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Sensitivity and Noise Evaluation of a Bonded Magneto(elasto)Electric Laminated Sensor Based on In-plane Magneto-capacitance Effect for Quasi-static Magnetic Field Sensing

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The quasi-static magnetic field detection of a layer-bonded Magneto(elasto)Electric (ME) laminate has been investigated by measuring the in-plane electric capacitance via its interdigital electrodes close to the piezoelectric resonant frequency. The ME layered composite is considered as a stress-induced dielectric effect, because there is practically no direct response of the electric capacitance to an external magnetic field [1]. The sensitivity is dominated by the magneto-elastic coupling in the magnetic layer and on the stress which is induced by the permittivity change in the piezoelectric layer. The low frequency magneto-capacitance effect is sensitive to an external magnetic bias which can modulate the electric permittivity by producing a stress. The magnetoelastic coupling is another important parameter for this magnetic field detection mode. For a given magnetic field, the amplitude of the magnetostriction is directly related to this parameter, too [2]. Therefore, an optimal magnetic bias can maximize the induced strain or stress which is coupled into the piezoelectric layer through the change of the electric permittivity in this layer. To evaluate the sensitivity and the noise performance based on the magneto-capacitance effect, we have used the piezoelectric and magnetic constitutive equations to predict the permittivity dependence [16]. Experimentally, this sensor achieved an equivalent magnetic noise spectral density, presently still limited, by the noise of the detection electronics, ~100 pT/√Hz at 1 Hz and offered a DC detection capability. Based on the model and experimental nonlinear factors, an equivalent sensor noise spectral density close to the pT/√Hz can be ultimately predicted taking into account the mechanical loss limitation of the sensor [16].

***Index Terms*—magnetoelectric, magnetic noise, modulation**

I. Introduction

A layered magnetoelectric (ME) laminated sensor consists of a magnetostrictive (MS) phase, a piezoelectric (PE) phase, bonding layers and associated electrodes. A magnetic induced strain can be generated in the MS phase via the magnetostrictive effect. This strain is coupled into the piezoelectric layer via the bonding layer. Many enhancements have been carried out by choosing the material and adjusting the ratio between the MS and PE phases of the composite [3], [4], [5], [6]. Thereafter, noise sources in the laminate have been investigated to evaluate the expected noise performance for magnetic sensor applications. For years, both intrinsic noise sources in the composite and extrinsic noise sources in the first amplification stage have been analyzed [7], [8], [9], [10], [11]. The ultimate noise performance of a ME layered laminate has been mathematically modeled and experimentally verified by means of diverse modeling and noise spectrum measurements [11]. It is mainly limited by the dielectric loss noise in the piezoelectric layers which result from electric dissipations induced by the electric domain wall random motions [12], [13]. Under an electric field excitation, especially at the piezoelectric resonance, the ME laminate can serve as a magneto-capacitance magnetic field sensor. This effect is based on the parametric modulation of the electric permittivity by a low-frequency magnetic-field-induced stress [14]. The magnetic field sensing capacitance of a ME laminate reaches it maximum around the piezoelectric resonant frequency, where the efficient dielectric coefficient is most sensitive to a low frequency external stress [15]. This detection method depends on the amplitude modulation of an excitation carrier which is actively driven by a sinusoidal electric field at a relatively high frequency. The low-frequency signal can be recovered from the envelope of the carrier by using a classical amplitude demodulation process.

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II. Sensitivity and Noise Floor

1) *Sensor description and experimental setup*

A ME laminate consists of three coupled layers. A PE layer consisting of 5 macro-fibers (40×2×0.2 mm^3) is sandwiched between two MS layers. Each MS layer is made of three bi-dimensional Metglas sheets (80×10×0.15 mm^3). The resulting ME laminate has a geometry of 80×10×0.35 mm^3. Two pairs of interdigital electrodes are disposed on both top and bottom surface of the PE layer with a center-to-center spacing of 850 μm. Thus, the electric signal can be sensed from the piezoelectric layer. Electrodes are connected to the negative input of a charge amplifier as shown in the Fig. 1. A sinusoidal excitation is applied on the positive input of the amplifier so as to electrically excite the ME laminated (*cf.* figure 1).

