Noise behavior of high sensitive GMI-based magnetometer relative to conditioning parameters

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The lowest measurable magnetic field of a high sensitive magnetometer based on Giant Magneto-Impedance effect will be determined by its noise level. Numerous previous works have showed that the equivalent magnetic noise level of GMI magnetometer presents a 1/*f* behavior at low frequencies and a white noise. Currently, performances of the magnetometer are still limited by the electronic conditioning as well as the intrinsic equivalent magnetic noise of the GMI sensor. To improve sensor performances, particularly at low frequency, we have investigated two focuses on research: reduce the electronic noise of the conditioning electronic by increasing the voltage sensitivity, in units of V/T, and reduce the intrinsic equivalent low frequency sensor noise. As previously reported, the equivalent magnetic noise at 1 Hz can be reduced by increasing the excitation current in addition to a DC bias current. By working on these bias conditions, on the given samples, we almost 1 pT/√Hz in white noise region and 15 pT/√Hz at 1 Hz.

***IndexTerms*—magnetometer, off-diagonal GMI, magnetic noise**

I. Introduction

The giant magneto-impedance (GMI) effect consists on the large variation of the impedance of a ferromagnetic material through which a high frequency alternative current flows when submitted to an external magnetic field variation [1, 2]. For this reason, GMI materials are good candidates to be used as magnetic sensing elements.

To develop highly sensitive magnetometers [2], a key parameter is the equivalent magnetic noise level. The latter limits the lowest detectable field. Usually, the noise presents a low frequency, one over *f*, excess noise and a white noise floor [3, 4]. Based on our previous work [4], we have showed that the limit of the GMI based magnetometer is currently determined by both the electronic conditioning noise and the intrinsic noise of the sensing element. Consequently, it would be of interest to increase the voltage sensitivity or to reduce the electronic noise such as its contribution in the output noise becomes comparable to the contribution of the intrinsic noise. On the other hand, we have recently proposed in [5] that the 1/*f* noise may be related to intrinsic noise of the sensing element arising from magnetization fluctuations.

Both noise levels, in white noise region and at 1 Hz are strongly related to material properties and conditioning electronic parameters such as the alternative current and DC bias current properties [4, 6, 8, 9].

In this paper, we present the experimental measurement of the equivalent magnetic noise level, in both white and 1/*f* region, under several excitation parameters. This study has been conducted for an off-diagonal GMI based magnetometer with both as-cast and annealed wires, similarly in [8, 10]. It aims to identify ways of optimization.

The paper is organized as follows. Section II recalls the GMI basic equations in addition to the description of the measurement set-up. A description of the sensing element with and a discussion on the choice of the working point depending on the bias field, currents, and frequency value are also detailed. Results and discussion are given in section III which is followed by a general conclusion.

II. Description of the measurement principle

A. GMI basic equations

In classical off-diagonal GMI set-up [4], the sensing element consists of a pick-up coil winded on an amorphous ferro-magnetic wire. The GMI wire is driven by a high frequency alternative current. This induces a voltage across the pick-up coil. This voltage is proportional to the off-diagonal term, Z_{21}, of the impedance matrix of the two-port network sensing element and so, reflects its dependence upon the applied magnetic field.

Due to the strongly nonlinear impedance variations versus the applied magnetic field [1], we usually consider that the sensing element operates in a field locked loop. In such a case, the applied induction magnetic field could be expanded into a static field working point, B_p, and a small signal variation, $b(t)$. For a sine wave excitation current of amplitude, I_{ac}, and frequency, f_p, the induced voltage is

$$v_{ac}(B,t) = I_{ac}\left[Z_{21}(B_p) + \left.\frac{\partial Z_{21}(B)}{\partial B}\right|_{B_p} . b(t) + z_n(t)\right] sin(\omega_p t) + e_n(t) \qquad (1)$$

where $e_n(t)$ is the output voltage noise induced by electronic conditioning circuitry and $z_n(t)$ is the intrinsic sensor noise, expressed as an equivalent impedance variation. A study of these noises contributions is given in [6].

