Theoretical Intrinsic Equivalent Magnetic Noise Evaluation for Magneto (Elasto) Electric Sensors Using Modulation Techniques

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Abstract—**The equivalent magnetic noise of magnetostrictive-piezoelectric composite sensors, in the passive mode or when magnetic modulation techniques are used, has been investigated theoretically and compared to measurements. Several main noise sources and their contributions to the equivalent magnetic noise spectral density have been analyzed by using the fluctuation-dissipation theorem and modeled via Nyquist's noise-expression in the linear and non-linear regime. These theoretical analyses show that the mechanical loss, related to the interfriction of composites, appears as the dominant noise source for such magnetoelectric modulation techniques.**

Index Terms—**Magnetoelectric effects, Low-frequency noise modeling, magnetic signal modulation, Magnetic field sensing**

I. Introduction

Strain-induced magnetoelectric (ME) effect has been proposed for magnetic field sensing as a replacement of single-phase materials with generally weak magnetoelectric couplings during the recent years. The induced electric polarization in the piezoelectric layer is linearly coupled to the magnetic field via an inter-mediated deformation between the magnetostrictive and piezoelectric layers. Prior efforts have been devoted to increasing the ME coupling in hetero-structural laminates, which is regarded as a fundamental problematic in condensed material physics, in order to satisfy applications for such devices. Several materials with high effective magnetostrictive coefficients (such as Terfenol-D, Nickel, Metglas) and high piezoelectric coefficients (such as PZT, PMN-PT) have been chosen for enhancing the ME effect [1-5]. Besides, the geometry of the ME laminates and the thickness ratio between magnetostrictive and piezoelectric layers have also been investigated to optimize the ME coupling [6]. To date, at quasi-static frequencies, the highest ME coefficient has been reported for a sandwiched structural laminate using two dimensional Metglas thin layers and one dimensional PMN-PT fibers, around 52 (V/cm)/Oe. For mechanical resonant detection, alternative thin film composites with tip-mass have demonstrated colossal ME voltage coefficients of about 1800 (V/cm)/Oe when working at the first mechanical bending resonance [7]. These enhancements of the ME coupling make such devices more attractive for engineering applications of magnetic field sensing, as magnetic sensors. The limit of detection (LOD) is an important parameter which characterizes the performance of a magnetic field sensing element for applications. For a magnetic sensor based on ME laminates, this limit is influenced by both the magnetic field sensitivity and the noise level in the composites [8].

The equivalent magnetic noise (EMN) spectral density has been used for determining the LOD of magnetic sensors based on ME laminates [9]. The contribution of all the noise sources measured at the output terminal of the sensor can be expressed as an input magnetic noise source at the input terminal, via the magnetic field sensing transfer coefficient. So far, the lowest reported EMN spectral density level is about 5 pT/√Hz at 1 Hz for sandwiched structural laminates using two dimensional Metglas thin layers and one dimensional PMN-PT fibers [10]. Electrical noise sources in the piezoelectric layer have been proved to be the principle noise sources that give the dominant contribution to the EMN spectral density level [11-14]. The first type of noise source in the piezoelectric layer is a Johnson noise that results from the free electric charge random motions which are related, for example, to the motion of oxygen vacancies [15]. Dielectric loss noise is another noise source related to the electric dissipation from electric polar domain wall motion [16]. Both of these two types of noise can be considered as thermo-electric noise sources, according to the fluctuation-dissipation theory. However, to lower the EMN spectral density level by orders in magnitude is a difficult task if considering only the current piezoelectric material fabrication techniques.

In order to avoid this limitation from piezoelectric materials, several research groups have tried to use the magneto-electric cross modulation technique for lowering the EMN spectral density level with a hope of enhancing the performance in magnetic field sensing by using ME composites [17-19]. This idea is feasible because of the fact that both the Johnson noise level and the dielectric loss noise level decrease as a function of frequency. The low frequency magnetic field to be sensed can modulate an excitation carrier which is applied on the ME

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composite at a high frequency, particularly around the first mechanical resonant frequency. The low frequency output signals can be separated from the carrier by means of classical demodulation techniques. Thus, the only expected noise is the one around the frequency of the excitation carriers. The noise contribution from the low frequency thermo-electric dissipations should be definitely avoided. However, the measurements have shown that a non-negligible noise is distributed around the excitation carrier and is presented as a $1/f$ noise after the demodulation process [20]. In order to enhance the performance with magnetoelectric cross modulation, the origin of the near-carrier noise and the noise transmission for diverse noise sources need to be investigated.

A magnetostrictive-piezoelectric composite response contains several intrinsic noise sources [21-25] associated to the energy losses such as thermo-electronic noise, thermo-mechanical noise, thermo-magnetic noise, etc. These intrinsic noise sources have their own contributions at the output terminals via their linear or non-linear transfer functions. Unlike the traditional passive detection mode, if a high frequency magnetic or electric signal is applied to the magnetoelectric composite as an excitation signal, the latter can be amplitude-modulated by the applied low frequency magnetic signal to be detected via any magnetic nonlinearities of the composite.

