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Inductance–capacitance resonance effect in the magnetoelectric composites characterization system

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Abstract This paper presents the inductance–capacitance (LC) resonance effect in the magnetoelectric (ME) composites characterization system. The measured magnetoelectric voltage coefficient is significantly affected by the LC resonance at the electromechanical resonant frequency, but not at 1 kHz, typically reported in the literature. Decreasing the measuring circuit inductance and/or capacitance helps to reduce the LC resonance effect. While it is impossible to completely eliminate the coil inductance and capacitance, they should be accounted for by proper circuit balancing. One can accurately calculate the sample intrinsic ME voltage coefficient knowing L and C of the measuring circuit. This study is helpful for designing and building the ME characterization systems.

1 Introduction

Recently, bulk magnetoelectric (ME) materials have drawn increasing attention due to their ME effect, which provides significant advantages for applications in devices operating at low (pico-tesla sensitivity magnetometer) [1, 2] and microwave frequencies (electrostatically tunable band-pass filter [3], band-stop filter [4], resonator [5], and phase shifter [6]). Most of these devices are based on layered ME composites that exhibit stronger ME effect compared with the particular ME materials [7].

The ME measurement system is used for the ME composites and devices characterization. The ME coefficient reflects the change in the electric field $\mathrm{d}E$ with respect to the applied magnetic field $\mathrm{d}H$, $\alpha_{\mathrm{E}} = \mathrm{d}E/\mathrm{d}H = \mathrm{d}V/(t \cdot \mathrm{d}H)$, and is the most critical indicator of the ME coupling properties in this kind of composites. Here, $\mathrm{d}V$ is the voltage generated in the piezoelectric materials, t is the piezoelectric materials thickness, and $\mathrm{d}H$ is the oscillating magnetic field amplitude generated by Helmholtz coils [8].[1]

2 Theoretical consideration

The ac magnetic field amplitude can be detected by using a magnetic meter. However, the detected frequency less than 30 kHz requires a special magnetic meter [9, 10]. In order to reduce the measurement system cost, it is built based on the virtual multichannel lock-in amplifier [11]. The system schematic along with the equivalent electrical circuit is shown in Fig. 1. The ac magnetic field is detected by measuring the voltage change across the resistor R_1 (Fig. 1). By analyzing the circuit in the figure, and assuming that the origin of all coherent signals is produced exclusively by the ME effect in the tested device, one can immediately obtain $\mathrm{d}H$ from $\mathrm{d}H \sim I_{\mathrm{L}} = \frac{V_{\mathrm{CH1}}}{R_1 Z_{\mathrm{in}}/(R_1+Z_{\mathrm{in}})}$, where I_{L} is the current passing through the inductor (Helmholtz coils), V_{CH1} is the measured voltage across R_1, and Z_{in} is the oscilloscope electrical impedance. The sample intrinsic ME voltage coefficient α_{E} is inversely proportional to

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[1] http://www.ets-lindgren.com/manuals/6402.pdf

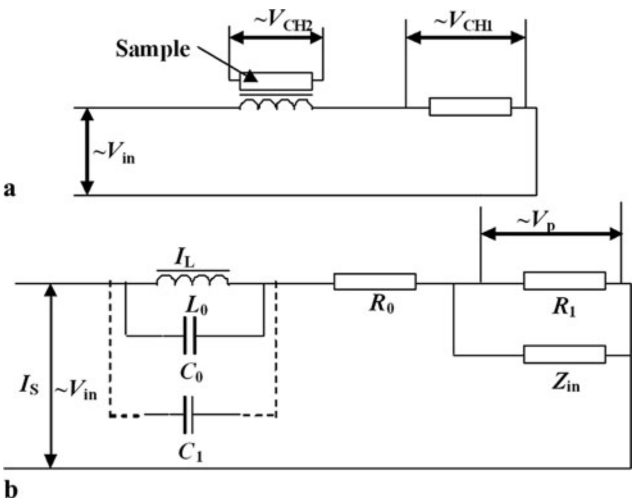

Fig. 1 (**a**) Schematic diagram for detecting ac magnetic field and sample output voltage; (**b**) equivalent electrical circuit (simulation circuit)

