

Digital Magnetometer Based on Giant Magneto Impedance Effect: a Feasibility Study

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Abstract: The presented work deals with a feasibility study related on the implementation of digital Giant Magneto-Impedance (GMI) magnetometer (sensor operating in closed-loop). The proposed measurement chain mainly includes an analog-to-digital conversion (ADC) and a digital amplitude demodulation based on a Digital Down Conversion (DDC). In this configuration, the voltage is digitized as close as possible to the sensing element. The DDC include digital mixer and filtering. The transfer function of the overall sensor in open-loop is modelled so as to discuss the stability of the digital magnetometer regarding the processing delay and the sensitivity. Simulations were performed using Matlab-Software with a different set of parameters of the sensor in order to discuss the stability of the magnetometer according to the time delay. The obtained results showed that with a careful adjustment of the sensor sensitivity and the decimation ratio of the digital filter associated with the digital demodulation, the digital magnetometer could be stable in closed-loop.

Keywords: Digital demodulation, Magnetometer, Processing time-delay, Giant Magneto Impedance (GMI) sensor.

1. Introduction

Magnetic sensors are used in a wide variety of applications ranging from high density magnetic recording, non-contact current measurement, to spatial, military and biomedical applications [1]. A non-exhaustive list of these measurement devices may include Fluxgates, inductive sensors, Anisotropic Magnetoresistance (AMR), Giant Magnetoresistance (GMR) sensors, etc. [1]. Over the past two decades, the Giant Magneto-Impedance (GMI) effect has been intensively studied due to its attractive potential for realizing a highly sensitive magnetic sensor [2, 3]. It is defined by a high impedance variation of a ferromagnetic material when it is supplied by a high frequency (HF) excitation current and submitted to an external magnetic field [4]. It has been shown that

GMI sensors offer several advantages compared to conventional sensors. Some of the decisive advantage is the high sensitivity, the potential for miniaturization and the low energy consumption.

A typical configuration of GMI sensor is shown in Fig. 1. It requires a high frequency excitation current provided by an oscillator associated to a voltage-to-current converter. When the sensing element (the ferromagnetic material) is submitted to an external magnetic field, Hz, to be measured, the voltage across the sensing element is amplitude modulated by the measured field. A demodulator is generally used to have the information of the measured field. The relation between the sensor output and the magnetic field is characterized by the sensitivity. The GMI characteristic is strongly nonlinear. To realize a sensor, it is generally magnetically biased in the region

having the maximum of sensitivity. Biasing creates an offset at the sensor output corresponding to the impedance value at the bias point. A difference amplifier is generally used to suppress the offset that could be affected by temperature and strength [5, 6].

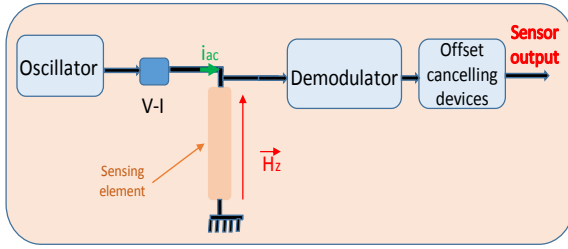


Fig. 1. Hardware architecture of a typical off-diagonal GMI sensor.

In the context of high sensitivity, the equivalent magnetic noise level need to be improved [7, 8]. It characterizes the smallest magnetic field that the sensor can measure. It is defined by the ratio between the voltage noise spectral density (including the electronic conditioning noise and the noise of the sensing element) and the sensitivity of the sensor. Actually, all GMI sensors are associated with an analog electronic conditioning and several studies show that the equivalent magnetic noise is limited in the $1/f$ region by the intrinsic noise of the sensing element attributed to the fluctuation of the magnetization movement. In the white noise region, the smallest magnetic field that the sensor can measure is limited by the electronic conditioning noise [9]. The ultimate noise of the sensing element is not yet achieved in this region. In our recent work [10 - 13], we have introduced the digital concept in order to reduce the electronic conditioning noise so as to achieve the ultimate noise performance. The proposed concept is based on a Digital Down Converter (DDC) for a quadrature digital demodulation. The voltage across the sensing element (generally in off-diagonal configuration for high sensitivity application [9]) is digitized as close as possible to the sensing element. However, as most of sensitive elements, the response to the magnetic field of the GMI element is strongly non-linear. It is not possible to consider them as magnetometers (sensor operating in closed loop) if they are used without suitable conditioning electronics. In order to overcome this problem, a controlled system in which the sensing element works around an operating point in a constant field is necessary. This is done using field feedback, as in the case of many magnetometers (fluxgates, SQUIDS [1], etc.).