In this paper, we analyze the intrinsic noise sources in sandwich type ME composites, by using the fluctuation-dissipation theorem with Nyquist's expression for noise. Linear and non-linear transfer functions for the applied magnetic field and for other possible noise sources have been investigated for a better understanding of the performances of a ME composite operating under passive and active modulation methods, respectively. The terms "passive" and "active" are utilized to distinguish between the classical detection mode and the ME modulation technique.

II. Intrinsic Noise Sources

A. *Description for sensor modeling*

A ME hetero-structure laminate composite consists of three layers, namely a magnetostrictive layer, a piezoelectric layer and an elastic inter-mediate layer, respectively. The magnetostrictive layer, also called the passive layer, serves for sensing the magnetic field and generating an elastic deformation. The inter-mediate layer is used for coupling the magnetostrictive and piezoelectric layers. Any mechanical deformation can be transferred via this layer to produce a strain in the piezoelectric layer which can induce ME effects. The piezoelectric material serves as a so-called active layer in the ME composite, generating electric signals via the deformation from the magnetostrictive layer [26]. Electrodes are often integrated across this layer to recover the electric signals. Neglecting the influence of the elastic inter-mediate layer, a simple schematic diagram of a ME composite working in longitudinally magnetic and electric polarization conditions, as a piezoelectric layer sandwiched between two magnetostrictive layers, is shown in Fig. 1. The parameters E, D, H, B, T, S are the electric field, electric displacement, magnetic field, magnetic induction, stress and strain in the longitudinal direction (noted "3"), respectively. The thickness and width direction are defined by "2" and "1", respectively. The geometrical dimensions are $l \times w \times t_p$ for the piezoelectric layer and $l \times w \times t_m / 2$ for either of the magnetostrictive layers. The induced electric voltage V or current I is collected along the longitudinal direction by means of the electrodes.

In an energy storage system, any damping induces corresponding dissipations [27, 28]. The fluctuation-dissipation theorem states that each type of dissipation produces random fluctuations. These random fluctuations in an enclosed system are usually represented as noise sources. With Nyquist's noise expression, the noise sources are directly related to the real part of the damping term in the damping system. A ME composite has magnetic, mechanical and electrical properties because of the magnetostrictive piezoelectric materials that are used and of the mechanical-mediated transferring method. Thus, the intrinsic noise sources can be investigated by analyzing the magnetic, mechanical and electric dissipations.

B. *Electric noise sources*

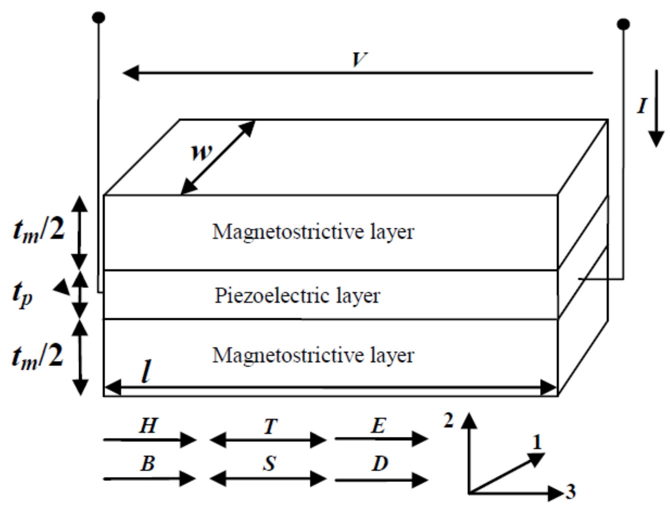

Fig. 1. Sketch view of the laminated magnetoelectric composite model. w, t_m, t_p, V, I, H, B, E, D T, S, are the width, of sensors, the thicknesses of the magnetostrictive and piezoelectric layers, the voltage and the current induced by the piezoelectric layer, the magnetic field and the magnetic induction, the electric field and electric induction, the stress and the strain , respectively.

In the piezoelectric layer of a ME composite, the thermoelectric noise induced by the electric dissipation consists of electric conduction loss and dielectric loss noise sources. Johnson noise is due to the random fluctuation of free electric charges such as oxygen vacancies. This free charge motion is related to the electrical resistance R which is a noisy element and the corresponding Johnson current noise can be written via the Nyquist's noise expression as

$$i_{n\_R}(f) = \sqrt{\frac{4k_B T}{R}} \qquad (1)$$

where k_B is the Boltzmann constant and T is the absolute temperature in Kelvin.

The dielectric loss noise in the piezoelectric layer is induced by the random fluctuations of domain wall motions. Both 180° and non-180° electric polar domain wall motions can contribute to the dielectric loss noise source where the 180° electric domain wall motion is dominant [29-32]. This noise is related to the loss factor $tan(\delta_{elec})$ which is defined by the ratio of ε'' the imaginary part and ε' the real part of the dielectric constant: i.e. $tan(\delta_{elec}) = \varepsilon'' / \varepsilon'$. The noisy element in this case, is the electric capacitance, C, of the piezoelectric layer. By using Nyquist's expression, the noise spectral density can be written as

$$i_{n\_C}(f) = \sqrt{4k_B T\ 2\pi f\ C\,tan(\delta_{elec})} \quad (2)$$

where f is the frequency.