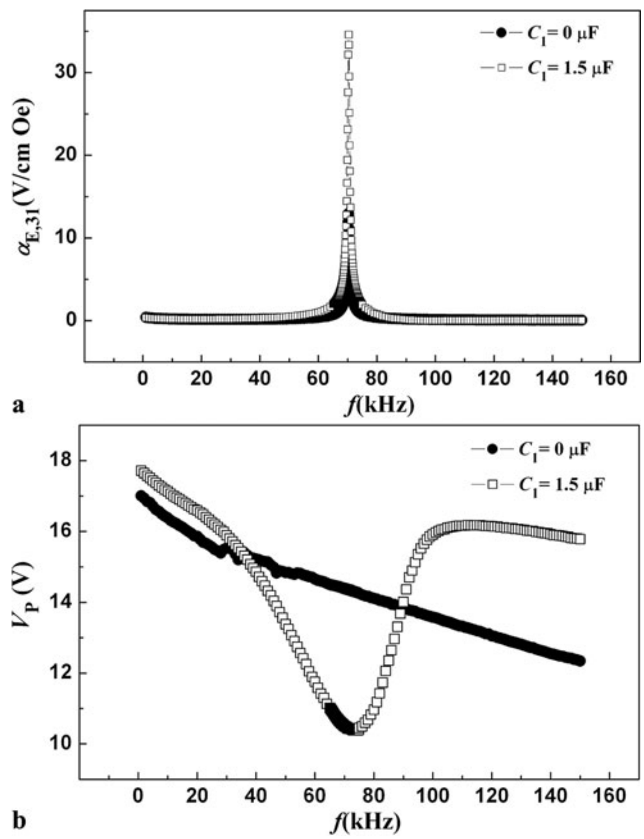

Fig. 2 (**a**) Measured magnetoelectric coefficient and (**b**) voltage change across R_1 when matched capacitance C_1 is 0 and 1.5 μF for a $10 \times 25 \times 0.8$ mm^3 Ni-PZT-Ni trilayered plate magnetoelectric composite. C_1 is the matching capacitance, $C_0 = 140$ nF is the coil capacitance

I_L ($\alpha_E \sim \frac{1}{I_L}$). In the currently used system, R_1 is a standard 10-ohm resistor, whose electrical resistance is much lower than Z_{in} (10^7 ohm). The ac magnetic field dH can be obtained from $I_L \approx \frac{V_{CH1}}{R_1}$. The voltage across the sample, V_{CH2}, is measured synchronously with V_{CH1}. The sample intrinsic magnetoelectric voltage coefficient can be calculated as $\alpha'_E = \frac{V_{CH2} \cdot R_1}{M \cdot t \cdot V_{CH1}}$, where M is denoted as induced magnetic field per unit of current passing across the Helmholtz coils, and has the units of Oe/A. For a given set of coils, M is a constant ignoring the effect of the winding capacitance. In this paper, we denote the current passing through R_1 as $I_R = V_{CH1}/R_1$. Therefore, $\alpha'_E \sim \frac{1}{I_R}$, and ideally, $\alpha_E = \alpha'_E$. However, due to the self-resonance of the Helmholtz coils, the output dH will change with the frequency, even if the input I is constant. In the next part, we will study the self-resonance effect of the Helmholtz coils used in the magnetoelectric measurement system.

