Magnetic-Field Sensitivity Enhancement by Magnetoelectric Sensor Arrays

Zengping Xing, Junyi Zhai, Junqi Gao, Jiefang Li, and Dwight Viehland

***Abstract*—We have investigated an array of magnetoelectric (ME) detection sensor units and an equivalent scheme by which to model their magnetic-field detection sensitivity. The signal response, noise level, and signal-to-noise ratio (SNR) of an array of m units connected in parallel and serial modes have been analyzed. Our research shows that ME arrays in parallel increase the signal and noise currents by factors of m and $\sqrt{m}$, respectively, while ME arrays in series do not increase the signal current but reduce the noise by $\sqrt{m}$. Accordingly, we predict and experimentally confirm that the SNR increases by a factor of $\sqrt{m}$, for both serial and parallel modes.**

***Index Terms*—Intrinsic noise, magnetoelectric (ME) effect, modeling, sensitivity.**

I. Introduction

MAGNETOELECTRICITY (ME) is a coupling between polarization and spin [1]. The ME effect in laminate composites of magnetostrictive and piezoelectric layers is known to be higher than either single phase or particulate composite. The said ME laminates offer potential applications in magnetic-field sensors and energy harvesting, etc. [2]–[8].

Detection of minute magnetic-field variations by sensors is practically limited by noise. This is also the case for ME laminate sensors. There are two kinds of noise sources that affect the lowest detectable signal: external (or extrinsic) and internal (or intrinsic). External noise affects the measurement system by coupling to the signal which is to be detected. One can mitigate some external contributions by specific techniques such as shielding, grounding, filtering, and isolation. However, even if the mitigation is entirely successful, the sensor and the measurement circuitry still contribute internal noise, which cannot be removed. The internal noise comes from random phenomena in nature: such as thermal agitation of electrons in resistors, radiation fluctuation between sensor and environment, generation and recombination of electron–hole pairs in semiconductors, and current flow across a potential barrier [9]–[12]. We cannot reject internal noise without changing sensor or detection circuit; rather, we can only optimize the sensor system to some specific performance. Such an optimization must include contributions from measurement circuitry and ME laminate design [13].

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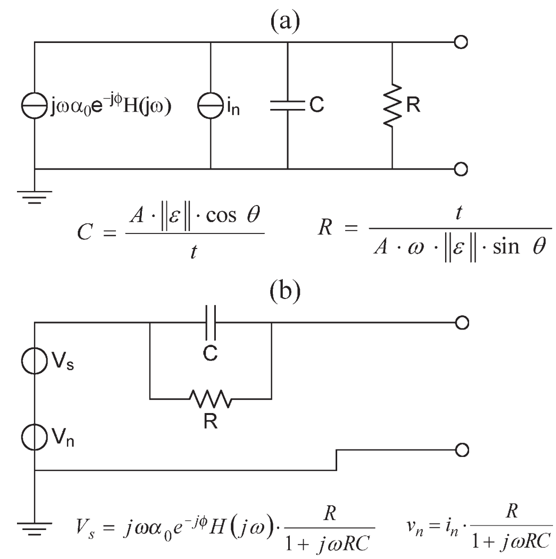

Fig. 1. Equivalent circuit model for the ME laminate sensor. (a) Current source model. (b) Voltage source model.

Measurement circuit optimizations have been reported. Parallel m circuit units can help to increase the sensitivity but will not work in large impedance source (such as ME sensors) measurement [9], [10]. This turned us to the consideration of the ME sensor design optimization.

An equivalent circuit is the best method by which to analyze and optimize ME sensor design. In prior studies, we developed an ME equivalent circuit model for such a purpose that also included noise. This model was based on the "ME system equation," where the sensors and the environment are lumped together. Based on this equation, we can set up the ME model shown in Fig. 1 [14].

In Fig. 1(a), $\|\varepsilon\|$ is the modulus of the complex permittivity and θ is the phase. The current source denotes the time differential of the magnetic-field-induced charge $Q = \alpha_0 e^{-j\phi} H$, with H as the magnetic field. H and Q are complex quantities.