Equation (1) exhibits a classical amplitude modulated signal where the modulation depth depends on the variations of the magnetic field applied. After demodulation and low-pass filtering, the output voltage, V_S, is given by

$$V_s = G I_{ac} \left.\frac{\partial Z_{21}(B)}{\partial B}\right|_{B_p} . b(t) \qquad (2)$$

where G is the gain associated to the demodulation stage of the electronic conditioning circuitry. Equation (2) allows us to define the voltage sensitivity as

$$S_v = \frac{\partial V_S}{\partial b}\frac{1}{G} = I_{ac}\frac{\partial Z_{21}(B)}{\partial B} \quad (3)$$

where $\frac{\partial Z_{21}(B)}{\partial B}$ is the intrinsic sensor sensitivity. Finally, the equivalent magnetic noise, b_n, is obtained as the ratio between the output voltage noise spectral density and the voltage sensitivity. It yields

$$b_n = \frac{e_n}{S_v} \quad (4)$$

in units of T/√Hz.

B. Electronic conditioning circuitry

Based on these equations, a GMI magnetic sensor consists of an excitation stage current and a demodulation system. This setup allows to obtain an output voltage proportional to the applied magnetic field variations. The set-up used in our experiments is defined in [4]. The excitation stage (a sine wave voltage generator) is converted into a current source generator by using a resistor. Its value was chosen in order to avoid impedance matching issues and taking into account the impedance value of the sensing element. In addition, a static current, I_{dc}, is applied to the GMI wire. Then, the induced voltage (sensed across the coil ends) is picked-up by a voltage buffer having a high input impedance. This buffer is made of an AD844 operational amplifier in a non-inverter configuration. The next stage is a band pass RLC filter tuned on the excitation frequency. It aims to reduce the total output voltage noise. Indeed, it limits the noise contributions of the higher harmonics carriers at the demodulation stage. The latter consists of a peak detector.

C. Choice of the bias conditions

As previously explained, the impedance variation versus the applied magnetic field is highly non-linear. Thus, it is of importance to advantageously choose the static magnetic field working point. This one is selected such as the intrinsic sensitivity, $\partial Z_{21}/\partial B$, is as high as possible. For an off-diagonal GMI sensor, maximum sensitivity is generally obtained in the low field area for which the applied field is lower than half the anisotropy field value [4, 7]. In this region the intrinsic sensitivity remains constant whereas the impedance value Z_{21} may vary.

In our case, we have studied the noise performances for several excitation current amplitudes, I_{ac}. In order to significantly compare the obtained results, it is of importance to keep the noise contribution arising from the generator at a similar level from one measurement to another. That is, to keep the term $Z_{21}(B_p)I_{ac}$ at a constant value. In order to keep this term constant when we change the excitation current amplitude, we accordingly adjust the field working point, B_p. In such a case, the voltage amplitude is detected by the demodulation stage, in a similar way. Thus, the electronic conditioning circuitry always operates in the same conditions.

D. The sensing elements

The GMI microwires, based on CoFeSiB amorphous materials, have been provided by the Sensors and Magnetics Laboratory of the Faculty of Electrical Engineering in Prague. They go through two slightly different manufacturing processes as exposed in [10]. The sample called "Annealed" suffered a thermal treatment consisting of heating the wire while a DC current flows through it [8, 9]. On the opposite, the sample "As-Cast" has not undergone this thermal treatment. Some sample characteristics are given in table I.

TABLE I: SAMPLE CHARACTERISTICS

Type	Length	Number of turns of the pick-up coil	Pick-up coil diameter	GMI wire diameter
A *"annealed"*	23 mm	224	1 mm	120 µm
B *"as-cast"*	23 mm	207	1 mm	120 µm

III. EQUIVALENT MAGNETIC NOISE MEASUREMENTS

Figure 1 compares both annealed, *A*, and as-cast, *B*, samples regarding to their voltage sensitivity and spectral voltage noise density (in both white region and at 1 Hz), as well as their equivalent magnetic noise level. These results have been obtained for an excitation frequency, f_p, equals to 1.1 MHz.

First of all, we note that a higher DC bias current value systematically leads to a decrease of the voltage sensitivity. This is in agreement with the measured curves of impedance variation, $Z_{21}(B)$, obtained from vector network analyzer measurements. Indeed, the classical GMI peak value (observed on these curves), and so the sensitivity (which is proportional to the slope between those GMI peaks) are reduced when a DC bias current is applied. Notice that this phenomenon is likely to be observed for samples exhibiting a purely circumferential anisotropy. It also appears that the voltage sensitivity is roughly proportional to the excitation current amplitude. This is noticeable regardless of the considered sample type or the applied DC current, except for the lowest value (1 mA) of sample *A*. In that case, the voltage sensitivity starts to decrease if the excitation current value exceeds 25 mA. This behavior agrees with the study presented in [8] where noise behavior was investigated in relation regarding to the excitation parameters (I_{dc} and I_{ac}) for an excitation current frequency of 100 kHz.