The use of the digital concept is generally accompanied by a delay which can destabilize the functioning of the sensor in closed loop system and affects performance of the sensor. The idea behind this article is to evaluate the transfer function of the sensor

and to discuss the stability of the digital GMI magnetometer.

This article is organized as follows. The principle of a GMI magnetometer is presented in Section 2. The hardware architecture of the digital GMI sensor is given in Section 3. Section 4 is devoted to modeling the transfer function of the sensor. Discussion on the sensor stability are given in Section 5. This is followed by a general conclusion.

2. Operating Principle of a GMI Magnetometer

A magnetometer has to exhibit a correct linearity and dynamic range of magnetic field. This can be done, in the GMI magnetometer, using a negative feedback method, by applying a negative magnetic field. The principle of this type of implementation is given in Fig. 2 where the variation of external magnetic field, H_z , around the operating point, is the quantity to be measured. This field-locked loop principle is common to several magnetometers [2].

In this concept, the GMI element ensure the transformation of the magnetic field into voltage through the transfer function, T_d , corresponding to the sensitivity of the open loop sensor. We assume that it is constant in the pass band of the magnetometer. For proper operation of GMI magnetometer, the sensing element is subjected to the difference between the external magnetic field to be measured, H_z , and that created by the feedback, H_{cr} . The feedback magnetic field is generated by a coil wound around the GMI wire. The closed-loop ensures that these two fields are opposed so that its difference is null. By doing so, the GMI wire element is always subjected to the same magnetic field. This structure allows to overcome the problems of non-linearity of the response regarding the measured field.

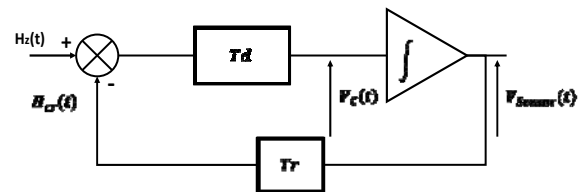


Fig. 2. Principle of the magnetic feedback loop.

The voltage at the output of the magnetometer can be expressed as:

$$V_{sensor} = \frac{T_d}{j\omega} (H_z - T_r * V_{sensor}) = \frac{B_{ext}}{T_r} \left(\frac{1}{1 + \frac{j\omega}{T_d T_r}} \right), \quad (1)$$

where T_r is the transfer function of the feedback loop.

Assuming that $|T_d T_r| \gg j\omega$, the output of the magnetometer is given by:

$$V_{\text{sensor}} \approx \frac{B_{\text{ext}}}{T_r} \quad (2)$$

According to Eq. (2), the output voltage of the sensor depends only on the gain of the feedback chain, T_r . This result is particularly important because it shows that the condition $T_r \gg j\omega/T_d$ allows to overcome the imperfections of the direct chain, T_d , due to the presence of distortion and its gain fluctuations (whether these fluctuations result from an aging of the material, a variation in the experimental conditions). The condition $T_r \gg j\omega/T_d$ is achieving if the field sensitivity, T_d , of the sensing element is very high. The presence of an integrator following the direct chain transfer allow to guarantee this relation, and therefore ensures the absence of static error at the output.

3. The Digital GMI Sensor

The architecture of the digital GMI sensor (representing the direct chain of the magnetometer) is presented in Fig. 3. The proposed concept is based on a new digital electronic conditioning for the high sensitivity GMI magnetic sensor and based on a Field Programmable Gate Array (FPGA).

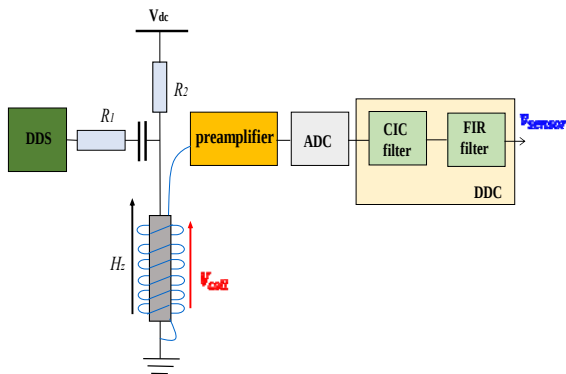


Fig. 3. Hardware architecture of the off-diagonal GMI sensor using a Direct Digital Synthesizer (DDS) and a Digital Down Converter (DDC).

