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Electric field feedback for Magneto(elasto)Electric magnetometer development

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Abstract. Magneto(elasto)Electric (ME) sensors based on magnetostrictive-piezoelectric composites have been investigated to evaluate their performances to sense a magnetic signal. Previous results have shown that the dielectric loss noise in the piezoelectric layer exhibits as the dominant intrinsic noise at low frequencies, which limits the sensor performances. Also, it has intrinsically no DC capability. To avoid a part of this limitation, modulation detection methods are evaluated through a frequency up-conversion technique [1-4]. Moreover, classical magnetic field feedback techniques can be used to increase the dynamic range, the sensing stability and the system linearity, too. In this paper, we propose a new method to feedback the system by using both the magneto-capacitance modulation and an electric field feedback technique. Our development shows the feasibility of the method and the results match with the theoretical description and material properties. Even if the present results are not totally satisfactory, they give the proof of concept and yield a way for the development of very low power magnetometers.

1. Introduction

A classical *ME_EE* modulation system [3] consists of a magnetoelectric composite as a sensitive element for picking up magnetic fields, a low noise operational amplifier to stress the sensor at the operating carrier frequency and to amplify the signal as well as a demodulation stage whose output is connected to a simple feedback loop. A ME laminate with multi-push-pull mode configuration [5] was chosen as the sensor. It provides a high sensitivity for magnetic-to-electric conversion due to a well-designed structure and the colossal piezoelectric and efficient magnetic coefficients of the ferroelectric and ferromagnetic materials. A rectangular piezoelectric layer of dimensions $40 \times 10 \times 0.2 \text{ mm}^3$, made of ferroelectric single crystal PMN-PT, is sandwiched between two ferromagnetic layers. Each ferromagnetic layer is made of three Metglas sheets with dimensions $80 \times 10 \times 0.15 \text{ mm}^3$. Two pairs of interdigital electrodes are stacked on both the top and bottom surfaces of the piezoelectric layer with a center-to-center space of 1.5 mm.

2. Modeling

2.1.1 Transfer function

In order to investigate the relation between the transfer functions in open loop and for a feedback loop, we need to specify the transfer function for an applied magnetic signal, first. Referring



to Fig. 1, the open loop transfer function is obtained by taking into account the sensor sensitivity, the charge amplifier and the demodulation circuit gains. It yields

$$A = \frac{\alpha_{ME_EE}^{NL}}{C_1} G_1 G_2 G_3 \quad (1)$$

where $\alpha_{ME_EE}^{NL}$ and C_1 are the nonlinear ME charge coefficient and the capacitance of the charge amplifier. G_1 , G_2 and G_3 are, respectively, the gains of the different succeeding stages. A quantitative evaluation of the deformation induced by a magnetic or electric field provides the key information for the feedback system. In a ME layered sensor, the mechanical capacitance, C_{mech} , is given by the constitutive equations. It yields a relationship between the mechanical force, F , and the micro displacement, Δu , both along the length direction of the sensor, as $\Delta u = F C_{mech}$. This force, F , can be generated by either a magnetic or electric field, which depends on the following expressions $F_m = \varphi_m H$ or $F_p = \varphi_p E$ [6-7]. The mechanical capacitance can be deduced from the mean flexibility, s_{33} , the sensor length, l , and the cross section area, A . It yields: $C_{mech} = s_{33} l/A$. The sensor mean flexibility can be obtained by taking into account those of the magnetostrictive layer and the piezoelectric layer and the thickness ratio n , between two layers [8]. Thus, an equivalent displacement due to a magnetic and an electric field results

$$\varphi_m H C_{mech} = \Delta u = \varphi_p E C_{mech} \quad (2)$$

Provided that the magnetic and piezoelectric phases match perfectly, the ratio between a magnetic field and an electric field is given by

$$\frac{H}{E} = \frac{\varphi_p}{\varphi_m} \quad (3)$$

Taking account of the magnetic susceptibility, χ , the feedback factor, β , representing the flux-to-voltage ratio in (T/V), is

$$\beta = \frac{B}{V} = \frac{\mu_0 H}{E l_p} = \frac{\varphi_p \mu_0}{\chi \varphi_m l_p} \quad (4)$$

where $\chi \varphi_m = 15 \text{ N}/(\text{A}\cdot\text{m}^{-1})$, $\varphi_p = 3 \times 10^{-5} \text{ N}/(\text{V}\cdot\text{m}^{-1})$ and $l_p = 1.5 \text{ mm}$, the center-to-center distance between interdigital electrodes [3]. The value of the flux-to-voltage ratio is $\beta = 1.7 \times 10^{-9} \text{ T/V}$. The term, $A/(1+A\beta)$, represents the feedback transfer function gain. This gain cannot be measured directly since the transfer function A combines the magnetolectric coefficient $\alpha_{ME/EE}$ which is related to the sensed magnetic field. However, we can apply an input voltage, V_{inFB} , at the positive input of the charge amplifier (*cf.* Fig. 1), to evaluate this term, $A\beta$. Therefore, we have

$$A\beta \approx \frac{1}{3} \alpha_{ME_EE}^{NL} G_1 G_2 G_3 \quad (5)$$

with the nonlinear voltage coefficient $\alpha_{ME_EE}^{NL}$. The factor of 1/3 is due to voltage divider induced by the resistances. The two equations (1) and (3) yield the predicted transfer function with a feedback loop as

$$\frac{A}{1+A\beta} \approx 3 \frac{\alpha_{ME_EE}^{NL}}{\alpha_{ME_ME}^{NL}} \approx \frac{1}{\beta}. \quad (6)$$