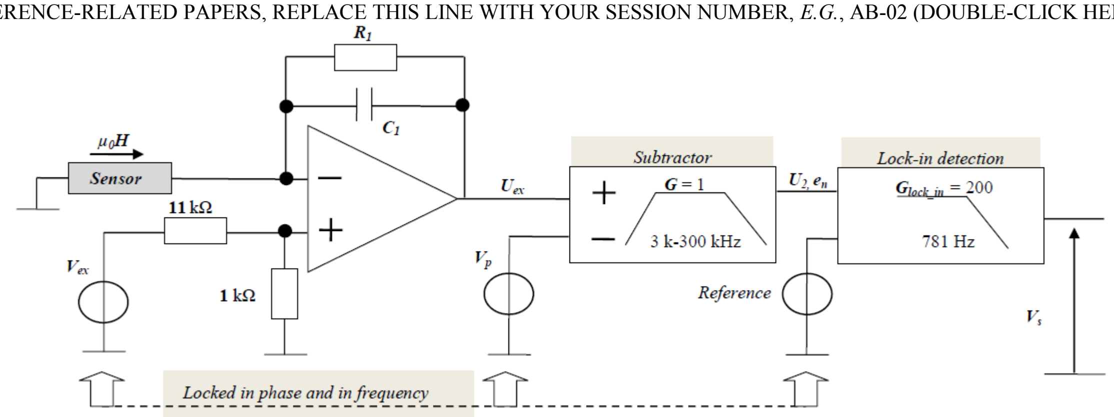

Fig. 1. Experimental scheme of the magneto-capacitance modulation and detection. The three locked generator used are HP33120A

The output signal from the charge amplifier is applied to one input of a subtracting amplifier having a [3 kHz, 300 kHz] bandwidth. A compensation of the carrier signal is made via the second input, in order to reduce its amplitude before the demodulation process with the lock-in amplifier [17]. The applied low frequency magnetic field signal is recovered by using the excitation signal as the reference signal.

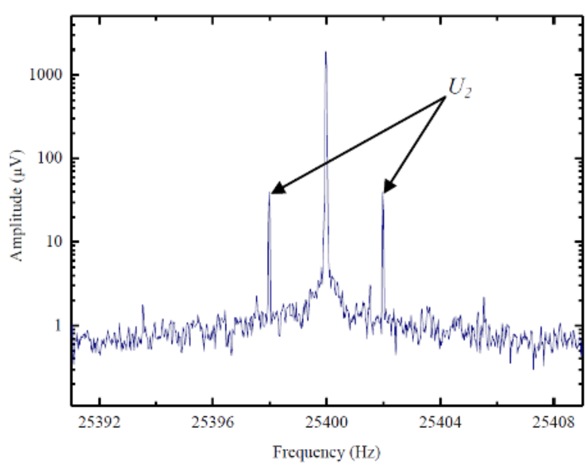

Fig. 2. Details of sideband reference signal (@ 2 Hz) around the excitation frequency appearing at the output U_2.

2) Nonlinearity and sensitivity

A sinusoidal magnetic field has been applied on the ME laminate along the longitudinal direction so that a low frequency reference signal (@ 2 Hz) is achieved. Here, the study is made for one freauency. However, the mqgnetic sensing content a bandzidth from DC to several hundred Hz according to the measurement. Fig. 2 represents the power spectrum curve of the output signal at the differential amplifier, showing the near carrier reference signal around the excitation carrier frequency of 25.4 kHz. These two peaks correspond to the frequency shifting of the low frequency reference signal around the excitation carrier frequency via the non-linearity in the ME laminate, the latter acting as a modulator at 25,400 ± 2 Hz with an amplitude of $G\times U_2$ for each peak. G is the gain of the subtractor. The nonlinear sensitivity is defined by the ratio between the carrier amplitude and that of one of the sideband reference signal at the output of the charge amplifier. The amplitude and noise spectrum curves were taken before the demodulation process in order to investigate the nonlinearity factor which can be defined as [16]

$$\gamma_1 = \frac{U_2}{U_{ex} H} \quad . \tag{1}$$

where U_{ex}, H are the amplitude of the carrier appearing at the output of the charge amplifier and the amplitude of the external applied magnetic field as low frequency reference signal, respectively.

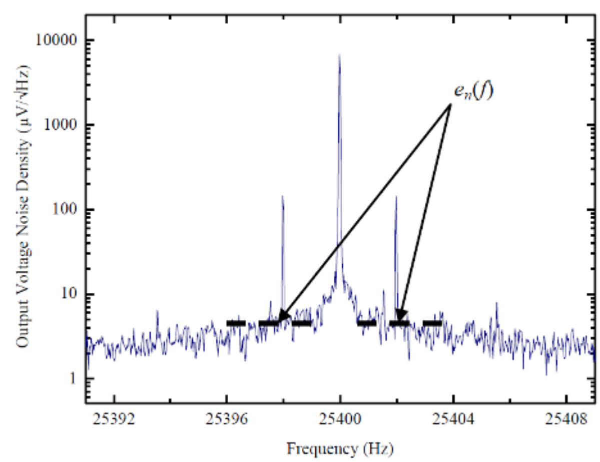

Fig. 3. Noise floor evaluation around the excitation frequency appearing at the output U_2.