3 Results and discussion

Figure 2(a) shows the dependence of measured magnetoelectric voltage coefficient (solid dots) on the applied magnetic field frequency varied from 1 to 150 kHz for a $10 \times 25 \times 0.8$ mm^3 Ni-PZT-Ni trilayered plate magnetoelectric composite prepared by electroplating [12]. It shows that the ME coefficient has a maximum value of about 13 V/(cm·Oe) when the applied magnetic field frequency is 70.5 kHz. The ME voltage coefficient resonance peak is associated with the electromechanical resonance (EMR) [13]. One can obtain a similar frequency spectrum of the ME voltage coefficient by matching a parallel capacitance C_1 (1.5 μF) on the Helmholtz coils (hollow squares). The main difference is that the ME voltage coefficient maximum value increases to 34.6 V/(cm·Oe). Voltages measured across R_1 when $C_1 = 0$ μF (solid dots) and $C_1 = 1.5$ μF (hollow squares) are shown in Fig. 2(b). There is a transition around resonant frequency when the balance capacitance $C_1 = 1.5$ μF, but not when $C_1 = 0$ μF. This phenomenon is very interesting and has not been reported in previous studies.

In the actual ME measurement system the detecting circuit is equivalent to an inductance–capacitance–resistance (LCR) circuit due to the inevitable inductance L_0 and the winding capacitance C_0 of the Helmholtz coils, as shown in Fig. 1(b). R_0 is the measurement circuit's load resistance, which in our case is 1.2 ohm, and C_1 is the balance capacitance. It is well known that there is an LC resonance in LC circuits. Because of the LC resonance, I_L is not equal to I_R at any given time. Therefore, the detected magnetoelectric voltage coefficient α'_E is not equal to the sample material intrinsic ME voltage coefficient α_E. The relationship between the two coefficients can be expressed as $\alpha'_E/\alpha_E = I_L/I_R$.

Circuit simulation software (Multisim, from National Instruments, TX, USA) was used to analyze the difference in ME voltage coefficients for $C_1 = 0$ μF and $C_1 = 1.5$ μF, and study the LC resonance effect along with the detecting circuit characteristics. Using the software, we calculated the

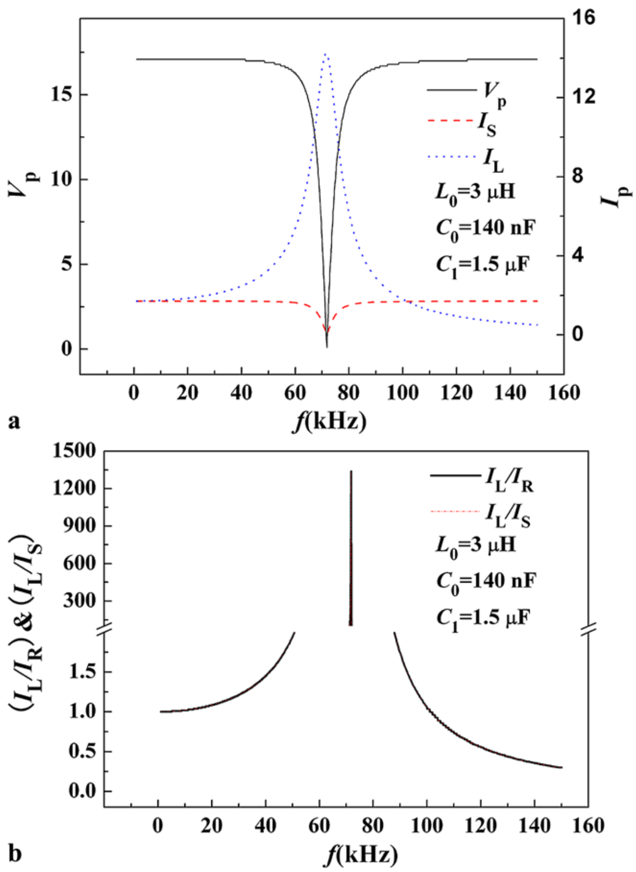

Fig. 3 (**a**) Calculated voltage V_p output and (**b**) (I_L/I_R) and (I_L/I_S) ratios for $C_0 = 140$ nF, $C_1 = 1.5$ μF and $L_0 = 3$ μH. (The I_L/I_R and I_L/I_S lines coincide with each other in (**b**))