As presented in our recent work [10, 13, 15] a Direct Digital Synthesizer (DDS) supplied the High frequency (HF) excitation current for the GMI sensing element, through a resistor R_1 . This DDS is mainly made of a Numerical Controlled Oscillator (NCO) associated to a Digital-to-Analog Converter (DAC). A dc current (provided by a battery, V_{dc} , and a resistor R_2) is also used so as to remove the bamboo domain [14]. The voltage across the sensing element is optionally amplified by a low-noise preamplifier before being digitized by an analog-to-digital converter (ADC). At the output of the ADC, the data are then transmitted to a Digital Down Converter (DDC) for a quadrature lock-in detection.

The voltage across the sensing element is optionally amplified by a low-noise preamplifier before being digitized by an analog-to-digital converter (ADC). At the output of the ADC, the data are then transmitted to a Digital Down Converter (DDC) for a quadrature lock-in detection. This DDC include a digital multiplier and a cascade of two low-pass digital filter: a Cascade Integrator Comb (CIC) decimation filter and a Finite Impulse Response (FIR) filter. Promising performance of $1.8 \text{ pT}/\sqrt{\text{Hz}}$ (roughly comparable to the best reported in the state of the art) are obtained in the white noise region that shows the potential of the proposed concept in the realization of high sensitivity sensors [12, 13].

4. Sensor Transfer Function

The objective of this section is to model the sensor transfer function in order to discuss the stability of the magnetometer. The concept presented in Fig. 2 can be divided into 2 parts, the excitation system associated with the sensing element (made of the DDS and the sensing element) and the demodulation stage (including the ADC and the DDC). The transfer function of each parts is detailed hereafter.

4.1. The Excitation System and the Sensing Element

The transfer function of the sensitive element is defined by the ratio between the voltage across the sensitive element, V_c , and the measured field, H_{meas} . The transfer function, H_1 is such that:

$$H_1 = \frac{v_c}{H_z} = \frac{Z_{21} \times I_{ac}}{H_z} = S_\Omega \times I_{ac} = S_v, \quad (3)$$

where

- I_{ac} is the amplitude of the excitation current;
- Z_{21} is the impedance of the sensing element in off-diagonal configuration;
- S_Ω and S_v are the intrinsic sensitivity of the sensing element in Ω/T (Ohm per Tesla) and the voltage sensitivity in V/T , respectively.

The voltage across the sensitive element is amplified by a preamplifier, having a gain, G_{preamp} . We assume here that the preamplifier gain remains constant in the bandwidth of the sensor. The voltage, V_{preamp} , at the preamplifier output is given by [16]:

$$V_{\text{preamp}} = G_{\text{preamp}} \times v_{\text{sens}} \times H_z = G_{\text{preamp}} \times S_v \times H_z \quad (4)$$

4.2. The Demodulation Stage

At the output of the preamplifier, the voltage is first digitized before being transmitted to a digital mixer and filtered by a 3rd order CIC decimation (also known as Hogenauer filter) with a decimation factor

N_{CIC} [17]. The transfer function of the filter, H_{CIC} , in the frequency domain is given by:

$$H_{CIC}(f) = N_{CIC}^3 e^{3j\pi f(N_{CIC}-1)} = G_{CIC} e^{j\phi}, \quad (5)$$

where G_{CIC} is the gain of the filter.

The delay due to the 3rd order CIC filter is given by (6) [16]:

$$\tau_{cic} = \frac{\partial \phi}{\partial \omega} = -\frac{\partial \left(\frac{3}{2} \omega (N_{CIC}-1) \right)}{\partial \omega} = \frac{3}{2} (N_{CIC}-1) \times \frac{1}{F_s} \quad (6)$$