The noise floor around the excitation frequency is given in Fig. 3. After the demodulation process, this noise level is transferred back to low-frequencies by considering the reference excitation signal. The ratio between the noise floor and the two peak amplitudes U_2 in Fig. 2 determines the noise performance for the magneto-capacitance modulation.

3) Noise evaluation

The expected intrinsic noise floor depends on the flexibility fluctuations due to mechanical dissipation. However, the observed noise level from the experiment was several orders higher than the expected theoretical noise level. This is due to a low nonlinear coefficient value and to the noise level induced by the sine wave generator used for the excitation signal and to the detection electronics. Firstly, the near carrier noise occurred because of the instability of the generator close to the carrier frequency as amplitude or phase noise, despite its high quality (close to the state of the art performance). This induces a *1/f* noise contribution which passes into the demodulation process. Secondly, the equivalent input voltage noise floor of the charge amplifier dominates the white noise floor.

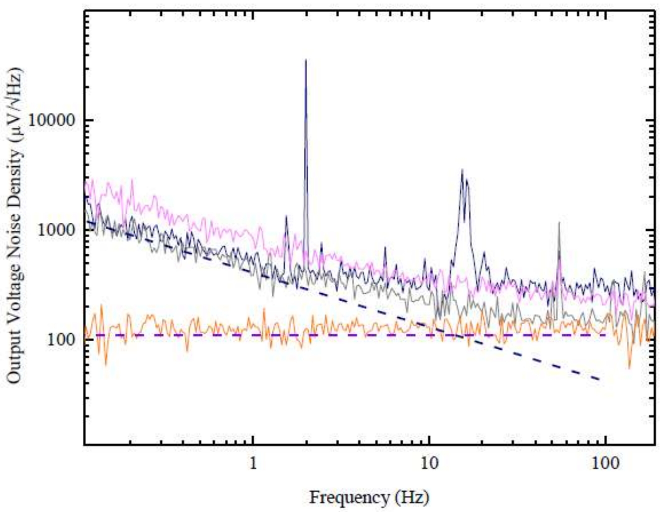

Fig. 4. Output voltage noise spectral density, V_s, as a function of the frequency.

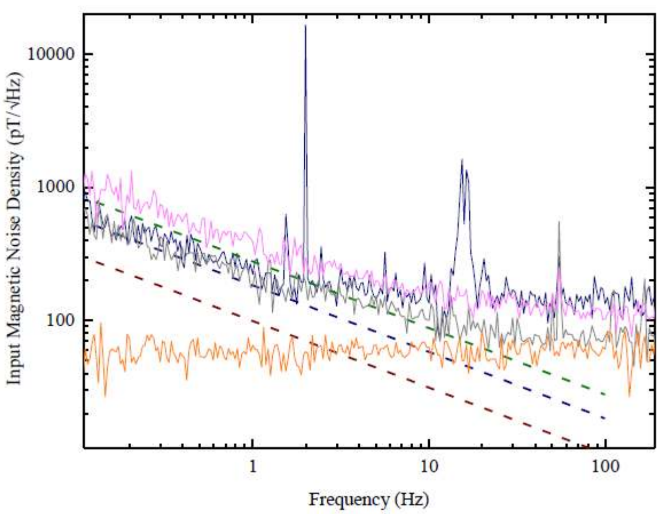

Fig. 5. Equivalent magnetic noise floor of the sensor as a function of the frequency.

Besides, the current noise of the resistance in the feedback loop of the charge amplifier produces a noise contribution as well. Taking the two noise sources, the output voltage noise expression under a certain voltage excitation is

$$e_n^2\left(f_{ex}\pm f\right)=\left(\frac{1}{2\pi f_{ex}C_1}\right)^2\left[i_{n\_R_1}^2\left(f_{ex}\pm f\right)+i_{n\_amp}^2\left(f_{ex}\pm f\right)\right]+\left(\frac{C+C_1}{C_1}\right)^2\left[e_{n\_amp}^2\left(f_{ex}\pm f\right)+e_{n\_exc}^2\left(f_{ex}\pm f\right)\right] \quad (2)$$

where $i_{n\_R1}\left(f_{exc}\pm f\right)$ is the current noise from the resistance R_1, $i_{n\_amp}\left(f_{exc}\pm f\right)$ and $e_{n\_amp}\left(f_{exc}\pm f\right)$ are the equivalent input current and voltage noise sources of the operational amplifier, respectively, $e_{n\_exc}\left(f_{exc}\pm f\right)$ is the noise of the sine wave excitation generator, C and C_1 are the sensor capacitor and the feed-back capacitor, respectively. By means of a classical demodulation process, the transfer function is observed with a value of 2.2×10^6 (in V/T). The output voltage noise floor and the equivalent magnetic noise floor are given in Fig. 4 and Fig. 5.

