An Ultrahigh Sensitive Self-Powered Current Sensor Utilizing a Piezoelectric Connected-In-Series Approach

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ABSTRACT

In this paper, we demonstrate a self-powered AC-current sensor using a piezoelectric connected-in-series approach to increase the sensitivity. The sensor consists of a CuBe-beam, piezoelectric-PZT-sheet, NdFeB hard-magnet, and mechanical-frame. When the sensor is placed in an alternative magnetic-field induced by an alternative current-carrying wire, the magnet fixed on the beam is subjected to an alternative magnetic-force produced by the magnetic-field. Therefore, the beam is oscillated. Consequently, the piezoelectric-sheet fixed on the beam is periodically deformed and continuously produces voltage-response. When beams are connected in-series, the total voltage-response is significantly enlarged while the background-noise remains the same. The experimental result shows the sensitivity of the sensor consisting 8 beams connected in-series under the magnetic-field generated by a wire of 8-Ampere from a breaker is enlarged from 130 mV/A to 640 mV/A.

Keywords: Piezoelectric effect, Current sensor, Self-powered, Connected-in-series

1. INTRODUCTION

Recently, novel smart structure based self-powered current sensors have been demonstrated by researchers [1-7]. These self-powered sensors consist a magnet fixed on a piezoelectric-PZT beam [8-18] to detect the ambient magnetic fields. For instant, when the sensors are placed nearby an AC current-carrying wire, the beam is accordingly actuated by magnetic-force-interaction between the magnet fixed on the beam and the magnetic-field produced by the current-carrying wire. Furthermore, a voltage output is produced in the actuated beam due to the piezoelectric effect. That is, through energy converting (i.e., converting the ambient magnetic energy to a mechanical energy, and eventually to an electrical output), the sensors with the smart structure is capable of measuring the magnetic-field produced by the AC current-carrying wire. Therefore, the deflection behavior of the actuated beams is one of the critical factors dominating the sensitivity of the sensors. Due to this, to increase the sensitivity, researchers must tune the resonant frequency of the beam (the major consideration of the deflection behavior of the beam) to match the frequency of the AC-current in order to cause the beam to have the largest deflection. However, even the frequency-matching is achieved to maximize the sensitivity, the current is difficult to be accurately measured by the sensors when the magnitude-change of the current is undistinguished in some conductions. Therefore, researchers are still searching an alternative approach to increasing the sensitivity. To address this problem, we demonstrate a self-powered AC-current sensor using a piezoelectric connected-in-series approach [19] to increase the sensitivity in this paper.

2. DESIGN

Figure 1 and 2 illustrates the sensor and its working principle, respectively. As shown in figure 1, the sensor consists of a CuBe-beam, piezoelectric-PZT-sheet, NdFeB hard-magnet, and mechanical-frame. In general, according to the Ampere's Law, a wire carrying an into-plane and out-of-plane DC current produces a clockwise and counterclockwise magnetic field, respectively, as shown in figure 2. This generates an alternating magnetic force between the magnet on the beam and magnetic field produced by the wire. Thus, the magnet with the beam is lifted up and pulled down by the alternating magnetic force. Due to this, when the sensor is placed in an alternative magnetic-field induced by an

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alternative current-carrying wire shown in figure 2, the magnet fixed on the beam is subjected to the continuous alternating magnetic-force produced between the magnet and magnetic-field and subsequently oscillated. Consequently, the piezoelectric-PZT-sheet fixed on the beam is periodically deformed. This produces a cyclic tensile and compressive strain in the piezoelectric-PZT-sheet. Due to the piezoelectric effect, voltage outputs are continuously produced. Therefore, changing the magnetization-direction of the magnet is capable of significantly changing the magnetic force interaction resulting in increasing the sensitivity. In addition, when beams are connected in-series, the total voltage-response is significantly enlarged while the background-noise remains the same. Thus, to utilize both above-mentioned approaches to increase the sensitivity from enhancing the signal-to-noise ratio, we change the magnetization-direction of the magnet from upward direction into lateral direction through modifying our previous research [18]. After changing, we connected 8 current sensors in series to gain larger voltage output.