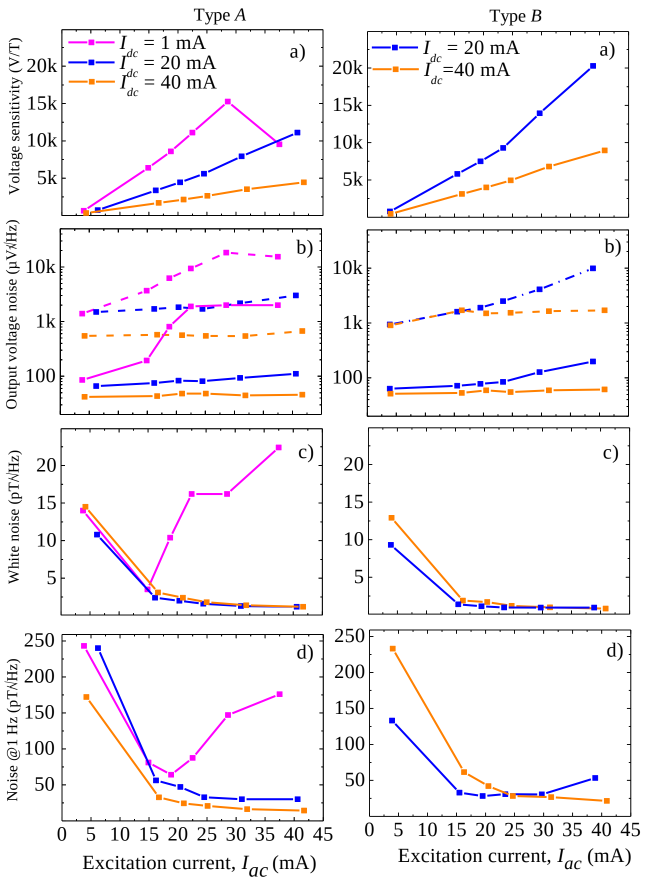

Fig. 1 Variations, for two tested samples (annealed "*A*" and as-Cast "*B*"), of the voltage sensitivity, S_V, a), of the output voltage noise spectral density in white noise region (solid line) and at @1 Hz (dashed line) b), as well as, the corresponding equivalent magnetic noise level in white noise region c) and at 1 Hz d), for different bias amplitude of the excitation current, I_{ac}, and DC bias current, I_{dc}. These measurements have been performed at an excitation current frequency of 1.1 MHz.

If we go further regarding the annealed sample, *A*, we notice that a high value of DC bias current (that is 20 mA or 40 mA) will result in a constant voltage noise level, both in the white noise region and at 1 Hz (over all the excitation current range). Associated with the increase of the voltage sensitivity, the equivalent magnetic noise decreases. However, for a low DC bias current value, the voltage noise increases when the amplitude of the excitation current exceeds 15-20 mA. In such a case, the resulting equivalent magnetic noise increases more rapidly than the voltage sensitivity as reported in [8, 9]. Consequently, the best performances are obtained for the highest value of excitation current associated with the highest value of bias current.

For the as-cast sample, *B*, the behavior is similar to the annealed one in the white noise region. That is, the lowest equivalent magnetic noise level is obtained for the highest values of excitation current and the highest DC bias current. Nevertheless, we notice that the noise level at 1 Hz starts to increase again if the excitation current exceeds 20-25 mA combined with a DC bias current of 20 mA. Conversely, the noise level at 1 Hz still decreases with the highest excitation current values if the DC bias is high enough. That is, the as-cast sample presents a behavior similar to the annealed sample except that a higher DC bias current is required. Concerning the measurements with a bias current of 1 mA for the sample *B*, the preliminary one showed that the GMI response was too low. So this hasn't been included in this study.

