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# Investigation of the near-carrier noise for strain-driven ME laminates by using cross-correlation techniques

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The near-carrier noise around the longitudinal mechanical resonance of a magnetoelectric laminated composite has been investigated. By simultaneously applying a high frequency electric field across the piezoelectric phase, the sensor response to low frequency magnetic signals can be shifted around the “carrier” frequency as side band modulation signals. This magnetoelectric response can appear either as an electric charge via piezoelectric to piezoelectric (PP) modulation effects or as a magnetic signal via piezoelectric to magnetic (PM) modulation effects. These two signals are detected either with a charge preamplifier or with a coil surrounding the sample and the low-frequency sensor response to the applied magnetic field can be recovered by using two independent synchronous detectors. We have designed an experimental setup to observe the direct (passive) low frequency noise and the noise corresponding to the two above modulations. Noise cross-correlating measurements were also carried out to investigate the origin of the near-carrier noise. No noise coherence was found between the direct low frequency noise and the noise resulting from either the PP or the PM modulations. However, a noise coherence factor of more than 50% has been found between the signals recovered from the two modulation techniques. A simple model has been used to explain this effect. The magnetoelectric sensor is considered as a nonlinear forced vibration system. Noise sources passing through such a system can be amplified and distributed around the carriers as side band noise where it hampers the equivalent magnetic noise performance. Electronic-thermal noise caused by dielectric dissipations in the piezoelectric phase can be considered as a noise source with a negligible contribution to the total noise floor. Mechanical-thermal low frequency excess noise is found to be the only intrinsic noise source which is filtered by the nonlinear ME system and is present as an output near-carrier noise which dominates the noise level after the demodulation processes.

*Index Terms*—Magnetoelectric, Equivalent magnetic noise, Strain modulation, Noise coherence

## I. INTRODUCTION

Magnetoelectric (ME) sensors based on piezoelectric and magnetic thin films have huge potential for magnetic field detection via the product properties between magnetic and electric phases [1], [2]. Magnetization and electric polarizations are mechanically coupled by mediated strains following certain direction. Magnetic sensibilities (usually defined as ME coefficients) are dominated by several aspects such as the piezoelectric and magnetic constants, a DC bias magnetic field, working frequencies and the volume fraction of the different phases [3], [4]. The performance of a ME sensor can be enhanced by increasing its sensitivity. However, noise sources determine the limit of magnetic signal detection. Among several intrinsic noise sources, the one originating from the piezoelectric phase is predominant at frequencies of a few Hz [5]. In general, at low frequencies, electro-thermal noise associated to the delay effect between electric induction and electric field exceeds the contribution of the other noise sources in dielectric materials with a  $1/f$  dependence of its voltage or current noise spectral density. In other words, this implies a harmful limit to the performance of a ME sensor at low frequencies and this is a physical obstacle in sensor designs and fabrication with piezoelectric dielectric materials, particularly with ferroelectric relaxors. Indeed, efforts on the reduction of such an electro-thermal noise can be achieved via advances of material science. But the progress of new materials cannot follow the rate of application development of such devices. However, another technique based on frequency shifting has been used to avoid the piezoelectric noise fluctuations at low frequencies. With the help of modulation techniques, low frequency magnetic signals can be transferred

to higher frequencies around an exciting carrier. In this paper, the noise origins and distributions of such a technique are investigated and discussed via noise coherence measurements.

It has been demonstrated that when a modulation scheme is used, ME sensors have sensitivities which are different from those obtained under a passive sensing method [6] - [8]. In the passive mode, ME effects depend on the first order nonlinearity of the sensor and furthermore, the ME coefficient can be enhanced by applying an appropriate magnetic field bias. However, dominant perturbations originate from piezoelectric dissipations. Contrariwise, ME effects due to the second order nonlinearity are proportional to the magnitude of carriers when working under a modulating mode. This does not mean an infinite performance because of the limit from the electronics, the saturation of the sensor, etc... Besides, the observable noise for the modulation technique corresponds to the near carrier noise level which increases as the carrier amplitude is increased.