At the CIC filter output, A FIR filter is used to fix the final bandwidth of the baseband. The transfer function of this a FIR filter, H_{FIR} , is given in the frequency domain by:

$$H_{FIR}(f) = \sum_{k=0}^{N_{FIR}} H_k \times e^{-j2\pi f k}, \quad (7)$$

where N_{FIR} is the number of coefficients of the filter. Assuming that $H_{FIR}(f) = V_{out}(f)/X(f)$, where $X(f)$ and $V_{out}(f)$ represent respectively the input and the output of the FIR filter in the frequency domain; the output of the sensor, v_{out} , can be expressed as:

$$v_{out}(f) = \sum_{k=0}^{N_{FIR}} H_k \times x(f) \times e^{-j2\pi f k} = G_{FIR} \times X(f) \times e^{-j2\pi f Z}, \quad (8)$$

where G_{FIR} is the FIR filter gain and Z , the number of delay stages. The delay, τ_{FIR} , due to the FIR filter is a function of the number of delay stages required for the filter implementation. For a filter with symmetrical coefficients (as the case in GMI sensor), the number of delay stages is given by [11, 12]:

$$Z = \frac{N_{FIR}-1}{2} \quad (9)$$

In GMI sensors, the choice of using FIR filter with symmetrical coefficients is justified by the will to reduce the delay of the demodulation stage [12], which can cause the instability of the magnetometer. As a results, the delay, τ_{FIR} , due to the FIR filter is expressed as:

$$\tau_{FIR} = \frac{Z}{F_s} = \frac{N_{FIR}-1}{2} \times \frac{1}{F_s} \quad (10)$$

The transfer function, F_{sensor} , of the sensor defined as the ratio between the output of the FIR filter and the measured magnetic field can be expressed as [17]:

$$F_{sensor}(f) = S_v \times G_{preamp} \times G_{DDC} \times e^{-j2\pi f \left(\frac{N_{FIR}-1}{2} + \frac{3[N_{CIC}-1]}{2} \right)}, \quad (11)$$

where G_{DDC} is the total gain of the DDC given by:

$$G_{DDC} = G_{CIC} * \frac{1}{2} * G_{FIR} \quad (12)$$

The $\frac{1}{2}$ factor is due to the 6 dB losses during mixing.

At the output of the integrator (necessary for proper operation of the magnetometer), the transfer function is given by:

$$F_{out}(f) = \frac{K}{1 + j\frac{f}{f_0}} S_v * G_{preamp} * G_{DDC} * e^{-j2\pi f \left(\frac{N_{FIR}-1}{2} + \frac{3[N_{CIC}-1]}{2} \right)}, \quad (13)$$

where K and f_0 are the gain and the cutoff frequency of the integrator.

5. Stability in Closed-loop

The stability of closed-loop systems can be studied starting from the open-loop system by quantifying the stability margins: gain and phase margins. It is therefore possible, knowing the transfer function of the sensor (open-loop), to discuss the stability of the magnetometer (closed-loop). In general, the magnetometer is stable if it has a positive gain margin and a positive phase margin.

Simulations were then realized using Matlab software in order to discuss the stability of the sensor in closed-loop according to the transfer function given in Eq. (13). The first simulations were conducted with the same parameters set in our recent work [10] to realize a sensor in open loop. The set of parameters was: $N_{CIC}=250$; $G_{preamp}=1$; $G_{DDC}=40$; $N_{FIR}=83$. Fig. 4 shows the Bode diagram of the open-loop sensor for a sensitivity, S_v of 620 kV/T.

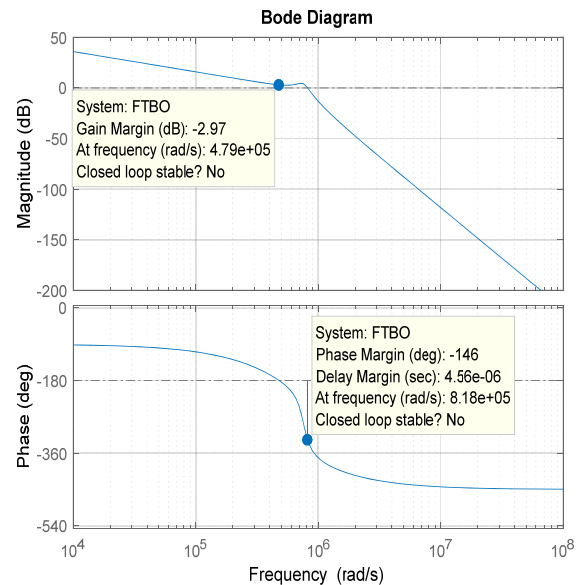


Fig. 4. Bode diagram of the open-loop sensor. The setting parameters was: $S_v=620\text{kV/T}$; $G_{preamp}=1$; $G_{DDC}=40$; $N_{FIR}=83$; $N_{CIC}=250$.