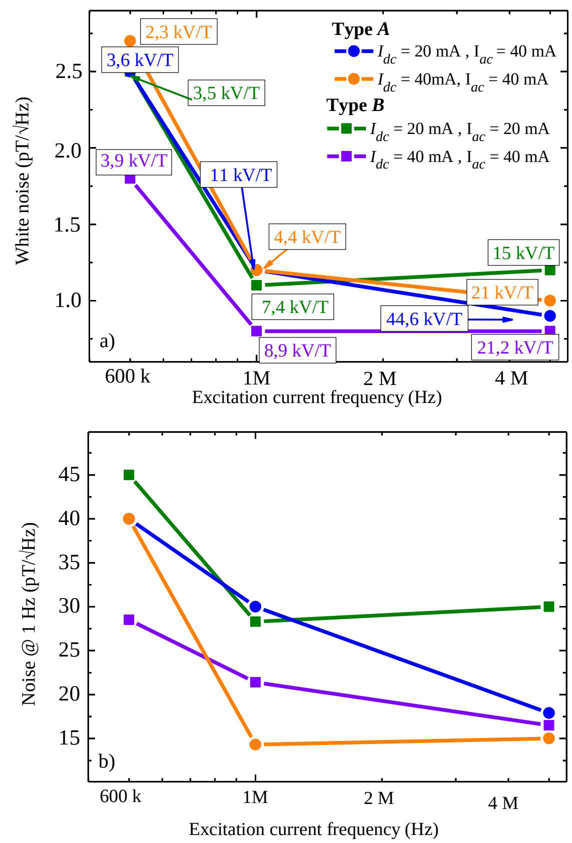

Fig. 2. Best equivalent magnetic noise level performances obtained at different excitation current frequencies: in white noise region a), at 1 Hz b).

Figure 2 presents the best equivalent magnetic noise level performances obtained, for different frequencies of the excitation current (range of 500 kHz to 5 MHz), in the white noise region and at 1 Hz. Obviously, a higher excitation current frequency leads to a better noise performance mainly due to the increase of the intrinsic sensitivity. For the two types of samples, we achieved similar performances of around 1 pT/√Hz in the white noise region and 15 pT/√Hz at 1 Hz.

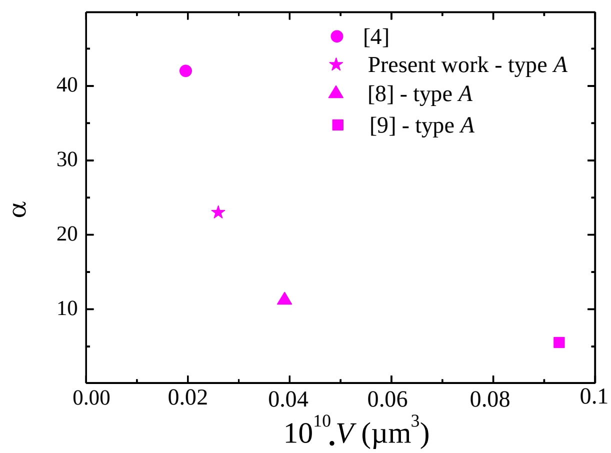

Fig. 3. Comparison of the normalized parameter, α, versus the sample volume, V, in units of (µm)^3 for two different GMI µwire types.

In order to refine the analysis, we compare in figure 3 several studies [4, 8, 9] with a normalized parameter, α, as a figure of merit. The latter is defined as the normalized product of the spectral noise density level, expected at 1 Hz, and the square root of the GMI sample volume, V, in units of (µm)^3, as

$$\alpha = 10^8 b_n \sqrt{(V/10)} \quad (5)$$

Based on a previous description [5], we expected that α would be constant versus the sample volume, with everything else being equal in terms of material properties and electronic conditioning circuitry [12]. Meanwhile, we observe a relative variation from one sample to another.

IV. Conclusion

We have studied the equivalent magnetic noise of an off-diagonal GMI based magnetometer regarding excitation parameters and bias conditions. We observed that this behavior depends strongly on the excitation parameters. We have showed that we were able to decrease the equivalent magnetic sensor noise level in the white noise region by increasing the excitation current for a high DC bias current value. Concerning the equivalent magnetic noise at 1 Hz, we have showed that we can decrease it by adding a higher value of DC bias current when the excitation current increases, in order to compensate the low frequency 1/*f* excess noise. This work is in accordance with the previous results reported in [8, 9] by M. Butta *et al.* for a lower frequency excitation. To go further, we will pursue our study on the excitation parameter effects on noise level and also study the influence of the geometric parameters such as the number of turns of the pick-up coil, the length and the number of GMI wires. Also, we plan to compare the experimental results with our noise models more accurately.

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