Up to certain point, the feedback loop permits to increase the bandwidth. Admitting that the cutoff frequency of the open loop transfer function is f_{c_OL} , we can deduce the closed loop bandwidth f_{c_FB} , with a feedback transfer function

$$T_{rFB}(f) = \frac{T_{rOL}(f)}{1+T_{rOL}(f)\beta} = \left(\frac{A}{1+A\beta} \right) \frac{1}{1+j \frac{2\pi f}{2\pi f_{c_FB}}} \text{ with } f_{c_FB} = f_{c_OL}(1+A\beta). \quad (7)$$

2.1.2 Equivalent magnetic noise (EMN)

By using the *ME/EE* modulation technique on a ME sensor in longitudinal vibration mode, the noise from the excitation source and the amplification electronics dominate over the noise performances of the sensor [9]. In the feedback loop, the voltage divider consisting of the three resistances, R , has little noise contribution since the associated voltage noise is small compared to other voltage sources. Presently, we believe that the dominant noise sources are originating from the excitation and amplification electronics. Thus, the total output voltage noise can be expressed as [2],

$$e_{nOL}^2(f) = G_1^2 G_2^2 G_3^2 \left(\left| \frac{R_1}{1+j2\pi R_1 C_1 f} \right|^2 (i_{nR1}(f)^2 + i_{namp}(f)^2) + \left| \frac{C_1+C}{C_1} \right|^2 (e_{namp}(f)^2 + e_{nexc}(f)^2) \right) \quad (8)$$

where $i_{nR1}(f)$ is the current noise source of the resistance R_1 , $i_{namp}(f)$ and $e_{namp}(f)$ are, respectively, the equivalent input current and the voltage noise sources of the charge amplifier. $e_{nexc}(f)$ is the noise source associated to the driving carrier voltage, V_{exc} . Thus, the output voltage noise spectral density and the transfer function with a feedback loop is defined by

$$e_{nsFB}(f) = \frac{e_{nOL}(f)}{1+A\beta}. \quad (9)$$

The EMN of this system is defined by the ratio of the output voltage noise, $e_{nOL}(f)$, and the magnetic signal transfer function, $T_{rOL}(f)$. In open loop mode, EMN can be directly evaluated from the output electric noise and the transfer function. Also, the EMN in feedback loop mode is expected to be equal to

$$b_{nFB}(f) = \frac{e_{nsFB}(f)}{T_{rFB}(f)} = \frac{\frac{e_{nOL}(f)}{1+A\beta}}{\frac{T_{rOL}(f)}{1+A\beta}} = \frac{e_{nOL}(f)}{T_{rOL}(f)} = b_{nOL}(f). \quad (10)$$

3. Experimental results

Several experiments were performed by applying a low frequency magnetic reference signal of two hertz. The latter was applied by a pair of Helmholtz coils in series with a resistance of 1 k Ω and having a transfer function of 6.8×10^{-4} T/A. The ME composite senses this magnetic field and induces a modulated signal which appears at the charge amplifier output. The voltage excitation carrier has a frequency of 25.3 kHz corresponding to the longitudinal sensor resonant frequency. The output signal from the charge amplifier is applied to the positive input of a differential amplifier presenting a high pass filter behavior having a voltage gain of 10 and a cut off frequency of 160 Hz. A sinusoidal

voltage, which is synchronized in phase and in frequency with that of the excitation carrier, is connected to the negative input of this subtractor to reduce the output carrier amplitude present in U_{ex} , as shown in Fig. 1. This is a critical step before the demodulation process since a too large carrier level prevents the noise measurements when using a spectrum analyzer. After demodulation and a further amplification through an amplifier G_3 , the signal is feedback towards the positive output of the charge amplifier. The schematic of the setup is given in figure 1.