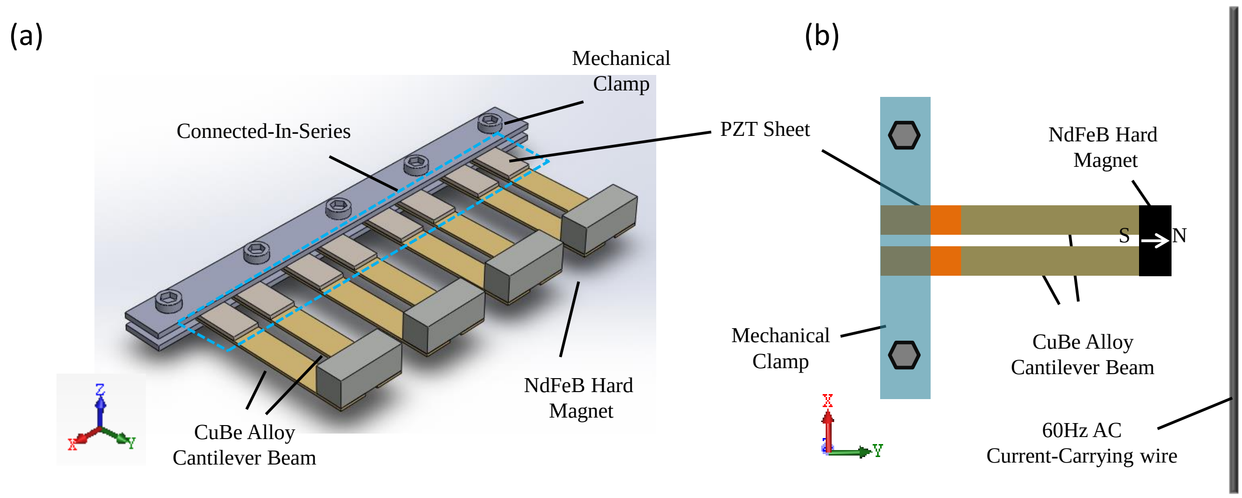

Figure 1. (a) The illustration of the series-connected self-powered current sensors. (b) The top view of one of the self-powered current sensor.

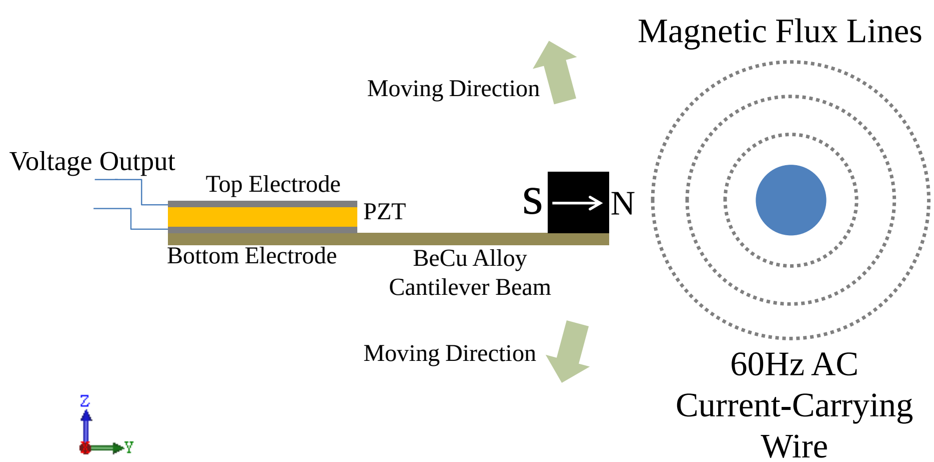

Figure 2. The illustration of the current-sensing principal of the self-powered current sensor (cross-sectional view).

3. FABRICATION

Figure 4 is the photograph of the self-powered current sensor we fabricated. The sensor consists of a CuBe-beam, piezoelectric-PZT-5H-sheet, NdFeB hard-magnet, and mechanical-frame. The dimension (length × width × thickness) of the CuBe-alloy and PZT sheet is 40 mm × 5 mm × 1 mm and 12 mm × 5 mm × 0.3 mm, respectively. The PZT sheet is attached on the root of CuBe-alloy beam. The root of PZT and CuBe-alloy beams is fixed by the mechanical clamp. A rectangular NdFeB hard-magnet ((length × width × thickness: 10 mm × 5 mm × 5 mm) is fixed on the free end of two CuBe-alloy beams. The resonant frequency of each beam (sensor) is tuned to 60Hz (to match the AC wire's frequency). After the fabrication process and frequency-tuning, the self-powered current sensor is fabricated. Through repeating above-mentioned fabrication process, 8 current sensors are fabricated and connected in series.