For the purpose of optimizing the noise reduction of ME sensors by such modulation techniques, the origin of near carrier noise must be investigated. If a ME sensor is excited by a harmonic electric carrier signal at high frequencies (e.g. several kHz) then, low frequency small magnetic signals (several Hz) can be detected across electrodes on piezoelectric layer. Thus, the PP modulation can be achieved. Unlike the PP modulation, another PM modulation can detect and recover the low frequency small magnetic signal via a pick-up coil surrounding the ME sensor.

In general, both the magnetic and electric modulation schemes can generate a strong strain in the ME sensors along the in-plane or along the out-of-plane directions. Thus, by applying an exciting electric carrier and measuring the noise

correlation from the piezoelectric and magnetic phases, the noise origins can be investigated.

## II. EXPERIMENTAL DETAILS

Our sensors are made of commercial Metglas foils and piezoelectric fibers in order to form a 2-1 structure ME sample which has been demonstrated to produce a giant ME effect. Metglas foils of 25  $\mu\text{m}$  in thickness were cut to a dimension of 8 cm long and 1 cm wide. Piezoelectric fibers were attached on both top and bottom surfaces by polymer isolators

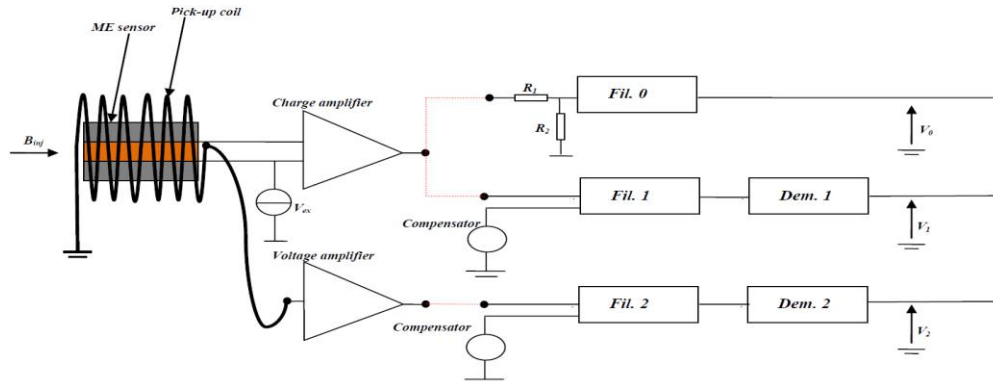


Fig. 1. Schematic setup of spectral cross-correlation technique for a ME sandwich laminates under the excitation of a sinusoidal electric polarization.

embedded with inter-digital electrodes by using epoxy resin to form a multi-push-pull structure [9].

Figure 1 shows our experimental setup. A magnetic flux density  $B_{inj}$  generated by a pair of Helmholtz coils is used as a reference magnetic signal. A charge amplifier circuit with a 10 pF capacitor and a feedback resistance of 10 G $\Omega$  serves as a first stage amplifier electronics with a transfer gain of 10<sup>10</sup> V/C, as described in [6]. Generated charges can be recovered and transferred to this circuit via the amplifier inverting input and a voltage exciting the piezoelectric layers at 27.1 kHz can be applied simultaneously to the non-inverting input of charge amplifier via a generator  $V_{ex}$ . The amplitude of this excitation signal has been chosen to 0.1 V to achieve an appropriate modulation effect without saturating the charge amplifier.

Thus, the reference signals under both PP and PM techniques can be recovered and amplified simultaneously via two independent electronic paths. The sensor response can be either observed directly in the passive (or classical) mode by connecting the output of the charge amplifier to **Fil. 0**, or detected after demodulation via **Fil. 1**. **Fil. 0** is a low-pass filter which preserves the low frequency response to the reference signal while suppressing the high frequency components resulting from the excitation signal. These high frequency components are so high that they make the direct measurement impossible for the passive mode. **Fil. 0** has a voltage gain of 100 and a bandwidth ranging from DC to 1 kHz. A simple 1 % attenuator was used to prevent the saturation of the filter. In order to recover the response of the ME sensor magnetic layers to the reference signal, a home-made 3000 turns pick-up coil surrounding the ME sensor was used, connected to a voltage amplifier having a voltage gain of 33 V/V. The output signal of this amplifier is then processed

with *Fil. 2* and then demodulated.