The first noise source (1) is white whereas the second (2) shows a $\sqrt{f}$ dependence. Thus, by using a charge amplifier, these two noise sources are integrated and lead to respectively a $1/f$ and $1/\sqrt{f}$ frequency dependence in the noise spectral density curves, which dominate at low frequencies and thus, determine the detection limit [14, 32].

C. Mechanical noise sources

Mechanical dissipation exists in both the magnetostrictive and piezoelectric layers of a ME laminate [33, 34]. This dissipation generates a thermo-mechanical noise source having two main origins: the viscous loss and interfriction which are related to the dynamic mass motion and the non-180° domain wall motions respectively [16]. The random fluctuation of the dynamic mass motion is related to the mechanical resistance, R_{mech}. The latter describes the relationship between the force and the vibration speed in the oscillation system. This random force noise source can be expressed as a Nyquist's noise formula

$$f_{n\_R_{mech}}(f) = \sqrt{4k_B T R_{mech}}\ . \quad (3)$$

By using the expression of $R_{mech} = 2\pi f_0\, m / Q$ [11], (3) can be rewritten as

$$f_{n\_R_{mech}}(f) = \sqrt{4k_B T m\ 2\pi f_0 / Q} \quad (4)$$

where m is the mass of the laminate, f_0 is the first resonance frequency and Q is the damping coefficient. In certain ME composites, Q is determined by the damping quality in the bonding layers.

The interfriction loss, related to the non-180° domain wall motion of both magnetostrictive and piezoelectric layers can be represented by a noise source resulting from a mechanical capacitance. For a longitudinal motion of the ME composite, this mechanical capacitance defines the relation between force and deformation as

$$C_{mech} = s_{33} l / w t_{lam} \quad (5)$$

where s_{33} and t_{lam} are the elastic compliance constant and the total thickness of the ME laminate, respectively. The mechanical compliance represents the relation between mechanical force and deformation. Actually, there exists a time delay between these two mechanical parameters, which can be expressed in a complex form as $s = s'\,(1 + j\,tan(\delta_{mech}))$ where the mechanical loss factor $tan(\delta_{elec}) = \varepsilon'' / \varepsilon'$ is the ratio between imaginary and real part of the composite flexibility coefficient.

The real part of the mechanical impedance $Z_{mech} = 1 / j\,2\pi f\,C_{mech}$ can be written as

$$Re\{Z_{mech}\} = \frac{tan(\delta_{mech})}{2\pi f C_{mech}}\ . \quad (6)$$

With the help of Nyquist's expression, the mechanical loss noise can be represented as a force noise source given by

$$f_{n\_C_{mech}}(f) = \sqrt{4k_B T\,Re\{Z_{mech}\}} = \sqrt{4k_B T\,tan(\delta_{mech}) / 2\pi f\,C_{mech}}\ . \quad (7)$$

Considering the ME laminate as a Kelvin-Voigt material, the displacement noise formula can obtained from the total mechanical force, $f_n^2 = f_{n\_R_{mech}}^2 + f_{n\_C_{mech}}^2$, and the mechanical impedance Z_{mech}, as

$$\begin{aligned} x_n(f) &= \frac{f_n(f)}{|2\pi f\ Z_{mech}|} \\ &= \sqrt{4k_B T\left(R_{mech} C_{mech}^2 + \frac{C_{mech}\,tan(\delta_{mech})}{2\pi f}\right)}\ . \end{aligned} \quad (8)$$

We notice that the displacement noise consists of a white noise part due to the viscous loss and a $1/f$ dependant term due to interfriction loss. This random motion can be directly transferred to the output terminal of the ME laminate as an electric noise via the piezoelectric layer.

D. Magnetic noise sources

In the magnetostrictive material, the motions of the two kinds of domain walls (180° and non-180°) are quite different. Temperature-induced domain wall motion results in a random magnetic fluctuation which can be considered as a thermo-magnetic noise source in the magnetic layers [35, 36]. Both 180° and non-180° domain walls motion induce a random fluctuation of the magnetization as a thermo-magnetic noise source in the magnetostrictive layer. Moreover, the 180° domain walls motions produce the dominant contribution to this noise source compared to the non-180° domain wall motion. Since the passage of a 180° domain wall through a certain region reverses the magnetization of that region, we conclude that 180° wall motions do not produce a net magnetostrictive change. Thus, only the non-180° domain wall motions will result in net mechanical random fluctuations that are coupled to the magnetic random fluctuations for this type of domain wall motions.

