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# A non-invasive electric current sensor employing a modified shear-mode cymbal transducer

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ABSTRACT

This paper presents a non-invasive sensor for electric current monitoring in electric power grid. The sensor consists of a modified shear-mode cymbal transducer and a Halbach array attached on the transducer. The Halbach array generates concentrated magnetic flux density on the side where the electric wire is placed and lowers the magnetic field on the other side. The wire experiences an enhanced Ampere force when energized, and the resulting reaction force of the Ampere force is further amplified by the cymbal transducer. The transducer works in shear mode and produces a voltage proportional to the applied electric current. At low frequencies, the sensor exhibits a flat voltage response. The non-resonant sensitivity of the sensor reaches ~6.98 mV/A over the frequency range of 10–80 Hz with a separating distance of $d = 3.0$ mm. The average sensitivity is 6.97 mV/A with high linearity at the power-frequency of 50 Hz, and a small current step change of 0.05 A can be clearly distinguished.

## 1. Introduction

Wireless sensor networks (WSNs) based on electric current sensors are deemed as a promising solution for electricity monitoring in electric power grid, which can improve the reliability and efficiency of the electric power distribution infrastructure. Conventional current sensors, such as Rogowski coils, Hall sensors, magnetoresistance (MR) sensors, and current transformers, have been reported in previous literatures [1–4]. However, Rogowski coils need to encircle the electric wire and are not suitable for small current sensing [1]. Hall sensors impose great demands on signal conditioners and constant current supplies [2]. MR sensors have the disadvantages of high nonlinearity and large thermal drifts [3]. Current transformers are usually used as protection and measurement applications [4], but they exhibit magnetic saturation and hysteresis under large current condition. Recently, magnetoelectric (ME) structures have attracted great interests due to their potential applications in the fields of sensors [5,6], transducers [7], and actuators [8]. Magnetoelectric devices have been used for current sensing [9,10], but the sensors also need to encircle the wire to improve the sensitivity. A non-invasive resonant current sensor based on a piezoelectric cantilever beam and NdFeB magnets is presented to sense electric current for two-wire power cords [11]. However, it is difficult for the sensor to accurately resonate at the power frequency (50 Hz or 60 Hz) due to the nonlinearity of the piezoelectric material [12]. Lately, a non-resonant current sensor is developed [13]. The length of the high permeability cuboids need to be large to reduce the demagnetization factor.

For the past few years, $0.71Pb(Mg_{1/3}Nb_{2/3})O_3$-$0.29PbTiO_3$ (PMN-PT) has attracted much attention due to the excellent electromechanical response [14], and shear-mode PMN-PT has the highest piezoelectric coefficient value [15]. To measure electric current in electric power grid, a non-invasive and non-resonant device might be preferred. In this paper, a non-invasive current sensor using shear-mode PMN-PT is proposed, which does not require a power source and operates non-resonantly, as shown in Fig. 1. The sensor is fabricated from a modified shear-mode cymbal transducer and a Halbach array which can concentrate magnetic field on the expected side. The operation of the proposed structure is essentially based on the enhancement effect of the magnetic force resulting from the Halbach array and the amplification effect of the cymbal transducer. A prototype is fabricated and tested. The experimental results have evaluated feasibility of the proposed device.

## 2. Structure and principle

Fig. 1 shows the schematic diagram of the proposed current sensor. The sensor is composed of a shear-mode cymbal transducer and

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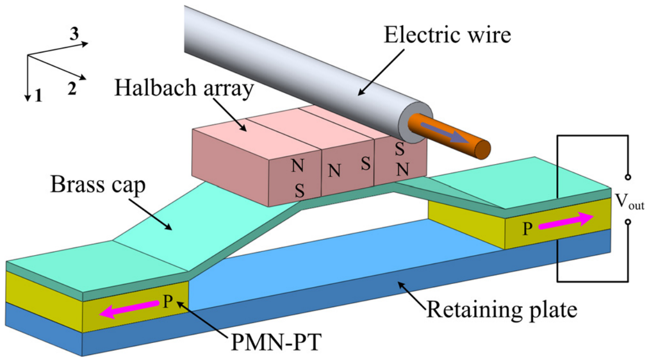