The signal-to-noise ratio (SNR) of the models follows directly from Fig. 1(a)

$$SNR = j\omega\alpha_0 e^{-j\phi} H / i_n. \tag{1}$$

In the following sections, we have extended this approach from "ME unit" to ME arrays. We predict the signal current level, noise current level, and SNR for both parallel and serial arrangements of ME units into arrays. We have confirmed the predictions by experimental measurements.

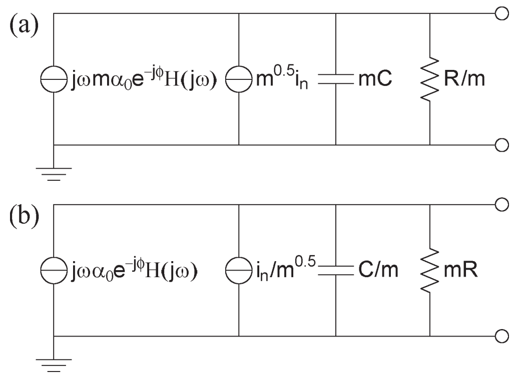

Fig. 2. Equivalent circuit of ME array in (a) parallel mode and (b) serial mode.

II. Theory Prediction

A. ME Array in Parallel Mode

In this case, m ME sensor units were connected in parallel. For simplification, we can assume that the signal response of all these ME units is harmonic to the applied magnetic field H, i.e., each has the same ME charge coefficient ($\alpha_0 e^{-j\phi}$ or α_{me}), impedance $(R//C)$, and noise level (i_n). When we apply a magnetic signal H to this ME sensor array, the response current signals add directly from each ME unit response, as follows:

$$I_{sP} = m \cdot j\omega\alpha_0 e^{-j\phi} H. \tag{2}$$

However, because inherent noise is nonharmonic, the terms cannot simply be added. Rather, assuming that all the noise sources are uncorrelated, the value of the total noise must be evaluated by a root-square sum of all noise contributions [9], [10]. We can estimate the rms noise current as

$$i_{nP} = \sqrt{i_{n1}^2 + i_{n2}^2 \cdots + i_{nm}^2} = \sqrt{m} i_n. \tag{3}$$

We can acquire the equivalent model for Fig. 2(a), from which we can determine the SNR of the ME array in parallel as

$$SNR_P = \sqrt{m} j\omega\alpha_0 e^{-j\phi} H/i_n. \tag{4}$$

From (2) and (3), we can find that the signal current increases by a factor of m, but the noise current increases by $\sqrt{m}$. By comparing (1) and (4), we can also see that the SNR of the ME array in parallel increases by a factor of $\sqrt{m}$.

B. ME Array in Serial Mode

In this case, m ME sensor units were connected in series. We used the voltage source model here for convenience in analysis. For simplification, we also assume that the signal response of all these ME units is harmonic to the applied magnetic field H, and we acquire the total voltage response as follows:

$$V_{sS} = m \cdot j\omega\alpha_0 e^{-j\phi} H \cdot R/(1 + j\omega RC). \tag{5}$$

Again, the voltage noise level must be calculated by a root-square sum [9], [10], which results in

$$v_{nS} = \sqrt{v_{n1}^2 + \cdots + v_{nm}^2} = \sqrt{m} i_n R \cdot /(1 + j\omega RC). \tag{6}$$

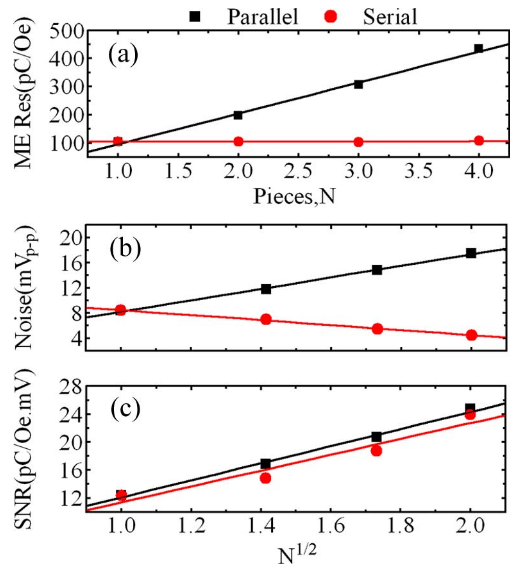

Fig. 3. (a) ME response. (b) Output noise level. (c) SNR of parallel and serial modes [(b) and (c) share the same x-axis].