In general, the non-180° domain wall motions also produce a thermo-mechanical noise source in the magnetostrictive layers. This can be described via the interfriction in the magnetostrictive materials by using the mechanical loss factor which is defined as the ratio between the imaginary and real parts of the elastic coefficients. This effect can be regarded as a mechanical delay between strains and stresses [24, 32, 37]. Viscous losses are another mechanical dissipations in ME hetero-structure composites. This type of loss occurs in all the three layers in the ME hetero-structure, which can be explained by the damping in the materials resulting from their dynamic mass. In general, the thermo-mechanical, which is related to the viscous loss, can be described by the mechanical quality factor. We consider that the thermo-magnetic random fluctuations have a negligible contribution to the piezoelectric layers without induced strain.

III. Signal and Noise

A. Equations for the sensor model

From the linear magnetostrictive and piezoelectric constitutive equations [14], we can obtain the relations between the magnetic field, the electric voltage and the current for a longitudinal magnetization and polarization mode for a ME composite [1] under free-free boundary mechanical conditions, as shown in Fig. 1. This can be expressed as

$$\begin{cases} \left(v_1+v_2\right)Z_{mech}+\varphi_m H+\varphi_p V=0 \\ \left(v_1+v_2\right)\varphi_p+j2\pi f\,CV+I=0 \\ F=\left(v_1+v_2\right)Z_{mech} \end{cases} \tag{9}$$

where v_1 and v_2 are the vibration speeds at the two free ends of the composite along the longitudinal direction, F is the applied force. $s_{33}\left(=\left(\left(1-n\right)/s_{33,p}+n/s_{33,m}\right)^{-1}\right)$ is the mean flexibility coefficient of the magnetostrictive and piezoelectric layer with a thickness ratio $n = t_m / t_{lam}$, the magnetic and electric coupling coefficients are $\varphi_m=\dfrac{d_{33,m}t_m w}{s_{33,m}}$ and $\varphi_p=\dfrac{d_{33,p}t_p w}{s_{33,p}l}$, respectively. C ($= \varepsilon\, w\, t_p / l$) is the electronic capacitance of the piezoelectric layer, and H, V and I are the applied magnetic field, the electric voltage and the current across the electrode, respectively.

As we know, the response of a ME laminate sensor is not always linear. Considering the first order of the magnetic nonlinearity, the magnetic coupling coefficient can be defined as

$$\varphi_m^{NL}=\frac{d_{33,m}^{NL}t_m w}{s_{33,m}} \tag{10}$$

where $d_{33,m}^{NL}$ term represents the first order nonlinear magnetostrictive coefficient.

Taking into account both the magnetic nonlinearity $\eta\left(=d_{33,m}^{NL}/d_{33,m}\right)$ and the mechanical nonlinearity $\kappa\left(=s_{33}^{NL}/s_{33}\right)$ and the piezoelectric nonlinearity $\zeta=\dfrac{d_{33,p}^{NL}}{d_{33,p}}$, (9) can be rewritten in its nonlinear form as

$$\begin{cases} F+\kappa F^2+\varphi_m\left(1+\eta H\right)H+\varphi_p\left(1+\zeta V\right)V=0 \\ \dfrac{F+\kappa F^2}{Z_{mech}}\varphi_p+j2\pi f\,CV+I=0 \end{cases}. \tag{11}$$

B. ME charge coefficient

In order to obtain the magnetic signal transfer function, we can find the relation between the current and the magnetic field under a short circuit condition ($V = 0$) from (11). This yields

$$\varphi_m\left(1+\eta H\right)H=\frac{Z_{mech}}{\varphi_p}I\,. \tag{12}$$

The magnetic current transfer function, defined by the current magnetoelectric coefficient, can be written by means of the derivative of (12) for a magnetic field H. This gives

$$\alpha_{ME}^{I}=\left|\frac{\partial I}{\partial H}\right|=\frac{\varphi_m\varphi_p}{Z_{mech}}+2\frac{\eta\varphi_m\varphi_p H}{Z_{mech}}\,. \tag{13}$$

The first and second terms in (13) are the linear and the non-linear magneto-elastic coupling coefficients, respectively. We find that the nonlinear ME coefficient depends on the magnetic nonlinearity and the applied magnetic field on the composite. The ME charge coefficient can then be expressed as

$$\alpha_{ME}^{Q}=\frac{1}{2\pi f}\left|\frac{\partial I}{\partial H}\right|=\frac{\varphi_m\varphi_p}{2\pi fZ_{mech}}+\frac{\eta\varphi_m\varphi_p H}{\pi fZ_{mech}}\,. \tag{14}$$

C. Charge noise

As we discussed in the above section, the thermo-magnetic noise in the magnetostrictive layer, due to 180° domain wall motion, does not induce any deformation on the laminate. Therefore, this noise source in the magnetostrictive layer has no output noise contribution because it does not result in a net deformation onto the piezoelectric layer. In other words, the transfer function of the thermo-magnetic noise is considered to be null. The electric loss induced Johnson noise and the dielectric loss noise from the random motion of the free electric charges and from the electric domain wall motions contribute to the output terminal of the ME laminate, directly. This means that the transfer function of such noise sources is equal to 1. However, the mechanical loss consists of the viscous loss and the interfriction loss, both in the magnetostrictive and piezoelectric layers. In this case, the transfer function depends on the piezoelectric coefficient and on the mechanical impedance.