The band-pass filter **Fil. 1** is used to select the components around the excitation frequency and it is associated with a compensation circuit, labeled “compensator” in figure 1, to reduce the large excitation carrier component, which is present at the output of the amplifier, to an appropriate level for the following demodulation stage. Filter **Fil. 2** is identical to **Fil. 1** for similar reasons. These two filters have the same gain of 100 and the same bandwidth from 3 kHz to 300 kHz to enhance the signals around the exciting carrier by filtering

signals and perturbations at others frequencies far from the

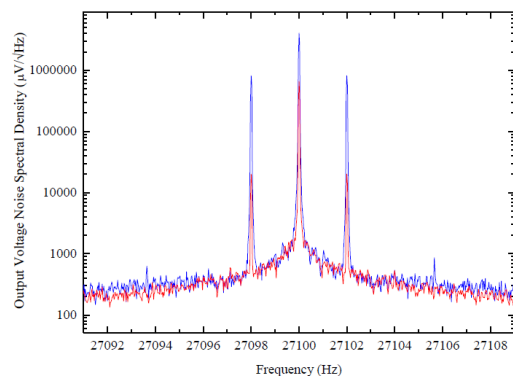


Fig. 2. Spectrogram of the near carrier noise and modulated signals around the excitation signal detected from the piezoelectric (red curve) and magnetic (blue curve) phases.

carrier. The noise and sensor response at low frequencies were then recovered via classical demodulation techniques by two phase-locked detectors.

### III. THEORETICAL ANALYSIS

The limit of detection for a laminated magnetoelectric sensor at low frequencies, of the order of a few Hz, is often influenced by the electronic-thermal noise which is caused by the dielectric dissipation in the piezoelectric phase. Besides, another important intrinsic dissipation existing in the ME sensor is the mechanical-thermal noise. This noise originates from the molecule agitation and represents a white mechanical force noise at high frequencies [10] and a  $1/f$  noise dependence at quasi-static frequencies [11]. In the passive mode and at low frequencies (e.g. around 1 Hz), this

mechanical noise is generally dominated by the electronic-thermal noise in the piezoelectric material for a magnitude of several orders. However, the mechanical-thermal noise is partly involved in the nonlinear system of ME sensor. Thus, a frequency dependant noise contribution originating from the mechanical-thermal noise source appears around the carrier via the ME sensor strain nonlinearity. The magnetic, electric and mechanical coupling coefficient can be written as a following constitutive equation

$$(\bar{c} + \bar{c}_1 S)S = AT + A_m e_m H + A_p e_p E \quad (1)$$

where  $\bar{c}$  and  $\bar{c}_1$  are linear and first order strain nonlinear rigidities,  $S$  and  $T$  are the strain and stress in sensor,  $A$  is the side-surface of sensor,  $A_m$  and  $A_p$  are respectively the side-surface of the magnetic and piezoelectric layers,  $e_m$  and  $e_p$  are the magnetostrictive and piezoelectric constants,  $H$  and  $E$  are the magnetic and electric fields, respectively. The low frequency mechanical-thermal noise source results in a near-carrier-noise around the exciting carrier. Through a magnetic and an electric detection, the noise formula can be written as  $H_n(f)$  and  $E_n(f)$  in (2). It yields to

$$\begin{cases} H_n(f) = \frac{\bar{c}}{e_m A_m} S_n(f) + \frac{2e_p \bar{c}_1 E_0}{c_p e_m A_m} [S_n(f_c - f) + S_n(f - f_c)] \\ E_n(f) = \frac{\bar{c}}{e_p A_p} S_n(f) + \frac{2\bar{c}_1 E_0}{c_p A_p} [S_n(f_c - f) + S_n(f - f_c)] \end{cases} \quad (2)$$

where  $S_n(f)$  is the mechanical noise source,  $c_p$  the linear piezoelectric rigidity,  $E_0$  the amplitude of the electric excitation signal,  $S_n(f_c - f) + S_n(f - f_c)$  is the noise distribution near the excitation signal.