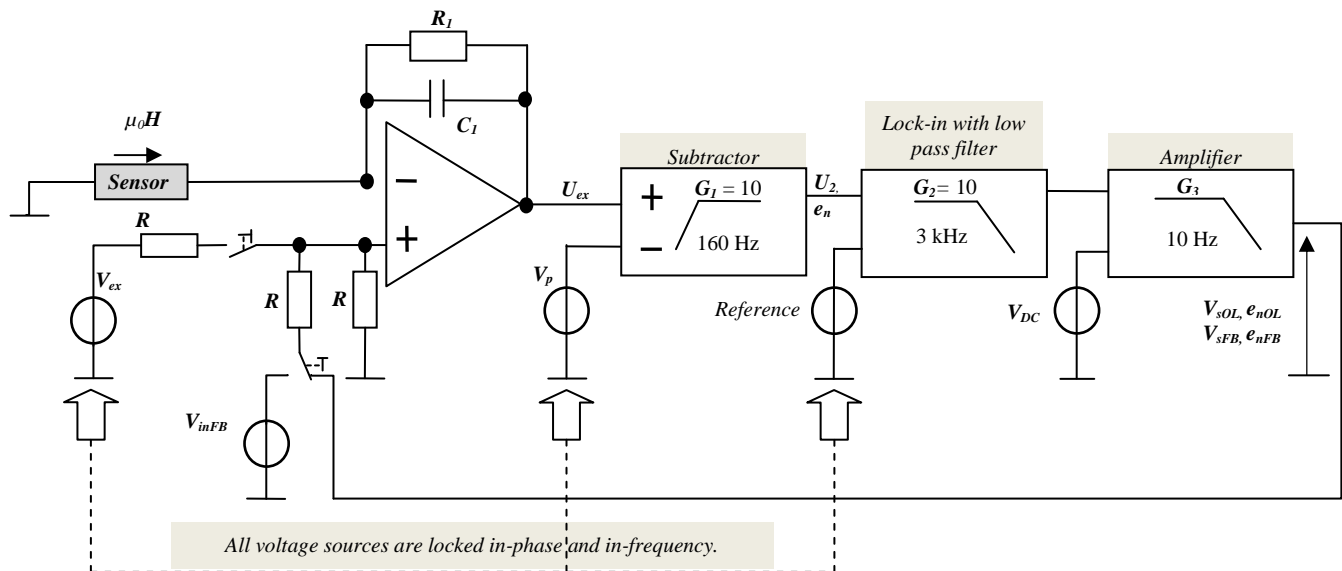


Fig. 1: Schematic of the magneto-capacitance modulation and detection principle, associated with an electric field feedback ($C_f = 100$ pF, $R_f = 10$ G Ω).

In order to characterize the sensing performance with the feedback loop, we measure each of the following transfer functions: the open forward gain A , the gain $A\beta$ of the feedback channel and the closed gain with the feedback loop $A / (1+A\beta)$. The pair of Helmholtz coils is used to generate the sinusoidal-sweeping magnetic signal along the length direction of the sensor.

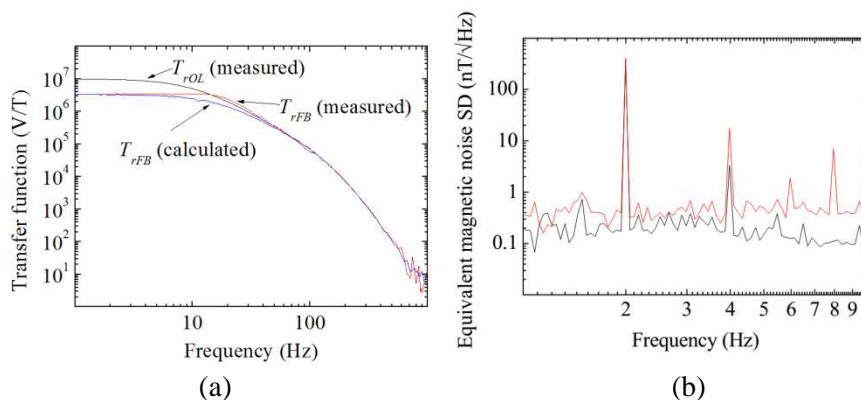


Fig. 2: Transfer function T_r (a) and observed equivalent magnetic noise b_n (b) in open mode (black) and feedback loop (red). In (a), the blue curve is the evaluated response.

By measuring the ratio between the output voltage and the input reference, one can separately measure the values of A and $A / (1+A\beta)$ for a gain of $G_3 = 50$, as shown in Fig. 1. The transfer function of the feedback channel, $A\beta$ can be deduced from A and $A / (1+A\beta)$ by taking into account the equality

$$T_{rFB_mes} = \left(\frac{A}{1+A\beta} \right). \text{ It yields}$$

$$A\beta = \frac{1}{T_{rFB_mes}} - 1 \quad (11)$$

where the index *mes* refers to measured values. The experimental and expected performances are compared in Fig. 2. According to our previous studies, the nonlinear charge coefficient $\alpha_{ME_EE}^{NL}$ for this given sample has a value around 250 nC/T at low frequencies for a voltage excitation of $V_{exc} = 400 \text{ mV}_{pk}$. Both the calculated and measured transfer functions in the feedback mode show a strong coherence with our previous measurements.

Conclusions

We have investigated the magnetic transfer function, the noise performance of a ME sensor working under modulation techniques, relying on an electric excitation and an electric feedback in the detection system in order to improve the linearity and the dynamic range. The performances between the measured values and the predicted ones have been compared. The gains and bandwidths have been found similar. The results give the proof of concept of the method and yield a way for the development of very low power magnetometers. To date, the performances of the feedback loop are limited by the nonlinear ME charge sensor coefficient, $\alpha_{ME_EE}^{NL}$, mainly.

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