Under the short circuit condition ($V = 0$), the second equation in (11) can be rewritten as

$$\frac{F+\kappa F^2}{Z_{mech}}\varphi_p + I = 0\,. \tag{15}$$

By taking the derivative of (15) with respect to the mechanical force, the transfer function for the force F to the electric current I can be obtained as

$$\left|\frac{\partial I}{\partial F}\right| = \frac{\varphi_p}{Z_{mech}} + \frac{2\kappa\varphi_p F}{Z_{mech}}\,. \tag{16}$$

Generally speaking, the magnetic induced force includes any magnetic nonlinearities and it can be written as $F = \varphi_m H + \varphi_m^{NL} H^2 + \ldots$ The first term, representing the linear response, is the predominant term. Therefore, by choosing a linear relationship between the mechanical force and the magnetic signal, $F = \varphi_m H$, and assuming there is no loss, (16) becomes

$$\left|\frac{\partial I}{\partial F}\right| = \frac{\varphi_p}{Z_{mech}} + \frac{2\kappa\varphi_p\varphi_m H}{Z_{mech}}\,. \tag{17}$$

Thus, the electric current noise spectral density due to the mechanical noise force can be written as in

$$i_n(f) = \frac{\varphi_p}{Z_{mech}} f_n + \frac{2\kappa\varphi_p\varphi_m H}{Z_{mech}} f_n\,. \tag{18}$$

By using the mechanical noise formula from (3) and (7), the output electric charge noise can be written as

$$\begin{aligned} q_n(f) = {} & \varphi_p\sqrt{\frac{4k_B T\tan(\delta_{mech})C_{mech}}{2\pi f} + 4k_B T R_{mech}C_{mech}^2} \\ & + 2\kappa\varphi_p\varphi_m H\sqrt{\frac{4k_B T\tan(\delta_{mech})C_{mech}}{2\pi f} + 4k_B T R_{mech}C_{mech}^2}\,. \end{aligned} \tag{19}$$

We thus find that without any magnetic excitation signal, the output electric charge noise is linearly distributed at quasi-static frequencies. However, if driven by a magnetic carrier, the low frequency mechanical noise can modulate the excitation signal and it will be distributed around the drive carrier frequency as we shall detail, hereafter.

IV. Equivalent Magnetic Noise

A. Equivalent Magnetic Noise for Passive Sensing

For passive sensing, the linear transfer function is the dominant ME sensitivity term and the electric and mechanical original noise sources have their own contributions to the total noise floor. Since the intrinsic thermo-magnetic noise source does not have any contribution to the total output electric noise, we take into account only a) the thermo-electric noise due to the

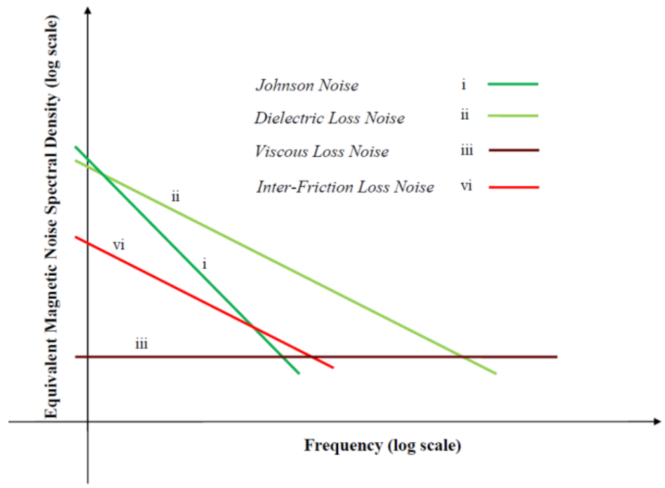

Fig. 2. Equivalent magnetic noise spectral densities as a function of frequency for the intrinsic noise sources in a magnetoelectric sensor (*cf.* (22)).

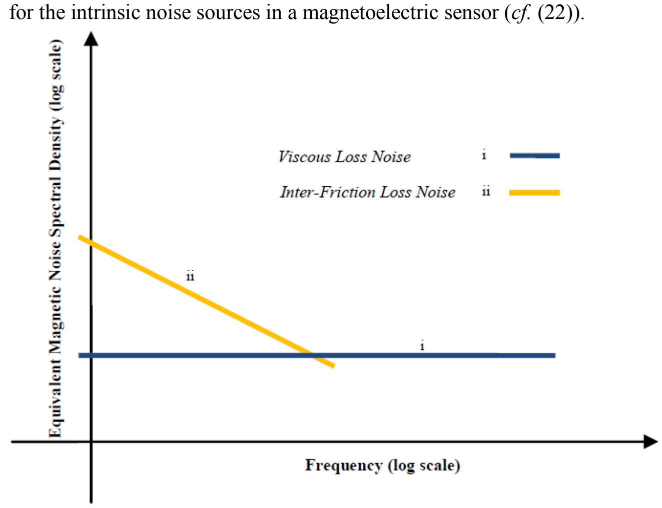

Fig. 3. Expected equivalent magnetic noise spectral density curve of a ME sensor appearing at low frequencies when modulation techniques are used, (*cf.* (29)). This apparent magnetic noise is due to the mechanical noise sources in the laminate.