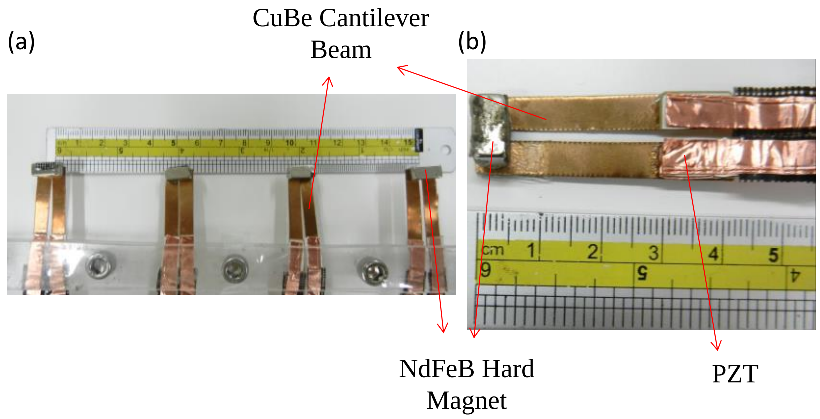

Figure 4. (a)The photograph of the fabricated current sensor connected-in-series, (b).the photograph of enlarged two current sensors (two beams).

4. TESTING

The sensor is tested by placing nearby a current-carrying wire of 8-Ampere from a breaker panel. Figure 5 shows the illustration and the photograph of the testing setup. The mechanical clamp and the clamped current sensors are fixed on the 3-axis positioning stage. The gap between magnets and the wire is 0.5 mm which is precisely adjusted by the 3-axis positioning stage. After the sensors were all set, we connected each sensor in series and used an oscilloscope to record the voltage response.

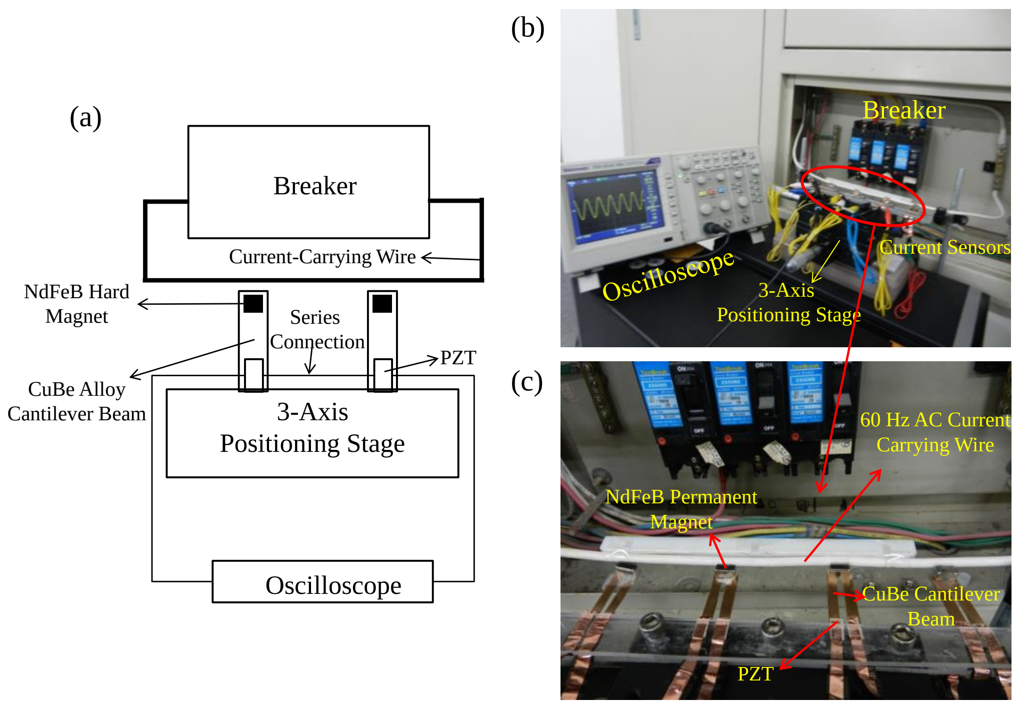

Figure 5. (a)The illustration, (b) photograph, (c) enlarged photograph of the testing setup.

5. RESULTS AND DISCUSSION

The testing results of each sensor (before connected-in-series) with the wire carrying 8 amperes are shown in figure 6. The significant difference of voltage output is attributed to the hand-made fabrication process (different to fabricate exactly geometric-identical current sensors). Another reason is due to the sharing magnet of two sensors. This may cause the magnetic force focus on only one specific sensor instead of evenly distributing to two sensors. Due to the difference voltage output of each sensor, we averaged voltage output of total 8 sensors which is 1.06 V. The averaged sensitivity of each sensor is 0.13V/A.

