



**HAL**  
open science

## Investigations on the equivalent magnetic noise of Magneto(Elasto)Electric sensors by using modulation techniques”, Key Engineering Materials

Xin Zhuang, Marc Lam Chok Sing, Christophe Dolabdjian, Peter Finkel, Jie Fang Li, Dwight Viehland

### ► To cite this version:

Xin Zhuang, Marc Lam Chok Sing, Christophe Dolabdjian, Peter Finkel, Jie Fang Li, et al.. Investigations on the equivalent magnetic noise of Magneto(Elasto)Electric sensors by using modulation techniques”, Key Engineering Materials. Key Engineering Materials, 2014, 605, pp.344. hal-01061767

**HAL Id: hal-01061767**

**<https://hal.science/hal-01061767>**

Submitted on 19 Jun 2015

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Investigations on the equivalent magnetic noise of Magneto(Elasto)Electric sensors by using modulation techniques

ZHUANG Xin<sup>1,a</sup>, LAM CHOK SING Marc<sup>1,b</sup>, DOLABDJIAN Christophe<sup>1,c</sup>,  
FINKEL Peter<sup>2,d</sup>, LI Jie Fang<sup>3,e</sup>, VIEHLAND Dwight<sup>3,f</sup>

<sup>1</sup>Normandie Univ, France ; UCBN, GREYC, F-14032 Caen, France; CNRS, UMR 6072, F-14032 Caen, France

<sup>2</sup>Naval Undersea Warfare Center, Newport, Rhode Island 02841, USA

<sup>3</sup>Materials Science and Engineering, Virginia Tech, Blacksburg, VA 24061, USA

<sup>a</sup>xin.zhuang@unicaen.fr, <sup>b</sup>marc.lam@ensicaen.fr, <sup>c</sup>christophe.dolabdjian@unicaen.fr,  
<sup>d</sup>peter.finkel@navy.mil, <sup>e</sup>jiefang@mse.vt.edu, <sup>f</sup>viehland@mse.vt.edu

**Keywords:** ME, magnetic noise, non-linearity, modulation.

**Abstract.** The equivalent magnetic noise of the magnetoelectric (ME) layered composite sensors has been investigated for various modulation techniques. The ME thin film response to an electric modulation or a magnetic modulation can be sensed by using either a charge amplifier or a coil wound around the sample and then demodulated by a synchronous detector. The equivalent magnetic noise for these excitations methods has been compared. As expected, the low-frequency fluctuations can be lowered when the magnetoelectric sensor is operated in a modulation mode. Results show that these methods can give the same level of equivalent magnetic noise for a certain strain-excitation. In theory, mechanical noise appears as the only dominant noise source after the demodulation process in the case of a certain strong amplitude excitation carrier signal. By using these modulation techniques, an equivalent magnetic noise level of 10-100 pT/ $\sqrt{\text{Hz}}$  at 1 Hz was achieved with DC capability.

## Introduction

The composite magnetoelectric (ME) effect has been explained by the interaction between the magnetic signal sensed in the ferromagnetic material and the electric signal generated in the piezoelectric material [1]. The intermediated strain and stress can be regarded as the mediated parameters to realize the indirect ME effect (differing from the direct ME effect which is explained by Maxwell equations). The magnetic, mechanical and electric parameters can be coupled by diverse effects in a ME composite. The magnetic flux density responding to the external magnetic field can generate a magnetostriction via Joule's effect in the ferromagnetic material. So, the electrostrictive and piezoelectric effects govern the coupling between the mechanical and electric parameters in the piezoelectric layer. The mechanical parameters are defined by Newton's law, the motion equation and Hooke's law, respectively.