180° domain wall motion and free charge random motion, b) thermo-mechanical noise sources due to the non-180° domain wall motion and dynamic mass random motion for analysis. At low frequencies and in the passive working mode, the total output electric charge noise spectral formula provided by the thermo-electric and thermo-mechanical random fluctuations can be calculated. It yields

$$\begin{aligned} q_n^2(f) = 4k_B T\Bigg(& \frac{1}{(2\pi f)^2 R} + \frac{C\tan(\delta_{elec})}{2\pi f} \\ & + \frac{\varphi_p^2 C_{mech}\tan(\delta_{mech})}{2\pi f} + (C_{mech}\varphi_p)^2 R_{mech}\Bigg)\,. \end{aligned} \tag{20}$$

It can be seen that the four terms in (20) correspond to the electric conduction loss, the dielectric loss, the mechanical interfriction loss and the viscous loss and have a $1/f$, $1/\sqrt{f}$, $1/\sqrt{f}$ and white noise density spectrum, respectively. The equivalent noise spectral curves are seen in Fig. 2.

At low frequencies, the linear part of the ME charge coefficient represents the main contribution to the ME coefficient. By replacing the mechanical impedance by $Z_{mech} = 1 / (2\pi f\, C_{mech})$, the charge coefficient at low frequencies can be deduced as

$$\alpha_{ME}^{Q} = \varphi_m \varphi_p C_{mech} \,. \tag{21}$$

By using the noise formula (20) and the sensitivity expression (21), we can find the equivalent magnetic noise power expression for the low frequency response as

$$\begin{aligned} b_n^2(f) &= \frac{\mu_0^2 q_n^2(f)}{\left(\alpha_{ME}^{Q}\right)^2} \\ &= \mu_0^2 4k_B T \left(\frac{tan(\delta_{mech})}{2\pi f \varphi_m^2 C_{mech}} + \frac{R_{mech}}{\varphi_m^2} \right. \\ &\quad \left. + \frac{1}{(2\pi f)^2 R\left(\varphi_m \varphi_p C_{mech}\right)^2} + \frac{C\, tan(\delta_{elec})}{2\pi f \left(\varphi_m \varphi_p C_{mech}\right)^2} \right) \end{aligned} \tag{22}$$

By using the physical parameters of the sensor and the relation $R = l\, \rho_{\mathrm{elec}} / t_p\, w$ and $f_0 = (1/2l)\sqrt{1/\rho s}$, (22) becomes

$$\begin{aligned} b_n^2(f) &= \left(\frac{\mu_0 s_{33,m} s_{33,p}}{n\omega\, d_{33,m} d_{33,p} s_{33}} \right)^2 \frac{4k_B T}{\rho_{elec} V_p} \\ &+ \left(\frac{\mu_0 s_{33,m} s_{33,p}}{n d_{33,m} d_{33,p} s_{33}} \right)^2 \frac{2k_B T \varepsilon_{33}^{S}\, tan(\delta_{elec})}{\pi f\ V_p} \\ &+ \left(\frac{\mu_0 s_{33,m}}{n d_{33,m}} \right)^2 \frac{2k_B T\, tan(\delta_{mech})}{\pi f\ s_{33} V_{lam}} \\ &+ \left(\frac{\mu_0 s_{33,m}}{n d_{33,m}} \right)^2 \frac{4k_B T \pi \sqrt{\rho / s}}{wtQ} \end{aligned} , \tag{23}$$

where ρ_{elec} is the resistivity, V_p the volume of the piezoelectric layer, V_{lam} the volume of ME composite and ρ the mean value of the volume density for the composite.

B. Equivalent Magnetic Noise when using modulation techniques

By using a frequency shift modulation technique, the ME composite is excited by an external sinusoidal signal. This can be a harmonic magnetic field, an electric field or a mechanical vibration of high frequency. An applied low frequency magnetic signal modulates the excitation signal via the nonlinearity of the composite. This is revealed as two side-band signal peaks around the excitation signal frequency in the spectrogram similar to a classical amplitude modulation (AM). Electric noise sources in the piezoelectric layer are directly observed at the output terminal of the ME composite. These electric noise sources are not influenced by any nonlinearity of the ME composite. Thus, there is no noise contribution from these noise sources using ME modulation techniques. The noise source related to the thermo-magnetic loss does not result in a mechanical random fluctuation in the ME composite. Therefore, it does not make any noise contribution either for the classical passive mode or for the frequency modulation technique(s). The mechanical noise sources related to the thermo-mechanical loss in the magnetostrictive and piezoelectric layers can modulate the excitation deformation and give a corresponding noise output when using a classical demodulation. This noise source is considered as the dominant noise source for the frequency modulation technique.

