated by eddy currents (B_{max}) can be estimated by equations described in [4-5], and depends on: magnitude of the primary magnetic flux density B_0 at the metallic object position h, radius of the spherical lead projectile *a*, frequency of the primary magnetic field f_0, magnetic permeability (μ_r) and electric conductivity (σ) of the projectile.

Assuming that the foreign body is a lead sphere with *a* = 5 mm at *h* = 5 cm, figure 2 shows an example of how the relative magnetic flux density B_{max}/B_0 varies with f_0, while maintaining other variables constant.

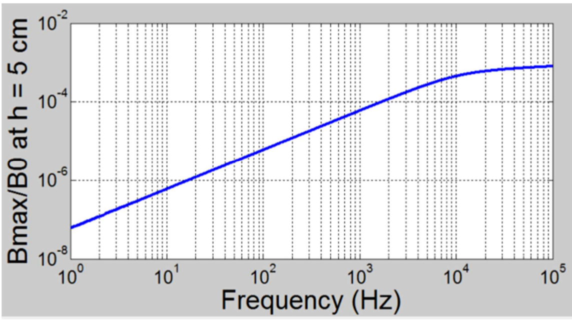

Figure 2. Relative magnetic flux density (B_{max}/B_0) at $h = 5$ cm, in function of the frequency f_0.

Figure 2 shows that higher frequencies result in higher peak values of the secondary magnetic flux density, until it saturates around 100 kHz. Other simulations were performed for different values of *a* and *h*, and all of them support that the response is enhanced by increasing the frequency until about 100 kHz. Above this frequency, no significant enhancement is achieved. Thus, devices with bandwidths of at least 100 kHz are highly desirable, such as the chosen GMR sensor.

On the other hand, the amplitude of the secondary magnetic flux density increases with the intensity of the primary one. Then, aiming at the detection of small foreign bodies, it is also desirable to increase the AC magnetic field generated by the solenoid. However, the GMR sensor must be kept within its linear region. Therefore, the GMR sensor was biased at 40 Oe and the AC field amplitude was settled to 25 Oe.

Combining the theoretical and simulated results of the secondary magnetic field with the characteristics of the chosen GMR sensors led to the definition of the solenoid parameters: *N* = 40 turns, a_s = 1.5 cm, l_s = 5 cm and the current *I* is comprised of a DC component $I_{DC} = 1.212$ A (H_{DC} = 40 Oe) and an AC component $I_{AC} = 0.757$ A (H_{AC} = 25 Oe) at $f_o = 100$ kHz.

3. GRADIOMETER DESIGN

The electronic circuit designed for the GMR gradiometer is shown in figure 3.

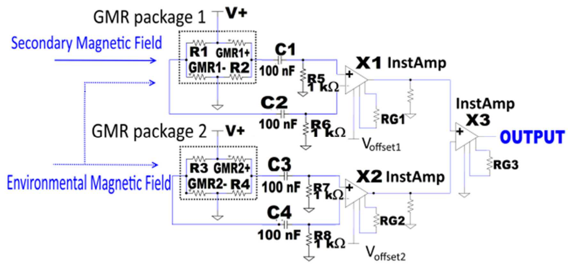

Figure 3. Simplified schematic showing the proposed circuit.

Each GMR sensor is connected to an instrumentation amplifier (INA129) and the outputs of these amplifiers are inputs to a third INA. This method comprises successive differential reading amplification stages, leading to an output signal proportional to the field gradient between the GMR ICs. The supply voltages for the GMR sensors are V_+ = 5 V and for the amplifiers, V_S = ±18 V.

Initially, the half bridge outputs of the two ICs containing the GMR sensors are connected to RC high-pass filters to remove DC components. Next, the filters outputs are connected to the inputs of instrumentation amplifiers (X_1 and X_2) that perform the differential reading. The voltage reference pins of these amplifiers are connected to V_{offset} for fine tuning the offset removal. In the next stage, the outputs of the previous amplifiers are connected to the inputs of X_3, responsible for the gradiometric measurement. The resistors R_{G1}, R_{G2} and R_{G3} are used to adjust the gains of the amplifiers. Simulation results for this circuit are presented in figure 4.

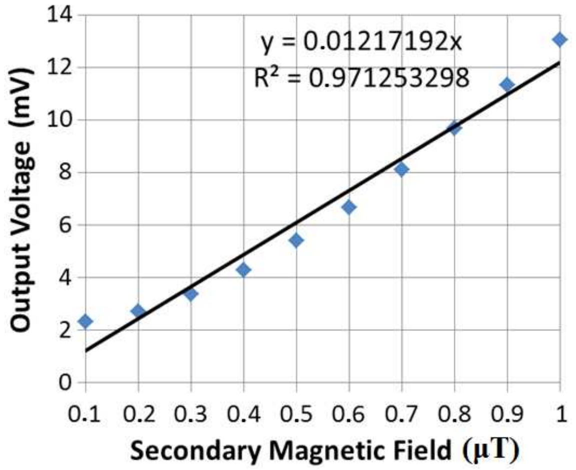

Figure 4. Simulated output voltages of the circuit, for secondary magnetic fields, at f_o, between 100 nT and 1 μT.

For a magnetic field of 500 nT, the output of the selected GMR sensor is about 11.3 μV. On the other hand, figure 4 shows that the output of the developed circuit is approximately 5.5 mV, at the same field. Then, as expected, the proposed circuit significantly increases the output voltage levels of the GMR ICs, leading to more suitable levels for the voltmeter used to measure the voltage output. However, figure 4 also highlights that the output of the circuit can be considered approximately linear only between 200 nT and 1 μT. At 100 kHz, the common-mode rejection ratio (CMRR) of the instrumentation amplifiers is considerably low and then it significantly affects low voltage outputs, such as those present in figure 4, distorting the signal.

4. CONCLUSIONS

This work presented a low-cost GMR transducer designed to locate non-magnetic metallic foreign bodies. The simulation results of the electronic circuit, with GMR sensors in gradiometric configuration, show the possibility to detect the secondary magnetic field generated by eddy currents in a non-magnetic metallic projectile.

Considering that the proposed design can detect 200 nT fields, it can be inferred that it is capable of locating objects with diameters as small as 6 mm at a 2 cm distance. In future works, the circuit will be optimized in order to avoid the CMRR distortions, leading to a resolution of 4.3 nT, which is compatible with the one presented by the employed GMR ICs. Furthermore, the use of more sensitive low cost transducers with better noise levels would greatly benefit the measurements and allow the detection of projectiles with smaller diameters, even at greater distances.

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