III. NOISE PERFORMANCE CHARACTERIZATION

The noise performance characterization of a ME laminate consists of 3 parts: Transfer function, output voltage noise and the equivalent magnetic noise characterization.

1) Magnetic signal transfer function

This sinusoidal magnetic field reference is fixed as a sweeping frequency. The ratio between the output of the lock-in amplifier and this signal permit evaluation of the transfer function. Considering the constitutive equation, we calculated the sensitivity in magneto-capacitance modulation mode [16]

$$\alpha_{ME\_EE}=\gamma_1\alpha_{EE}E_{exc} \quad (3)$$

where, α_{EE} is the direct electronic voltage sensitivity which is defined by

$$\alpha_{EE}=\frac{\partial Q}{\partial E}=\varepsilon_{33,p}A_p+\varphi_p^2C_{mech}\,. \quad (4)$$

where E and Q are respectively the applied voltage field and generated charge value across the interdigital electrodes. $\varepsilon_{33,p}$ and A_p are respectively the in-plan permittivity and the section surface of the piezoelectric layer. φ_p is the piezoelastic coupling coefficient and C_{mech} is the total mechanical capacitance of the composite. This equation consists of a non-elastic term and an elastic term [16]. The magneto-capacitance modulation mechanism is due to the piezoelastic coupling, φ_p, change in function of a magnetic-induced stress. Here, the stress was produced by the low frequency magnetic field. So, by applying this reference signal the demodulated output was maximized at low frequency. The transfer function was measured by using a frequency-sweeping sinusoidal signal in the working bandwidth of the system under the modulation mode. It yields

$$Tr_{ME\_EE}=\frac{\alpha_{ME\_EE}}{C_1}\times G\times G_{lock\_in} \quad (5)$$

where G_{lock_in} is the gain of the lock-in amplifier.

2) Equivalent magnetic noise floor

The equivalent magnetic noise of the ME composite under the magneto-capacitance working mode was characterized by the ratio between the output voltage noise spectral density and the magnetic transfer function. In Fig. 4, the dashed blue line and the dashed purple are respectively the simulation for the noise limits induced by the generator and by the voltage noise source of the charge amplifier. Gray and orange curves are respectively the measured limitation from the generator and lock-in amplifier. Above these curves, the noise level in blue and in pink are respectively the output voltage noise level for the magneto-capacitance modulation techniques with the sensor and the one with a passive capacitor (which value is close to the sensor capacitance) for the present setup.

Shown in Fig. 5 is the equivalent magnetic noise of the detection electronics. The noise measurement were made in a magnetic shielding room to avoid the environmental magnetic noise influence. The curves in the Fig. 5 are the equivalent noise levels referring to the output voltage noise limitation and the low frequency magnetic field transfer function of the magneto-capacitance modulation with present nonlinear coefficient. The colors correspond to the ones in Fig. 4 with two additional dashed lines in dark green and dark red for the top and bottom limitations. Several 100 pT/√Hz was achieved at 1 Hz and 100-150 pT√Hz was achieved at white bandwidth. These limitations are due to the incertitude of the noise limitation from the generator. So, we found that the excitation noise from the generator is the main contribution at low frequency. However, the amplifier voltage noise gives the main noise contribution in the white regime.

IV. Conclusion

By using the magneto-capacitance effect, a quasi-static magnetic field can be sensed in a layered ME composite by measuring the modulated electric capacitance. This effect was used for low frequency magnetic field sensing. The output sensitivity depends on the nonlinearity in the ME laminate. Noise limitations have been analyzed and experimentally measured by considering the noise contribution from the excitation and detection electronics. Based on the magneto-capacitance effect, the equivalent magnetic noise floor was still limited by the instability from the excitation electronics in low frequency (1/*f* noise) and from the detection electronics in white frequencies, presently. Besides, a further higher performance is expected by reducing the electronic noise from the excitation and detection circuits and by improving the nonlinear factor, γ_1, of the laminate.