Replacing the magnetic excitation H by a harmonic magnetic signal of amplitude H_0 at a frequency f_0, we can express the nonlinear magnetoelectric transfer function as

$$\alpha_{NLME}^{Q} = \frac{\eta \varphi_m \varphi_p H_0}{2\pi f\ Z_{mech}} * \left(\delta(f - f_0) + \delta(f + f_0) \right). \tag{24}$$

Similarly, the thermo-mechanical noise distributed around the excitation signal carrier can be written as

$$q_{n\_mod}(f) = \left(\delta(f + f_0) + \delta(f - f_0) \right) * \frac{\kappa \varphi_p \varphi_m H_0}{2\pi f Z_{mech}} \sqrt{\frac{4k_B T\, tan(\delta_{mech})}{2\pi f\, C_{mech}} + 4k_B T R_{mech}} \,. \tag{25}$$

By using a synchronous detector, Cos($2\pi f_0\, t$), the magnetic transfer function at low frequencies is given by

$$\alpha_{NLME}^{Q} = \frac{\eta \varphi_m \varphi_p H_0}{2\pi f Z_{mech}} \,. \tag{26}$$

The thermo-mechanical noise expression at low frequencies can be written as

$$q_{n\_demod}(f) = \frac{\kappa \varphi_p \varphi_m H_0}{2\pi f Z_{mech}} \sqrt{\frac{4k_B T\, tan(\delta_{mech})}{2\pi f\, C_{mech}} + 4k_B T R_{mech}} \,. \tag{27}$$

For the frequency shift modulation technique, the equivalent magnetic noise spectral density is given by

$$\begin{aligned} b_{n\_demod}(f) &= \mu_0 \frac{q_{n\_demod}}{\alpha_{NLME}^{Q}} \\ &= \frac{\mu_0 \kappa}{\eta} \sqrt{\frac{4k_B T\, tan(\delta_{mech})}{2\pi f\, C_{mech}} + 4k_B T R_{mech}} \end{aligned} \,. \tag{28}$$

By using (13) and (17), we have $\eta \approx 2\, \varphi_m\, \kappa$ by hypothesis. So, the equivalent magnetic spectral density is ultimately given by

$$b_{n\_demod}(f) = \frac{\mu_0}{2\varphi_m}\sqrt{\frac{4k_B T \tan(\delta_{mech})}{2\pi f C_{mech}} + 4k_B T R_{mech}}\ . \quad (29)$$

Also, by using the corresponding physical parameters (*cf.* (22)), (28) can be rewritten as

$$b_{n\_demod}(f) = \frac{\mu_0 s_{33}^{NL} d_{33,m}}{s_{33} d_{33,m}^{NL}}\sqrt{4k_B T\left(\frac{s_{33} l \tan(\delta_{mech})}{2\pi f\ wt} + \frac{m 2\pi f_0}{Q}\right)}\ . \quad (30)$$

So, we find that the EMN noise spectral density, related to the mechanical loss from the interfriction and the viscosity in a laminate, presents a $1/f$ noise behavior and a white noise behavior, respectively. Moreover, one can notice that the equivalent magnetic noise spectral density is independent of the excitation carrier amplitude, H_0 as we (and some other groups) have experimentally observed at a certain level of this magnetic field amplitude [19, 20, 38, 39, 40]. The expected EMN noise spectral density behavior due to intrinsic noise sources in ME laminate in these conditions is represented in Fig. 3.

V. Measurement and Discussion

A ME sensor fabricated with commercial Metglas foils and PZT layers was used for our experiments. The sensor was excited around its first longitudinal mechanical resonance of 26.6 kHz by applying a magnetic field along the longitudinal direction, using a Helmholtz coil in series of a resistance of 100 Ω. This Helmholtz coil has a transfer function of 7.78 G/A. Another Helmholtz coil of 5.37 G/A was used to generate the low frequency reference signal in series with a resistance of 10 kΩ. An analyzer (HP 3562A) was used to measure the output signal transfer functions and noise spectral densities.

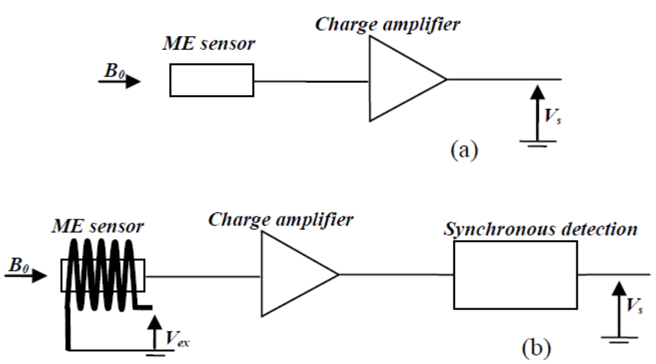

Fig. 4. Sketch view of the (a) passive detection and (b) active detection modes. We notice that V_{ex} induced the modulation field. B_0 is the sensed signal.

