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

ZHUANG Xin¹,a, LAM CHOK SING Marc¹,b, DOLABDJIAN Christophe¹,c, FINKEL Peter²,d, LI Jie Fang³,e, VIEHLAND Dwight³,f

¹Normandie Univ, France ; UCBN, GREYC, F-14032 Caen, France; CNRS, UMR 6072, F-14032 Caen, France
²Naval Undersea Warfare Center, Newport, Rhode Island 02841, USA
³Materials Science and Engineering, Virginia Tech, Blacksburg, VA 24061, USA

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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 excitation 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 10⁻¹⁰⁻¹⁰₀ pT/√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 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. $\varepsilon$ 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.](image)

**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]

\[
\begin{align*}
D &= d_{33,p} T_p + \varepsilon E \\
S &= s_{33,p} T_p + d_{33,p} E \\
B &= d_{33,m} T_m + \mu' H \\
S_m &= s_{33,m} T_m + d_{33,m} H
\end{align*}
\]

In the harmonic regime [4], the coupling equations can be deduced as
\[
\left\{ \begin{align*}
(v_1 + v_2), & \quad \zeta \quad \tilde{\gamma} \\
\zeta, & \quad j \omega \mu \tilde{Y}_m(H - M) = 0 \\
\zeta, & \quad j \omega \tilde{V}_m(D - e^\varepsilon E) = 0 \\
F = \tilde{\gamma}, & \quad v_2 
\end{align*} \right.
\] (2)

where \( \tilde{\gamma} \) is the mechanical impedance. In the present example, the mechanical capacitance \( \zeta \) is considered equal to:
\[
\tilde{\gamma} = \frac{1}{j \omega \varepsilon} \int_{-I_{\mathrm{in}}} \int_{t_{\mathrm{in}}} \int_{t_{\mathrm{in}}} \cdots
\] (3)

where \( I, l, w \) and \( t_{\mathrm{in}} \) 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 \( \zeta = + \kappa_l F_m + (\kappa_2/2) F_m^2 + \cdots \) with first and second order mechanical nonlinearity factors, \( \kappa_l \) and \( \kappa_2 \). The magneto-elastic coupling coefficient is
\[
\tilde{\gamma} = \zeta_33, m
\] (4)

where the magnetostrictive and piezomagnetic constant can similarly be developed as a function of a magnetic excitation \( H_m \) or a force excitation \( F_m \) in terms of the first and second magnetostrictive nonlinear coefficients \( \eta_l, \eta_2 \) as \( \tilde{\gamma} = \zeta_33, m (1 + \eta_l H_m + (\eta_2/2) H_m^2 + \cdots) \) or with first and second piezomagnetic nonlinear coefficients \( \tau_l, \tau_2 \) as \( \tilde{\gamma} = \zeta_33, m (1 + \tau_l F_m + (\tau_2/2) F_m^2 + \cdots) \). The elasto-electric coupling coefficient is:
\[
\tilde{\gamma} = \zeta_33, p, l
\] (5)

with the piezoelectric coefficient developed as a function of an excitation voltage \( \tilde{\gamma} = \zeta_33, p (1 + \eta_p V_m + (\eta_2/2) V_m^2 + \cdots) \) or an excitation force \( \tilde{\gamma} = \zeta_33, p (1 + \psi_p F_m + (\psi_2/2) F_m^2 + \cdots) \).

From the coupling equations, the interactions between the magnetic and electric parameters are given by
\[
\begin{bmatrix}
0 & \tilde{\gamma} & \tilde{\gamma} \\
\tilde{\gamma} & 0 & \tilde{\gamma} \\
\tilde{\gamma} & \tilde{\gamma} & 0 \\
\end{bmatrix}
\begin{bmatrix}
\frac{\partial^2 I}{\partial H_m \partial H} \\
\frac{\partial^2 V}{\partial H_m \partial H} \\
\frac{\partial^2 H}{\partial V_m \partial H} \\
\end{bmatrix}
\begin{bmatrix}
E \\
D \\
H \\
\end{bmatrix}
= 0
\] (6)

So, the magnetoelectric coefficients are deduced from (6), as
\[
\left| \begin{array}{c}
\frac{\partial^2 I}{\partial V_m \partial H} \\
\frac{\partial^2 V}{\partial V_m \partial H} \\
\frac{\partial^2 H}{\partial V_m \partial H} \\
\end{array} \right| = \eta_1 \Phi_m \Phi_p Z_{\text{mech}} \quad \text{and} \quad \left| \begin{array}{c}
\frac{\partial^2 V}{\partial H_m \partial H} \\
\frac{\partial^2 H}{\partial V_m \partial H} \\
\frac{\partial^2 I}{\partial V_m \partial H} \\
\end{array} \right| = \frac{-\eta_1 \Phi_m \Phi_p}{\Phi_p^2 - j \omega C_{\text{mech}} Z_{\text{mech}}} \] (7)

for a magnetic excitation and as
\[
\left| \begin{array}{c}
\frac{\partial^2 I}{\partial V_m \partial H} \\
\frac{\partial^2 V}{\partial V_m \partial H} \\
\frac{\partial^2 H}{\partial V_m \partial H} \\
\end{array} \right| = \tau_1 \Phi_m \Phi_p^2 Z_{\text{mech}} \quad \text{and} \quad \left| \begin{array}{c}
\frac{\partial^2 V}{\partial H_m \partial H} \\
\frac{\partial^2 H}{\partial V_m \partial H} \\
\frac{\partial^2 I}{\partial V_m \partial H} \\
\end{array} \right| = \frac{\tau_1 \Phi_m \Phi_p^2}{\Phi_p^2 - j \omega C_{\text{mech}} Z_{\text{mech}}} \] (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
\[
b_n^2 = \left( \frac{\kappa_1}{\eta_1} \right)^2 4(k_B T m 2\pi f_o / Q + 4k_B T \tan(\delta_{\text{mech}})) / 2\pi f C_{\text{mech}} \] (9)

and
\[
b_n^2 = \left( \frac{\kappa_1}{\Phi_m \tau_1} \right)^2 (4k_B T m 2\pi f_o / Q + 4k_B T \tan(\delta_{\text{mech}})) / 2\pi f C_{\text{mech}} \] (10)
where \( k_n^2 \) 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/√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.](image)

**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.

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**References**