Several conclusions can be drawn: I) Any environmental magnetic noise can be amplified and distributed via the ME sensor nonlinearity as near-carrier noise. But, for our measurement setup, they are negligible in our magnetic shielded chamber. II) Electric-thermal dissipations are exhibited as an output noise which is not influenced by the nonlinear properties of the sensor. III) However, mechanical-thermal noise is partly influenced by the strain nonlinearity of the sensor and can be transferred to the output of the sensor as a phase noise distribution around the excitation carrier.

#### IV. RESULTS AND DISCUSSION

We first measured the sensor response to the reference magnetic signal at 2 Hz and the output noise floor in order to study later the increase of noise near the excitation carrier. We then applied a sinusoidal excitation voltage. The latter is modulated at the sensor output by the low frequency reference signal (cf. Fig. 2). We can obtain a giant enhancement in the sensitivity of ME effects by choosing the carrier frequency close to the mechanical resonance. The sensor response to the reference signal can be observed as two side-band signals at  $27.1 \text{ kHz} \pm 2 \text{ Hz}$  in Fig. 2. Signal spectra recorded for the PM modulation method are one order of magnitude higher than those given by the PP modulation method.

It is known that the sensitivity of a laminated ME sensor under nonlinear modulation techniques depend on several parameters namely the total nonlinearity, the piezoelectric and magnetic constants and the coupling coefficients. To better

understand and compare the input equivalent magnetic noise floor corresponding to the classic passive mode, to the PM and PP modulation techniques, we performed the measurement of ME sensitivities of these three methods as a function of the frequency. We found that all of the three present good responses at low frequencies. As we mentioned above, the sensitivity of the PM modulation is higher than that for the PP modulation due to a higher nonlinear response. However, the low sensitivity in the classical passive mode can be explained by the absence of DC magnetic bias. In order to compare the noise level under the same magnetic conditions, no magnetic bias has been applied in all of our measurements.

Next, we obtained the transfer functions for the case of the passive mode, the PP and PM modulations. A reference magnetic flux of  $38 \text{ nT}_{\text{rms}}$  was generated by a pair of commercial Helmholtz coils with a magnetic coefficient of  $537 \text{ } \mu\text{T/A}$ . The ME sensor, surrounded by a home-made pick-up coil, is placed in the center of the Helmholtz coils by adjusting the sensing direction along the direction of the reference magnetic signal. These three transfer functions were directly measured at the  $V_0$ ,  $V_1$  and  $V_2$  outputs by using the ‘‘Sweep-sine’’ method of the spectrum analyzer.

Next step, we measured the noise floor with the three methods. We performed the experimental manipulations simultaneously two by two in order to analyze the coherence of the near-carrier noise. The sensor is driven by a voltage of

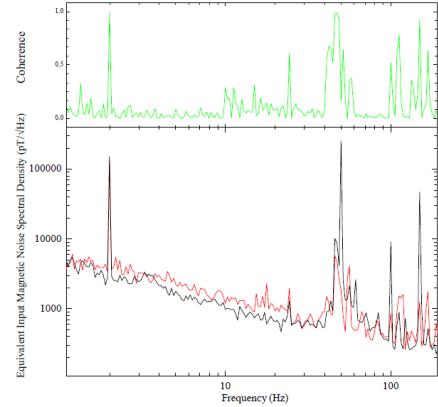


Fig. 3. Input equivalent magnetic noise for passive detection (black curve) and PP (red curve) modulation techniques and the spectral coherence between the two curves.

0.1 V in peak value around the sensor resonant frequency of  $f_s = 27.1 \text{ kHz}$ . By applying a reference magnetic signal to make sure that the system is operating correctly, the noise and the ME voltage introduced across inter-digital electrodes on both top and bottom sides of the piezoelectric layer of the laminate was measured as a function of frequency, using a dynamic spectrum analyzer. We measured the noise and the coherence for the passive mode and the two modulation techniques from either  $V_0$  and  $V_1$  or  $V_0$  and  $V_2$  outputs.