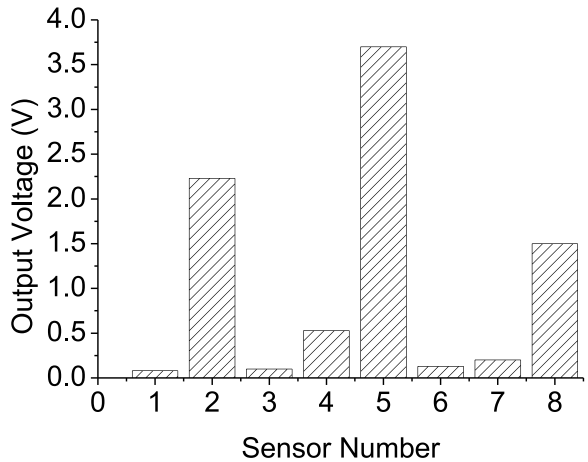

Figure 6. The testing results of each sensor with the wire carrying 8 amperes.

The voltage output of total 8 sensors connected-in-series is shown in figure 7. In figure 7, the red line is the total theoretical voltage output of the PZT sheets versus the current applied to the wire. The black line is the total experiment voltage output versus the current applied to the wire. According to the results of the series-connection case, the experimental voltage output shows a good linearity. However, the experiment results are smaller than the theoretical results. The reason is attributed to that the magnetic-force-induced mechanical deflection of each of the 8 sensors are insufficiently synchronized. The insufficient synchronization of the sensors leads to the phase shift of the voltage output which consequently causes to the experiment voltage output less than the theoretical voltage output.

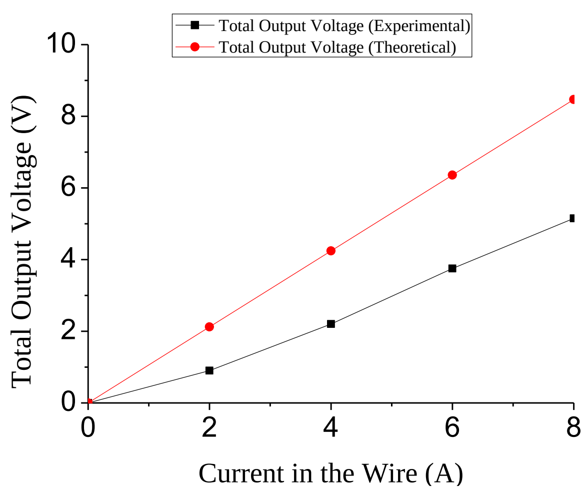

Figure 7. The testing results of 8 sensors connected-in- series versus the current applied to the wire.

Table 1 shows the testing results of 8 sensors connected-in-series. The voltage in table 1 is the maximum magnitude of the voltage response of the current sensor when the gap between the sensor and the current-carrying wire is 0.5 mm.

Table 1. Summary of the testing results of 8 sensors connected-in-series

Current in the Wire (A)	0	2	4	6	8
Experimental Total Output Voltage (V)	0	0.9	2.2	3.75	5.15
Theoretical Total Output Voltage (V)	0	2.12	4.24	6.36	8.47
$\frac{\text{Experimental Output}}{\text{Theoretical Output}}\text{X}100\%$	0	42.45%	51.89%	58.96%	60.80%

In table 1 and figure 7, the experimental total output voltage is less than the theoretical total output voltage when the current applied to the wire is in the range of 2 to 8 amperes. However, when the current applied to the wire is gradually increased, discrepancy between the experiment and theoretical results are gradually eliminated (i.e., experimental-output/theoretical-output is increased from 42.45% to 60.8%). According to these results, the sensitivity of the self-powered piezoelectric current sensors is successfully increased from 0.13 V/A (before connected-in-series; averaged sensitivity of 8 sensors) to 0.64 V/A (8 sensors connected-in-series).

6. CONCLUSION

In this paper, we successfully demonstrated a series-connected approach for enhancing the sensitivity of a self-powered piezoelectric AC-current sensor. According to the experimental results, the sensitivity of the sensors is increased from 0.13 V/A (before connected-in-series) to 0.64 V/A (8 sensors connected-in-series) when the sensor is tested by placing the sensor nearby a wire of 8 ampere at 60 Hz from the breaker. In the future, the sensitivity of the sensors connected-in-series will be optimized. The optimized sensors will be integrated with wireless sensor node toward a self-powered wireless current sensor.

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