This gives again an SNR that is proportional to $\sqrt{m}$.

For a direct comparison with the signal current and noise current in the parallel mode, we can convert it to a current source model by the Norton theorem, as shown in Fig. 2(b). In this case, the signal current (I_{sS}) and noise current level (i_{nS}) are

$$I_{sS} = j\omega\alpha_0 e^{-j\phi} H \tag{7}$$

$$i_{nS} = i_n/\sqrt{m}. \tag{8}$$

The SNR of the ME array in serial mode then is

$$SNR_S = \sqrt{m} j\omega\alpha_0 e^{-j\phi} H/i_n. \tag{9}$$

From (7) and (8), we can see that the signal current is unchanged by a serial arrangement of ME units, whereas the noise current is decreased by a factor of $\sqrt{m}$: Thus, the SNR is increased by a factor of $\sqrt{m}$.

III. Experimental Verification

We next tested the predictions of (2)–(4) and (7)–(9). We constructed several longitudinal-transverse (L-T) ME laminate sensors and arranged them in serial and parallel arrays. Each unit in the array was constructed from two pieces of $Tb_{1-x}Dy_xFe_{2-y}$ (size $14 \times 6 \times 1.1$ mm^3) and one piece of $Pb(Zr,Ti)O_3$ (size $15 \times 6 \times 0.5$ mm^3). For signal (noise) amplification, we also designed a low-noise $(< 1\ \mathrm{fA_{rms}})$ low-power-consuming $(\sim 10\ \mu\mathrm{W})$ charge amplifier with a gain of $\sim$1 pC/V over the frequency bandwidth of 0.2–10 Hz. Care must be taken in construction and measurement, including excellent grounding and shielding techniques, low humidity, stable environment temperature, and vibration noise isolation. The detection system was also kept under constant operation conditions for several hours before measurements were performed.

The output noise level, the ME charge response, and the SNR are shown in Fig. 3.

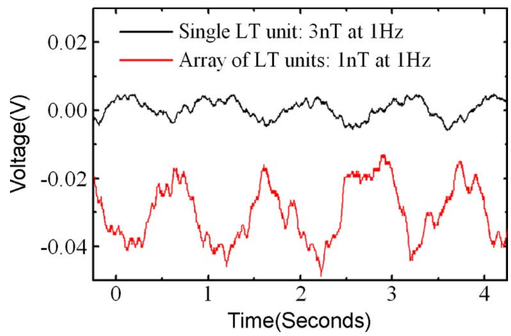

Fig. 4. Waveforms in real time for a L-T ME unit and a ME array in 1-Hz sinusoidal magnetic fields of 3 and 1 nT, respectively.

From the data, we can see that the signal for the parallel mode increases linearly with the number of elements N in the array, whereas in serial arrangement, the signal is independent of N. In addition, we can see that the noise level increases by $\sqrt{N}$ in the parallel mode but decreases proportionally to $\sqrt{N}$ for the serial. Because of these opposite trends in signal and noise, both the parallel and serial arrangements have the same resultant effect on the SNR, which increased linearly with $\sqrt{N}$. These findings confirm the predictions of (4) and (9).

Finally, we determined the lowest detectable signal for an ME array consisting of eight L-T units and compared this to the result for a single sensor unit. In Fig. 4, we can see that a single L-T unit can only detect a magnetic-field change of 3 nT at 1 Hz, whereas the ME array can detect a signal as low as 1 nT at 1 Hz. These results, again, confirm our prediction for the SNR enhancement by array constructions.

IV. Conclusion

We have demonstrated the importance of array constructions for increasing the SNR and for decreasing the detection limit of minute low-frequency magnetic-field variations using ME laminate composites. Experimental results have confirmed the predictions, and we have shown that the arrays of ME sensors are capable of increasing the sensitivity by a factor of $\sqrt{m}$ in both serial and parallel modes.

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