Figure 3 shows the input equivalent magnetic noise for the passive detection mode and the PP modulation technique and their coherence curve. It was found that the coherence is almost zero in the measurement bandwidth although the two noise curves were quite similar indicating that the noise sources are of different origins.

Similar measurements have been performed between the

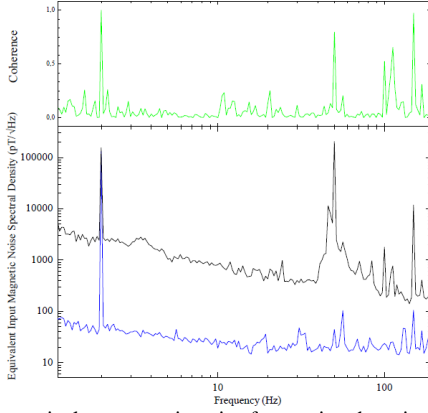


Fig. 4. Input equivalent magnetic noise for passive detection (upper black curve) and PM (lower blue curve) modulation technique and their spectral coherence (green curve).

passive mode and PM modulation. Because of the strong ME sensitivity related to the giant nonlinearity of magnetostrictive layers, the equivalent magnetic noise floor for the PM

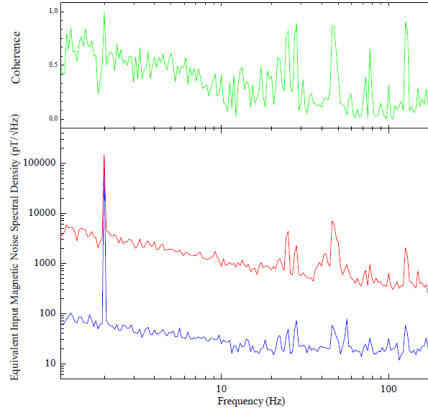


Fig. 5. Input equivalent magnetic noise for PP (upper red curve) and PM (lower blue curve) modulation techniques and the spectral coherence (green curve) between these two curves.

modulation technique is much lower as shown in Fig. 4. As for the preceding measurement, the coherence curve revealed different noise origins between the passive detection method and the PM modulation.

Finally, we determined the noise correlation between the PP and PM modulation techniques. We found a significant correlation factor ( $> 50\%$ ) at low frequencies as shown in Fig. 5.

These measurements results can be explained as follows: At low frequencies, the dominant noise for the passive mode originates from the electronic-thermal noise sources of sensor or noise sources in amplifier. None of them are real input noise sources for the ME nonlinear system which means that they cannot be distributed by the strong exciting carrier signal as a near-carrier noise. However, any environmental magnetic noise can be detected by the ME sensor system as an input perturbation. Such a noise source is detected by the ME sensor in the same way as the reference magnetic signal. In our magnetic shielded room, the environmental magnetic noise level is below the  $\text{pT}/\sqrt{\text{Hz}}$  at low frequencies. Therefore, the contribution from the environmental magnetic noise can be

neglected compared to the observed noise level of the order of a few hundreds  $\text{pT}/\sqrt{\text{Hz}}$  at 1 Hz. Thus, the mechanical-thermal noise is the only noise source expected at low frequencies, modulated via the strain nonlinearity of laminated sensor.

## V. CONCLUSIONS

Due to the intrinsic electric-thermal noise limit, caused by the dissipation in piezoelectric phases, the performance of ME sensors is hampered from achieving a considerable ME response under passive detection mode. Modulations techniques can be applied to overcome this inconvenience by shifting low frequency reference magnetic signals near a carrier at much higher frequencies via the nonlinearity of ME sensors. The intrinsic electric-thermal dissipation which presents itself as a dominant noise distribution in ME sensor can be avoided because of its presence after the nonlinear system of sensors. Therefore, the mechanical-thermal noise source in ME sensor appears as the only intrinsic noise source which is filtered by the nonlinear system and produces a frequency-dependent noise distribution around the exciting carriers. Our experiments with noise coherence techniques revealed the existence and the predominance of this noise distribution.

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