A gain margin of -2.97 dB and a phase margin of -146° is obtained that leads us to an unstable functioning of the magnetometer. Using this parameters, the estimated delay is of $3.32 \mu\text{s}$.

A second simulation was conducted for the same delay to see the influence of the sensitivity on the magnetometer stability. According to (3), the sensitivity can be reduced by reducing the amplitude of the I_{ac} high frequency excitation current. The setting parameters was: $N_{CIC}=250$; $G_{preamp}=1$; $G_{DDC}=40$; $N_{FIR}=83$. Fig. 5 shows the Bode diagram of the open-loop sensor for a sensitivity, S_v of 100 kV/T .

A gain margin of 12.9 dB and a phase margin of 71° is obtained that leads us to a proper functioning of the magnetometer with this setting parameters. Using this parameters, the estimated delay is also of $3.32 \mu\text{s}$.

The results of the simulation show that for a given delay, there are a maximum of sensitivity to ensure the functioning of the closed loop sensor.

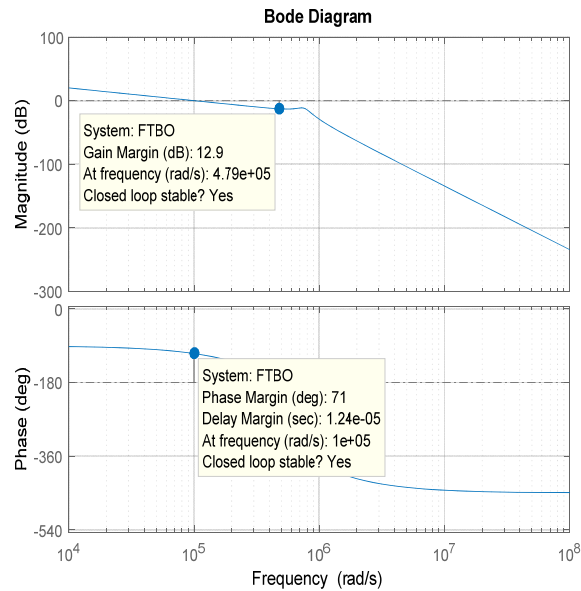


Fig. 5. Bode diagram of the open-loop sensor. The setting parameters was: $S_v=200 \text{ kV/T}$; $G_{preamp}=1$; $G_{DDC}=40$; $N_{FIR}=83$; $N_{CIC}=250$.

Simulations were then carried out to show the impact of the time-delay on the stability of the magnetometer for a given sensitivity. The sensitivity value of 620 kV/T , measured in our previous work [13] where the sensor operates in open loop, is retained in our simulation. The variation of the delay is done by adjusting the decimation ratio of the CIC filter or the number of filter coefficients. Fig. 6 shows the Bode diagram of the open-loop sensor for the given parameters hereafter: $N_{CIC}=100$; $G_{preamp}=1$; $G_{DDC}=40$; $N_{FIR}=83$.

A gain margin of 3.8 dB and a phase margin of 35.9° is obtained that leads us to a proper functioning of the magnetometer with this setting parameters. Using this parameters, the estimated delay is of $1.52 \mu\text{s}$.

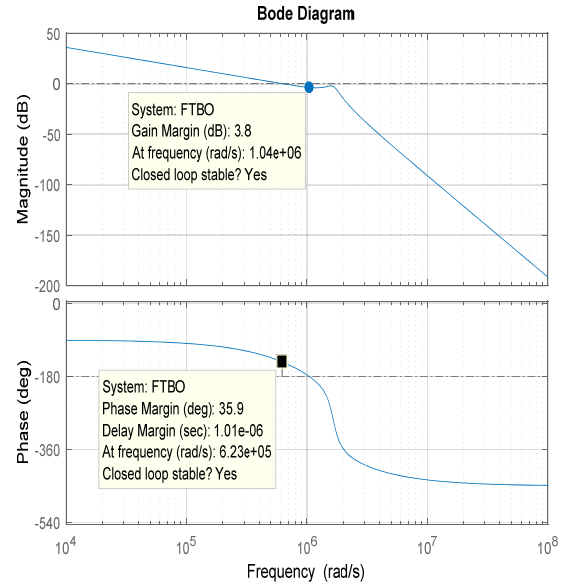


Fig. 6. Bode diagram of the open-loop sensor. The setting parameters was: $S_v=620 \text{ kV/T}$; $G_{preamp}=1$; $G_{DDC}=40$; $N_{FIR}=83$; $N_{CIC}=100$.