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References

[1] N. A. Pertsev, S. Prokorenko, and B. Dkhil, "Giant magnetoelectric of strained ferroelectric-ferromagnetic hybrids," *Physical Review B,* vol. 85, p. 134111, 2012

[2] D. C. Jiles, "Theory of the magnetomechanical effect," *Journal Physics D: Applied Physics,* vol. 28, pp. 1537-1546, 1995

[3] G. Sreenivasulu, U. Laletin, V. M. Petrov, V. V. Petrov, and G. Srinivasan, "A permendur-piezoelectric multiferroic composite for low-noise ultrasensitive magnetic field sensors," *Applied Physics Letters,* vol. 100, p. 173506, 2012

[4] S. Dong, J. Cheng, J. F. Li, and D. Viehland, "Enhanced magnetoelectric effects in laminate composites of Terfenol-D/Pb(Zr,Ti)O_3 under resonant drive," *Applied Physics Letters,* vol. 83, p. 4812, 2003

[5] Z. Fang, S. G. Lu, F. Li, S. Datta, Q. M. Zhang, and M. EI Tahchi, "Enhancing the magnetoelectric response of Metglas/polyvinylidene fluoride laminates by exploiting the flux concentration effect," *Applied Physics Letters,* vol. 95, p. 112903, 2009

[6] H. Greve, E. Woltermann, H. -J. Quenzer, B. Wagner, and E. Quandt, "Giant magnetoelectric coefficients in $(Fe_{90}Co_{10})_{78}Si_{12}B_{10}$-AlN thin film composites," *Applied Physics Letters,* vol. 96, p. 182501, 2010

[7] Y. Wang, D. Gray, D. Berry, J. Gao, M. Li, J. Li, and D. Viehland, "An extremely low equivalent magnetic noise magnetoelectric sensor," *Advanced Materials,* vol. 23, pp. 4111-4114, 2011

[8] X. Zhuang, M. Lam Chok Sing, C. Cordier, S. Saez, C. Dolabdjian, J. Das, J. Gao, J. Li, and D. Viehland, "Analysis of noise in magnetoelectric thin-layer composites used as magnetic sensors," *IEEE Sensors Journal,* vol. 11, p. 2183, 2011

[9] S. Marauska, R. Jahns, H. Greve, E. Quandt, R. Knochel, and B. Wagner, "MEMS magnetic field sensor based on magnetoelectric composites," *Journal of Micromechanics and Microengineering,* vol. 22, p. 065024, 2012

[10] Z. Xing, J. Li, and D. Viehland, "Modeling and the signal-to-noise ratio research of magnetoelectric sensors at low frequency," *Applied Physics Letters,* vol. 91, p. 142905, 2007

[11] X. Zhuang, C. Cordier, S. Saez, M. Lam Chok Sing, C. Dolabdjian, J. Gao, J. F. Li, and D. Viehland, "Theoretical analysis of the intrinsic magnetic noise spectral density of magnetostrictive-piezoelectric laminated composites," *Journal of Applied Physics,* vol. 109, p. 124512, 2011

[12] Y. Zhuang, S. O. Ural, A. Rajapurkar, S. Tuncdemir, A. Amin, and K. Uchino, "Derivation of piezoelectric losses from admittance spectra," *Japanese Journal of Applied Physics,* vol. 48, p. 041401, 2009

[13] F. A. Levinzon, "Noise of piezoelectric accelerometer with integral FET amplifier," *IEEE Sensors Journal,* vol. 5, p. 1235, 2005

[14] Q. Liu, X. Bian, J. Zhou, and P. Liu, "Colossal magnetodielectric effect cause by magnetoelectric effect under low magnetic field," *Indian Academy of Sciences,* vol. 34, pp. 238-286, 2011

[15] C. Israel, V. M. Petrov, G. Srinivasan, and N. D. Mathur, "Magnetically tuned mechanical resonances in magnetoelectric multilayer capacitors," *Applied Physics Letters,* vol. 95, p. 072505, 2009

[16] X. Zhuang, M. Lam Chok Sing, C. Dolabdjian, Y. Wang, P. Finkel, J. Li, and D. Viehland, "Mechanical noise limit of a strain coupled magneto(elasto)electric sensor operating under a magnetic or an electric field modulation around its resonant frequency," *IEEE Sensors,* to be submitted

[17] M. Malatek, B. Dufay, S. Saez, C. Dolabdjian, "Improvement of the off-diagonal magnetoimpedance sensor noise," *Sensors & Actuators A,* vol. 204, pp. 20-24, 2013

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