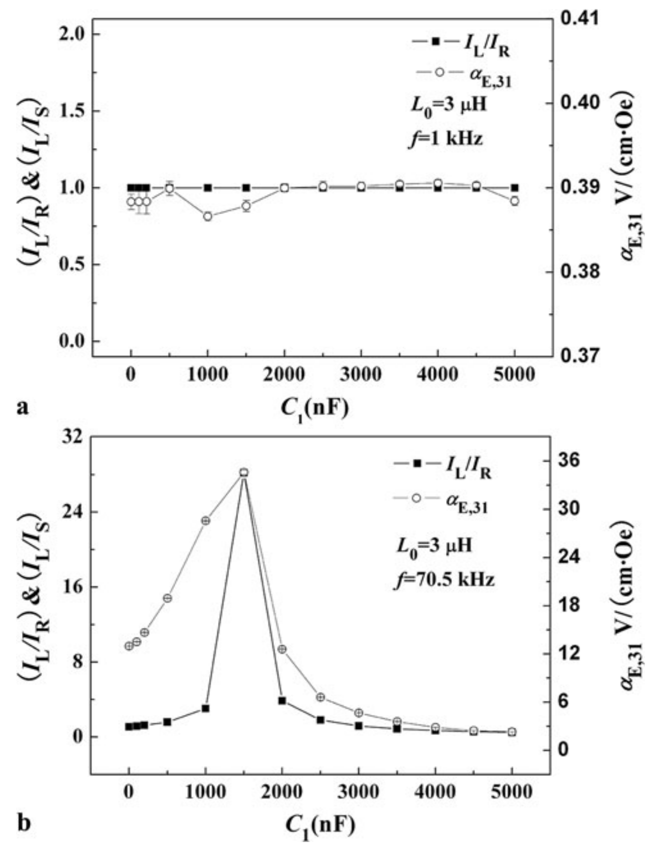

Fig. 4 Calculated (I_L/I_R) and (I_L/I_S) ratios (*left axis*) and measured magnetoelectric voltage coefficient (*right axis*) for a $10 \times 25 \times 0.8$ mm^3 Ni-PZT-Ni trilayered plate magnetoelectric composite dependence on the matching capacitance C_1 at (**a**) 1 kHz and (**b**) 70.5 kHz (electromechanical resonance frequency)

output voltage of R_1 (V_p, the output voltage of the CH1, V_{CH1}) and the current of L_0 (I_L), as shown in Fig. 3(a). The V_p and I_L behavior changes at around 71.8 kHz, which is associated with the LC circuit resonance. The choice of 71.8 kHz LC resonant frequency is helpful in illustrating the strong effect of LC resonance on the measured ME voltage coefficient when the LC resonance approaches the EMR of the composites. A good qualitative comparison is seen between the measured and calculated voltage change across R_1, shown in Figs. 2(b) and 3(a), respectively, indicating that the calculation is appropriate. Then, one can calculate the (I_L/I_R) ratio with the frequency varied from 1 to 150 kHz, as shown in Fig. 3(b). The (I_L/I_R) ratio also has a peak of about 1350 at 71.8 kHz (calculated resonant frequency). This indicates that α'_E/α_E ratio is about 1350 when the circuit capacitance $C_0 = 140$ nF, balance capacitance $C_1 = 1.5$ μF and the circuit inductance $L_0 = 3$ μH. C_0 and L_0 are the measured Helmholtz coils capacitance and inductance of the setup, respectively. At 71.8 kHz LC resonance frequency the calculated ME coefficient deviates far from the actual sample intrinsic coefficient. However, at low frequency of 1 kHz, the (I_L/I_R) ratio is constant and equals 1 (Fig. 3(b)). This indicates that the calculated ME voltage coefficient is equal to the sample intrinsic coefficient at low frequency, and the LC resonance does not affect the measurements. Sine the ME voltage coefficients detected at 1 kHz and the resonant frequencies are most interesting, and commonly reported in the literature, we focus on the measurements at these frequencies [14–19].