According to the inverse of Hooke's law, the magnetic field induces strain. Then, the latter can achieve a stress in the ferromagnetic material. This stress can be transferred into the piezoelectric material via Newton's second law. A strain in the piezoelectric layer can generate an electric charge via the piezoelectric effect across the electrodes. An electric amplifier can be used to sense the signals. This is the passive detection method with a ME composite. When a voltage is applied onto the electrodes across the piezoelectric layer, a strain can be generated in this layer and a corresponding stress in this layer is transferred into the magnetostrictive layer. Therefore, a magnetization appears along the ferromagnetic layer which could be sensed by a coil wound around the ME composite. These two effects can be considered as the strain induced direct and indirect ME effects. The first effect has been widely investigated as passive mode for magnetic field sensing since several years [2]. The second effect has been investigated as the converse ME effects for studying the material properties. Besides the passive mode detection, parameter modulation is another method for magnetic

field detecting. A low frequency magnetic signal can modulate the magnetic or electric carrier. The low frequency magnetic signal can be recovered by using a lock-in. Generally speaking, the ME composite can work as a magnetic sensor in passive and active modes by using a charge amplifier or a coil wound around the sensor.

### ME modulations

An excitation signal can be applied as a carrier signal at a relative high frequency on the magnetic sensor to achieve a strong magnetic or electric output. These carrier signals can be modulated by the low frequency magnetic signal. Thus, by using a strong magnetic field excitation, a generated strain of the sensor can be created which is modulated by a low frequency magnetic signal via the nonlinearity of the sensor. Due to the properties of the ferromagnetic and piezoelectric layers, there exist the magneto-flux, electro-charge (or voltage), the magneto-charge (or voltage) and electro-flux modulations for magnetic field sensing. The first two methods depend respectively mainly on the piezoelectric or magnetostrictive layers. The latter two are determined by the cross magnetoelectric properties, nonlinear factor and the interaction between the sensed low frequency signals and excitation carriers.

Because the sensor performance depends on not only the output signal corresponding to the sensed magnetic signal but also on the output noise level, the contributions of diverse noise sources for modulation sensing methods must be investigated. According to dissipation theories, fluctuations originate from the loss terms between magnetic, electric and mechanical parameters. These diverse loss terms can result from the charge particulars and the magnetic or electric domain walls motions. The relations between the magnetic field  $H$ , flux  $\Phi$  and flux density  $B$ , electric field  $E$  (voltage  $V$ ), charge  $Q$  and current  $I$ , mechanical stress  $T$ , strain  $S$  and motion speed  $v$  and their coupling coefficients or equations are shown in Fig. 1.  $\epsilon$  is the dielectric constant,  $\rho$  is electric resistivity,  $\mu$  is the magnetic permeability,  $s_m$  and  $s_p$  are magnetic and electric flexibility coefficients,  $\gamma_m$  and  $\gamma_p$  are friction factors of the ferromagnetic and piezoelectric layer,  $t$  is the time and  $A_m$  is the surface of the ferromagnetic layer [3].

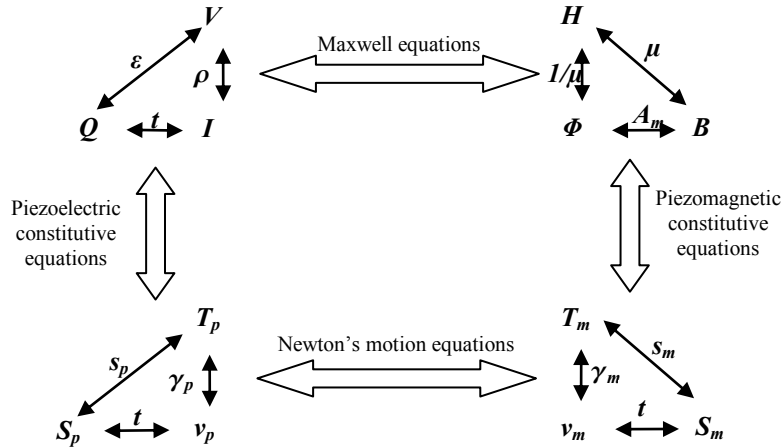


Figure 1: Magnetic, mechanical and electric parameters with associated coupling coefficients and links.