After a classical demodulation process, we measured the transfer function of the ME sensor, which is DC capable, and its equivalent magnetic noise level using this modulation technique. The sketch view of the passive and active detection modes are given in Fig. 4. A magnetic excitation signals 8.25 μT_{rms}, were applied on the ME sensor for the modulation detection. We can obtain the transfer function of 6 kV/T in the low frequency range. The normalized transfer functions at 1 Hz for classical detection method and modulation technique are

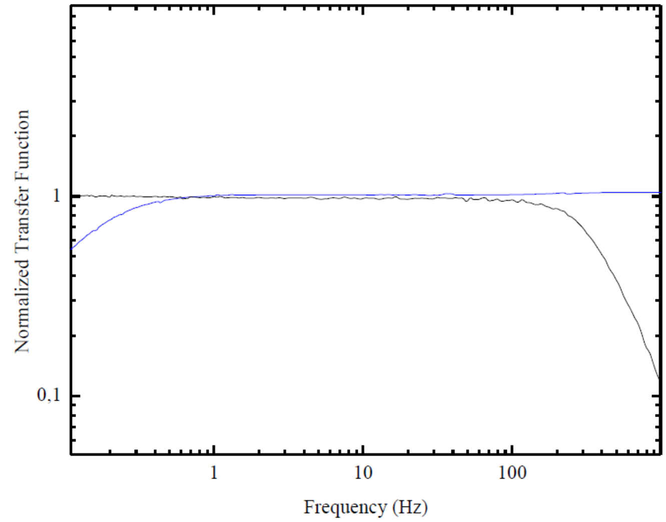

Fig. 5. Experimental transfer function of a ME sensor appearing at low frequencies observed after the demodulation process when using modulation techniques (black curve) and passive mode detection (blue curve). Both curves are normalized by its value at 1 Hz.

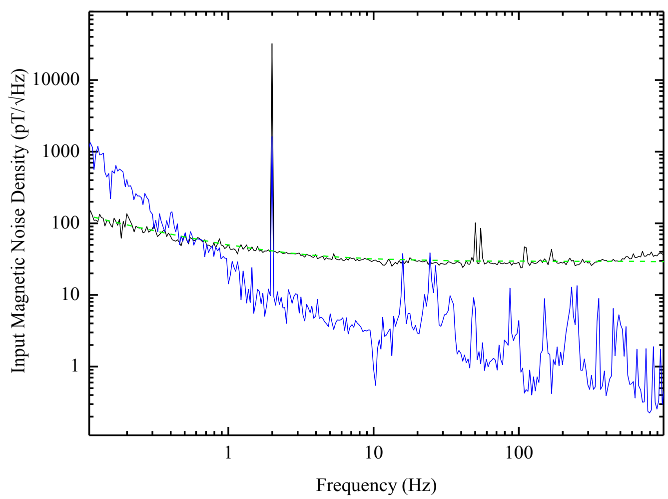

Fig. 6. Experimental equivalent magnetic noise spectral densities of a ME sensor appearing at low frequencies when using modulation techniques (black curve) and passive mode detection (blue curve). The green dashed curve is the simulated curve by using parameters given in table I.

also compared. (*cf.* Fig. 5).. The equivalent magnetic noise spectral densities for modulation and passive mode detections are given and compared in Fig. 6. We observed that in low frequency (*eg.* below 0.5 Hz) the extrinsic sensor fluctuation can be avoided via the modulation technique. Both the simulation and theoretical EMN level are around 50 pT/√Hz at 1 Hz.

Table I: Physical, sensors & material parameters

μ_0	$4\pi\ 10^{-7}$ H/m	$d_{33,m}$	$6.5\ 10^{-10}$ (T m^2)/V
t_m	150 µm	w	1 cm
$s_{33,m}$	$9.1\ 10^{-12}$ m^2/N	φ_m	$9\ 10^{-5}$ T m^2
k_B	$1.38\ 10^{-23}$ J/K	T	300 K
$\tan(\delta_{mech})$	0.11 %	C_{mech}	$4\ 10^{-7}$ m/N
R_{mech}	254 kg/s		

$s_{33,m}$ and $d_{33,m}$ are adjusted to fit with the experimental measurement.

VI. CONCLUSION

The effects of temperature induced thermo-magnetic, thermo-electric and thermo-mechanical losses has been analyzed. All of them can be represented as low-frequency intrinsic noise sources in a strain coupled ME laminate composite. The thermo-magnetic noise contribution to the output electric noise can be considered to be negligible. In the passive mode, the thermo-electric noise sources (Johnson noise and dielectric loss noise) appear as the dominant intrinsic noise sources. However, when the magnetoelectric sensor is operated in a modulation mode, low-frequency thermo-mechanical noise will modulate the excitation carrier signal via the mechanical non-linearity of the system and will thus be distributed around the carrier frequency. This noise appears as the dominant noise after the demodulation process when excitation carriers of large amplitude are used, as we and some other groups have observed and investigated, but not well explained yet [19, 20, 38, 39, 40]. From this theoretical analysis, we can conclude that when using a magnetic field modulation on a ME sensor in the longitudinal vibration mode, a weaker mechanical non-linearity κ and/or a stronger magnetic non-linearity η (ratio $\alpha\ 1/\varphi_m$) can lead to a lower equivalent magnetic noise level spectral density as given by (28, 29).

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