**Fig. 1.** Schematic diagram of the proposed current sensor.

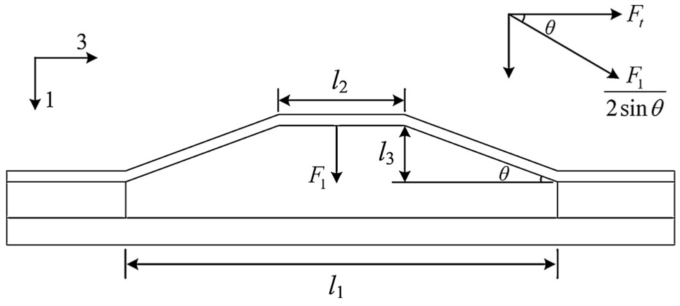

**Fig. 2.** Configuration of the modified cymbal transducer.

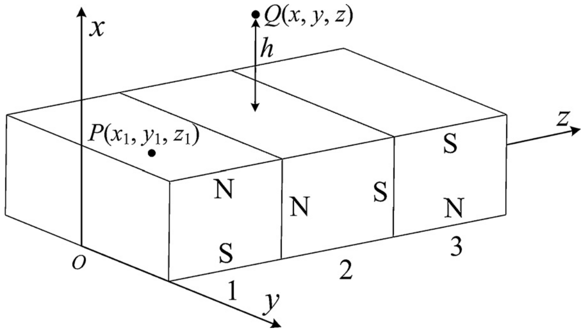

**Fig. 3.** Schematic diagram of the Halbach array.

a Halbach array consisting of 3 NdFeB magnets. The transducer is fabricated from a brass cap, a retaining plate, and shear-mode PMN-PT plates. The Halbach array is a specific arrangement of permanent magnets which concentrates magnetic field on one side (active-side) and reduces the magnetic field on the other side (quiet-side) [16,17]. The sensor is placed directly beneath the electric wire, leading to an augmented magnetic force (which is the reaction force of the Ampere force) on the array. The magnetic force is then further amplified by the cymbal transducer and transfers into shear stress on the PMN-PT plates. Under the piezoelectric effect of the PMN-PT, a voltage is induced proportional to the input current.

As shown in Fig. 1, the PMN-PT plates are polarized along 3-direction. The piezoelectric constitutive equations can be expressed as [18]

$$T_5 = c_{55}^D S_5 - h_{15} D_1, \tag{1}$$

$$E_1 = -h_{15} S_5 + \beta_{11}^S D_1, \tag{2}$$

where $T_5$ and $S_5$ are the shear stress and strain, respectively, $c_{55}^D$ is the shear elastic stiffness coefficient at constant electric displacement, $h_{15}$ is the shear mode piezoelectric stiffness constant, $D_1$ and $E_1$ are electric displacement and the electric field in 1-direction, respectively, and $\beta_{11}^S$ is the dielectric impermittivity in 1-direction at constant strain. The magnetic force on the Halbach array is equal in amplitude and opposite in direction to the vertical Ampere force on the wire, which is given by

$$\begin{aligned} F_1 &= -\frac{I_0}{\pi r^2} \iiint_{V_e} B_3 \sin(\omega t + \theta) dV_e \\ &= -B_m J_0 \sin(\omega t + \theta) \end{aligned} ,\tag{3}$$

where $I_0$, $\omega$, and $\theta$ are the amplitude, angular frequency, and phase angle of the electric current, respectively, $\omega = 2\pi f$, $f$ is the frequency in Hz, $r$ is the radius of the conductor of the wire, $V_e$ is the conductive volume of the electric wire taking into account, $B_3$ is the magnetic flux density along the 3-direction (produced by the array), $B_m$ is the integral of $B_3$ over the volume $V_e$, and $J_0$ is the current density which equals to $I_0/\pi r^2$. For the configuration of the cymbal transducer shown in Fig. 2, the shear force on each PMN-PT plate can be calculated by

$$F_t = \frac{F_1}{2\sin\theta} \cdot \cos\theta = \frac{F_1(l_1 - l_2)}{4 l_3}, \tag{4}$$

The shear stress can be expressed as

$$T_5 = \frac{F_t}{A} = \frac{F_t}{lb}, \tag{5}$$

where $l$ and $b$ are the length and the width of the piezoelectric plate, respectively. Under open-circuit condition, $D_3 = 0$. The induced voltage is obtained from Eqs. (1)–(5), which is given by

$$V_1 = E_1 t_p = \frac{B_m I_0 h_{15} t_p (l_1 - l_2) \sin(\omega t + \theta)}{4\pi r^2 c_{55}^D l b l_3}, \tag{6}$$

where $t_p$ is the thickness of the piezoelectric plate. Eq. (6) shows that the induced voltage is proportional to the input current. Obviously, after determining the geometric and material properties, the induced output voltage of the sensor has a linear response to the electric current.

The Halbach array significantly increases the magnetic field on the active-side. Fig. 3 shows the structure of the array consisting of 3 NdFeB magnets. Using the concept of magnetic charge [19], the $B_z$ components along the lines which are parallel to $z$-axis (directly above or beneath the array) are given by

$$B_z = \sum_{i=1}^{3} B_{Qiz} = \sum_{i=1}^{3} \iint_{S_{ai}+S_{pi}} dB_{Qiz}(x, y, z) dS_i, \tag{7}$$

where $B_{Qiz}$ is the magnetic flux density ($z$-component) which is produced by the magnetic pole surfaces $S_{ai}$ and $S_{pi}$. The calculated results (e.g., $h = 3.0$ mm) are shown in Fig. 4(a). It can be seen from Fig. 4(a) that, the $B_z$ components on the active-side is obviously strengthened, which can potentially improve the sensitivity of the sensor.

## 3. Results and discussion

The current sensor is fabricated according to Fig. 1 ($l_1 = 14$ mm, $l_2 = 6$ mm, $l_3 = 0.4$ mm). The geometric and material characteristics of the PMN-PT are shown in Table 1. The dimension of each magnet is 5.0 mm × 5.0 mm × 3.0 mm. Fig. 4(b) shows the output voltage ($V_1$) versus the frequency ($f$) of the current ($I$). It can be seen from Fig. 4(b) that, the experimental results approximate to the analytical results. The experimental voltage exhibits a flat response with a high sensitivity ($S = V_1/I$) of ~6.98 mV/A over the frequency range