### Constitutive and Coupling equations

The magnetic, electric and mechanical behaviors of a composite ME laminate can be summarized by the magnetic constitutive equations combined with the piezoelectric constitutive equations in the L-L mode [4]

$$\begin{cases} D = d_{33,p}T_p + \epsilon E \\ S_p = s_{33,p}T_p + d_{33,p}E \end{cases} \text{ and } \begin{cases} B = d_{33,m}T_m + \mu^T H \\ S_m = s_{33,m}T_m + d_{33,m}H \end{cases} \quad (1)$$

In the harmonic regime [4], the coupling equations can be deduced as

$$\begin{cases} (v_1 + v_2) \tilde{z} \\ \tilde{\zeta} \\ \tilde{\zeta} \\ F = \tilde{z} \end{cases} + j\omega \mu^S V_m (H - M) = 0 \quad (2)$$

$$\begin{cases} \tilde{\zeta} \\ \tilde{\zeta} \\ F = \tilde{z} \end{cases} + j\omega V_p (D - \varepsilon^S E) = 0$$

where  $\tilde{z}$  is the mechanical impedance. In the present example, the mechanical capacitance  $\tilde{z}$  is considered equal to:  $\tilde{z} = \frac{1}{\omega \tilde{\zeta}}$  (3)

where  $\tilde{\zeta}$ ,  $l$ ,  $w$  and  $t_{lam}$  are the mean flexibility, the length, the width and the thickness of the sensor, respectively. The nonlinear development of the flexibility in a Taylor series expansion for the mechanical force excitation is given by  $\tilde{\zeta} = \zeta_0 + \kappa_1 F_{ex} + (\kappa_2/2) F_{ex}^2 + \dots$  with first and second order mechanical nonlinearity factors,  $\kappa_1$  and  $\kappa_2$ . The magneto-elastic coupling coefficient is

$$\tilde{\zeta} = \frac{\rho_{33,m}}{\omega} \quad (4)$$

where the magnetostrictive and piezomagnetic constant can similarly be developed as a function of a magnetic excitation  $H_{ex}$  or a force excitation  $F_{ex}$  in terms of the first and second magnetostrictive nonlinear coefficients  $\eta_1$ ,  $\eta_2$  as  $\tilde{\zeta} = \zeta_0 (1 + \eta_1 H_{ex} + (\eta_2/2) H_{ex}^2 + \dots)$  or with first and second piezomagnetic nonlinear coefficients  $\tau_1$ ,  $\tau_2$  as  $\tilde{\zeta} = \zeta_0 (1 + \tau_1 F_{ex} + (\tau_2/2) F_{ex}^2 + \dots)$ . The elasto-electric coupling coefficient is:

$$\tilde{\zeta} = \frac{\rho_{33,p} l}{\omega} \quad (5)$$

with the piezoelectric coefficient developed as a function of an excitation voltage  $\tilde{\zeta} = \zeta_0 (1 + \gamma_1 V_{ex} + (\gamma_2/2) V_{ex}^2 + \dots)$  or an excitation force  $\tilde{\zeta} = \zeta_0 (1 + \psi_1 F_{ex} + (\psi_2/2) F_{ex}^2 + \dots)$ .

From the coupling equations, the interactions between the magnetic and electric parameters are given by

$$\begin{bmatrix} \tilde{\zeta} \\ \tilde{\zeta} \\ 0 \\ \tilde{\zeta} \\ \tilde{\zeta} \\ -\tilde{\zeta} \end{bmatrix} \begin{bmatrix} -\mu^S V_m \\ 0 \\ \tilde{\zeta} \\ -\tilde{\zeta} \\ (\tilde{\zeta} C_{mech} - \mu^S V_m) V_p \\ 0 \end{bmatrix} \begin{bmatrix} E \\ D \\ H \\ M \end{bmatrix} = 0 \quad (6)$$