Another simulation was conducted by reducing the decimation ratio of the CIC filter (consequently reducing the delay according to Eq. (6)) in order to analyze the impact of the time-delay. Fig. 7 shows the Bode-diagram of the open-loop sensor. The setting parameters was $S_v=620 \text{ kV/T}$; $G_{preamp}=1$; $G_{DDC}=40$; $N_{FIR}=83$; $N_{CIC}=160$.

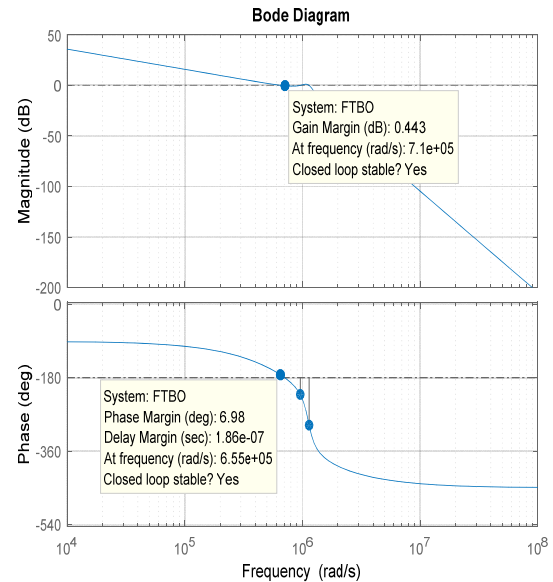


Fig. 7. Bode diagram of the open-loop sensor. The setting parameters was: $S_v=620 \text{ kV/T}$; $G_{preamp}=1$; $G_{DDC}=40$; $N_{FIR}=83$; $N_{CIC}=160$.

An estimated delay of $2.24 \mu\text{s}$ is obtained. A gain margin and a phase margin of 0.44 dB and 6.98° is obtained, respectively that leads us to a stable magnetometer. It should be noted that if the system is

at the limit of stability or if the stability margins are not sufficient (as in the case in Fig. 7), parasites could potentially introduce instabilities of the closed-loop system.

Fig. 8 shows the Bode-diagram for this parameters: $S_v=620\text{kV/T}$; $G_{\text{preamp}}=1$; $G_{\text{DDC}}=40$; $N_{\text{FIR}}=83$; $N_{\text{CIC}}=200$. With this setting parameters, the decimation ratio is increased resulting on the increase of the processing time-delay.

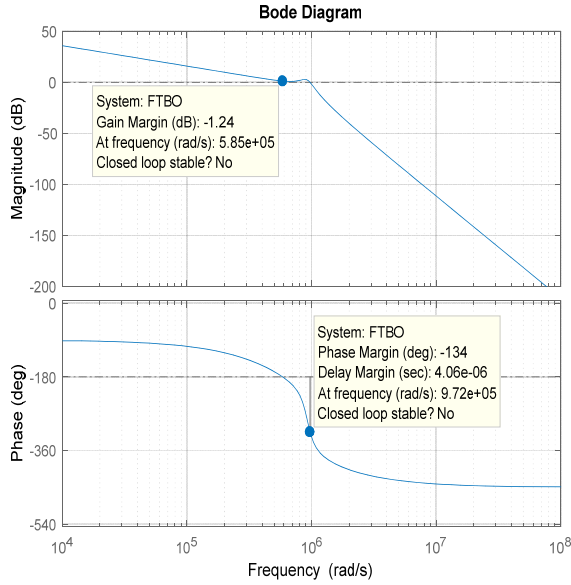


Fig. 8. Bode diagram of the open-loop sensor. The setting parameters was: $S_v=620\text{kV/T}$; $G_{\text{preamp}}=1$; $G_{\text{DDC}}=40$; $N_{\text{FIR}}=83$; $N_{\text{CIC}}=200$.

An estimated delay of $2.72 \mu\text{s}$ is obtained. A gain margin and a phase margin of -1.24 dB and -134° is obtained, respectively that leads us to a unstable magnetometer. Regarding Fig. 6, Fig. 7 and Fig. 8, results show that for a given sensitivity, there are a maximum of time-delay to ensure the functioning of the closed loop sensor.