Figure 4 (right axis) shows the measured ME voltage coefficient $\alpha_{E,31}$ of the $10 \times 25 \times 0.8$ mm^3 Ni-PZT-Ni trilayered plate magnetoelectric composite as a function of the balancing capacitance C_1 at 1 and 70.5 kHz (electromechanical resonance frequency determined experimentally in Fig. 2(a)). The coefficient $\alpha_{E,31}$ is basically unchanged, with an almost constant value of about 0.39 V/(cm·Oe) at 1 kHz. However, $\alpha_{E,31}$ initially increases and then decreases with the C_1 rise at 70.5 kHz. It achieves the maximum value up to 30 V/(cm·Oe) when C_1 is 1.5 μF. Moreover, $\alpha_{E,31}$ is only 13 V/(cm·Oe) or 2.3 V/(cm·Oe) when C_1 is either 0 or 5 μF. This indicates that the measured ME voltage coefficient is strongly affected by the balance capacitance C_1 at the electromechanical resonant frequency, but not at 1 kHz.

In order to understand these results, we also calculated (I_L/I_R) using the software with C_1 varied from 0 to 5 μF.

The simulated results are shown in Fig. 4 for 1 and 70.5 kHz, respectively. Figure 4(a) shows that the (I_L/I_R) ratio is 1 at 1 kHz with varying balance capacitance C_1. The (I_L/I_R) ratio behavior is similar to the one of $\alpha_{E,31}$ in the varied capacitance range. Both of them have a maximum when C_1 is set at 1.5 μF $(I_L/I_R = 28.2)$. However, the calculated (I_L/I_R) ratio values are 1.09 or 0.494 when C_1 is either 0 or 5 μF, respectively. Comparing the left and right vertical axes data in Fig. 4(b), the behavior of $\alpha_{E,31}$ and (I_L/I_R) ratios is the same at 70.5 kHz. This similarity indicates that at 1 and 70.5 kHz the measured ME coefficients are disproportionately affected by the LC resonance at lower than 1 kHz and higher than 70.5 kHz resonant frequencies.

In the present study, we denote the sum circuit current as I_S (measured in series), as shown in Fig. 1(b). We also simulated I_S and calculated the (I_L/I_S) ratio, shown in Fig. 3. Ratios (I_L/I_S) and (I_L/I_R) are the same at any given frequency for all balance capacitances (we show only the result for $C_1 = 1.5$ μF in this paper). For the sinusoidal applied magnetic field, there are mainly two methods to calculate the ME voltage coefficient. The one is the constant voltage mode used in our previous studies and the other is the constant current mode [14–20]. The main difference is that in the constant voltage mode, constant voltage is applied to the detecting circuit, while constant current is applied in the constant current mode.

From the above analysis, in the constant voltage and constant current modes, the (I_L/I_S) and (I_L/I_R) ratios have the same values, respectively. This indicates that the effect of LC resonance on the measured ME voltage coefficient is the same in both modes. Therefore, it is possible to utilize either one of the two methods to measure the ME voltage coefficient.

Figures 3 and 4 indicate that one should decrease the capacitance C and inductance L of the Helmholtz coils in order to minimize the effect of LC resonance on the ME voltage coefficient measurements. One can also determine the validity of the measured ME voltage coefficient when L and C of the Helmholtz coils are known. Moreover, the measured ME coefficient can be modified using circuit simulation software if L and C of the detecting circuit are directly measured.

4 Summary

In summary, the effect of LC resonance on the ME measurement system was experimentally and theoretically studied. Inevitably, the LC resonance influence is present in the ME voltage coefficient measurements. One should decrease the inductance and capacitance of the circuit as much as possible to decrease the effect of LC resonance on the ME coefficient. The measured ME voltage coefficient is strongly affected by the balance capacitance C_1 at the electromechanical resonant frequency, but not at 1 kHz, especially when the LC resonance frequency is approaching the EMR frequency of the composites. One can also modify the measured ME coefficient using the circuit simulation software with the precise measurements of L and C in the detecting circuit. The constant voltage and current modes produce the same measured ME voltage coefficient results from the LC resonance standpoint. This study is helpful for properly designing and building ME measurement systems and correctly processing the measured ME voltage coefficient data.

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