So, the magnetoelectric coefficients are deduced from (6), as

$$\left| \frac{\partial^2 I}{\partial H_{ex} \partial H} \right| = \eta_1 \frac{\varphi_m \varphi_p}{Z_{mech}} \quad \text{and} \quad \left| \frac{\partial^2 V}{\partial H_{ex} \partial H} \right| = \frac{\eta_1 \varphi_m \varphi_p}{\varphi_p^2 - j\omega C Z_{mech}} \quad (7)$$

for a magnetic excitation and as

$$\left| \frac{\partial^2 I}{\partial V_{ex} \partial H} \right| = \frac{\tau_1 \varphi_m \varphi_p^2}{Z_{mech}} \quad \text{and} \quad \left| \frac{\partial^2 V}{\partial V_{ex} \partial H} \right| = \frac{\tau_1 \varphi_m \varphi_p^2}{\varphi_p^2 - j\omega C Z_{mech}} \quad (8)$$

for an electric excitation. Taking account of the intrinsic noise of the sensor [5] and by using the previous results, the equivalent magnetic noise of the modulated sensor can be evaluated as

$$b_n^2 = \left( \mu \frac{\kappa_1}{\eta_1} \right)^2 4(k_B T m 2\pi f_0 / Q + 4k_B T \tan(\delta_{mech}) / 2\pi f C_{mech}) \quad (9)$$

and

$$b_n^2 = \left( \mu \frac{\kappa_1}{\varphi_m \tau_1} \right)^2 (4k_B T m 2\pi f_0 / Q + 4k_B T \tan(\delta_{mech}) / 2\pi f C_{mech}) \quad (10)$$

where  $b_n^2$  is the equivalent magnetic noise power spectral density,  $k_B$  the Boltzmann constant,  $m$  the mass of sensor,  $f_0$  the mechanical resonance,  $Q$  the mechanical quality factor,  $T$  the temperature,  $\tan(\delta_{mech})$  the mechanical loss and  $f$  the working bandwidth of the sensor.

## Results

One example of our experimental results is given in Fig. 2 for a multi-push pull ME sensor with magnetic, electric excitations at the input and an electric and flux detection circuit as amplifier. The equivalent magnetic noise spectral densities are around 10- 100 pT $\sqrt{Hz}$  for magneto-electric cross modulation.

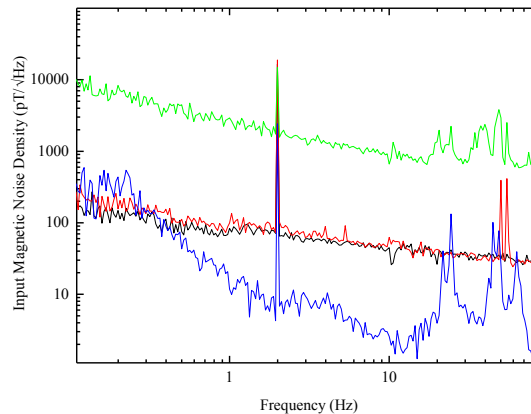


Figure 2: Equivalent magnetic noise spectral density for the magnetic excitation with electric detection, the electric excitation with magnetic detection, electric excitation with electric detection and passive detection (black, red, green, blue curves, respectively). A signal at 2 Hz is used as the reference.

## Summary

The nonlinearity from the ferromagnetic and ferroelectric layer can be considered as the mechanism for the modulation. The sensor sensitivity has been theoretically calculated and explained by using a noise formula developed from the piezoelectric and magnetic constitutive equations. The noise spectral densities have been experimentally measured and compared for the modulation techniques and the passive working modes. These results confirm a better magnetic field sensing at low frequencies with the help of the modulation techniques by using the nonlinearities in ferromagnetic and ferroelectric layers.

## Acknowledgement

This work is supported by the Office of Naval Research.

## References

- [1] C. Nan, M. I. Bichurin, S. Dong, D. Viehland and G. Srinivasan: J. Appl. Phys., 103(2008), p. 31101
- [2] C.-W. Nan: Physical Review b, Vol. 50 (1994), p. 6082
- [3] Z. Wang, R. Zhang, E. Sun et W. Cao: J. Appl. Phys., Vol. 107 (2010), p. 014110
- [4] S. Dong, J. Li and D. Viehland: IEEE Trans. Ultra.. Ferro.. Freq. Control, Vol. 50 (2003), p. 1253
- [5] S. Dong, J. Li and D. Viehland: J. Appl. Phys., Vol. 95 (2004), p. 2625
- [6] X. Zhuang, M. Lam Chok Sing, C. Dolabdjian, P. Finkel, J. Li and D. Viehland, IEEE.Sensors. J., DOI: 10.1109/JSEN.2013.2274098