In summary, the sensor parameters (sensitivity, delay) must be chosen judiciously in order to ensure the stability of the closed-loop magnetometer. These results were confirmed by practice.

In fact, firsts measurements were then realized in order to prove the proposed modelling and simulation. The block diagram of the proposed digital GMI magnetometer is given in Fig. 9. The polarization stage of the measurement chain is made of a Direct Digital Synthesizer (DDS), a battery and the two injection resistors, R_g et R_{bias} . The DDS provide the sinusoidal signal to the GMI element, through the resistor R_g . In a ferromagnetic wire having a circumferential anisotropy (as the case in the use GMI element), a dc current is necessary in order to observe the off-diagonal component. The dc current creates a circumferential dc field in the ferromagnetic wire. This dc field combines with the axial field to be measured produces a helical field which magnetizes the conductor along a helical path. This dc current is

obtained using a battery and the resistor R_{bias} . The voltage across the pick-up coil which is amplitude-modulated by the measured field, is first amplified by a low noise preamplifier, having a gain, G_{preamp} , before being digitized by an analog-to-digital converter (ADC) at a sampling frequency (F_s).

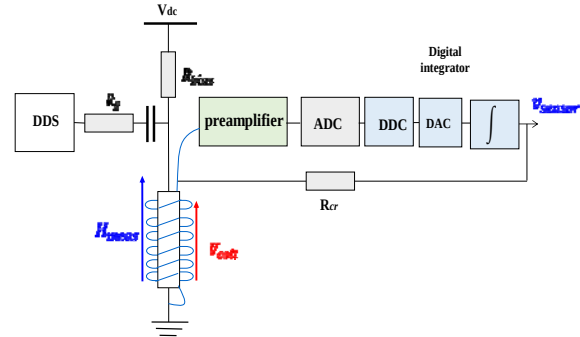


Fig. 9. Hardware architecture of a digital GMI magnetometer.

At the output off the DDC, data are transmitted to the DAC and then to a digital-to-analog converter (DAC). The DAC output is applied at the input of an integrator necessary to overcome the imperfections of the direct chain [18, 19]. The voltage at the output of the sensor is used to create the feedback magnetic field, H_{cr} . This is applied to the GMI wire via the resistor, R_{cr} and a coil wound around the GMI wire.

Closed-loop measurement has then been operated for the digital magnetometer in order to compare the results of the theoretical model with the measurement. The comparison procedure consisted in fixing a given delay (by fixing the decimation ratio of the CIC filter) and by varying the current I_{ac} so as to obtain the limit value of the current I_{ac} ensuring the stability of the magnetometer.

Fig. 10 shows the comparison of the maximum value (threshold) of the I_{ac} excitation current obtained by measuring and by our theoretical model (according to Eq. (11)) for different value of the decimation filter.

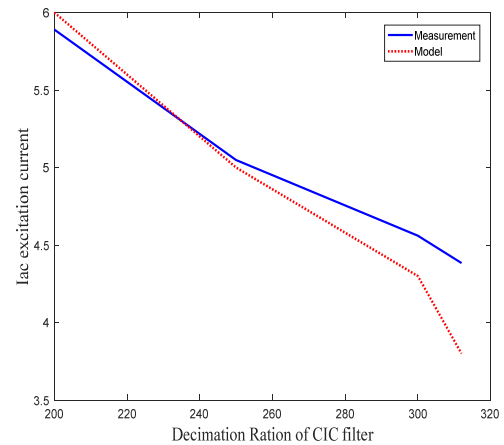


Fig. 10. Maximum value of excitation current in function of the decimation filter.

The obtained results validate our proposed theoretical model. Ongoing will focus on the characterization of the digital magnetometer.

6. Conclusions

In this paper, we have investigated the impact of the delay in the stability of the digital GMI magnetometer. The presented electronic conditioning is mainly based on digital down converter including low pass decimation filter induces time-delay due to processing. Each function of the open loop sensor is modelled in order to discuss the stability of the closed-loop by analyzing the stability margins: gain and phase margins. Obtained results show the possible operating of the digital magnetometer by making a trade-off between the sensitivity (by the I_{ac} excitation current) and the delay (by the decimation ration). Comparison between the proposed theoretical model and measurement of the digital magnetometer were performed. Results validates the theoretical approach for digital GMI magnetometer applications.

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