Three-axis MEMS DC magnetic sensor using magnetic force interaction with the piezoelectric effect

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Abstract. In this paper, we report a novel three-axis MEMS DC magnetic sensor using magnetic force interaction and piezoelectric effect. The sensor includes a back-side-etched silicon diaphragm, a sol-gel PZT thin film with electrodes, and two patterned electroplated Ni thick films. Each patterned Ni film has specific magnetization direction, defined as specific sensing area. As a DC magnetic fields is applied to the sensor, impulse magnetic force and torque are induced to deflect and twist specific Ni films, respectively. Through the mechanical coupling between the Ni films and the PZT film, the deflection and bending are transmitted to the PZT film to produce piezoelectric peak voltages. Experimental results show that, by analysing full duration and half maximum of voltage outputs produced in two sensing areas, the sensor is able to sense three-axial DC magnetic fields.

1. Introduction

Today, magnetic sensors are widely used in personal electronics, data storage systems, automotive and navigation systems, etc. [1]. Among these applications, Hall-effect sensors and magnetoresistive (MR) sensors are two major magnetic sensors used in the applications. However, the Hall-effect sensors need a magnetic concentrator to sense a magnetic field parallel to the sensors, while the MR sensors require an additional reset-coil to reset the magnetization direction of magnetic materials used in the sensors. In addition, an additional power source is required for both sensors (i.e. not “self-powered”). Recently, piezoelectric based magnetoelastic (ME) sensors [2] have been intensively studied. Due to the ME effect, the ME sensor can directly sense an AC magnetic field under a specifically applied DC magnetic bias field. However, regardless of AC or DC magnetic field sensing, these typical ME sensors can only achieve single axis magnetic field sensing due to the sensing mechanism. In addition, the ME sensors also require an additional power source to provide the DC magnetic bias field. This means the sensor is not fully self-powered.

Hence, to address these issues (i.e. only can achieve single axis magnetic field sensing and must require additional power source), we recently demonstrated a self-powered three-axis piezoelectric MEMS AC magnetic sensor [3]. However, although the AC magnetic field sensing has many applications [4], the DC magnetic field sensing is more practical and thus has more general applications [5]. Thus, based on our previous research work [6], we provide a novel piezoelectric three-axis MEMS DC magnetic sensor in this paper.
2. Design

Figure 1(a) is an illustration of top view of the magnetic sensor. Figure 1(b) and Figure 1(c) shows the cross-section view of the sensor along C-C’ line in figure 1(a). As shown in figure 1(a) and 1(b), the sensor consists of a back-side-etched silicon diaphragm, a sol-gel lead-zirconate-titanate (PZT) piezoelectric thin film with top and bottom Pt/Ti electrodes, and two patterned electrodeposited Ni thick films. The two Ni films are magnetized orthogonally as two different sensing areas (i.e., area A and B has magnetization direction along +Z and +X axial direction, respectively).

When applying a DC magnetic field to the sensor, impulse magnetic force and torque are induced, and consequently corresponding deflection and torsion are produced in specific sensing areas (i.e., in specific magnetized Ni films). The mechanical coupling between the Ni films and the PZT film transmits the deflection and torsion to the PZT film. These further transform PZT film to produce peak voltage outputs due to the piezoelectric effect. The instant peak voltages are generated/detected while the DC magnetic field is switched “on” and “off”. Based on this, sensing principle of three-axis magnetic fields is shown in figure 1(b)-(c). When applying a X- or Y- axis DC magnetic field to the sensor, an impulse magnetic torque is induced in sensing area A while an impulse magnetic force is induced in sensing area B. Similarly, when applying a Z-axis DC magnetic field, an impulse magnetic force is induced in area A while an impulse magnetic torque is induced in sensing B. These forces and torques produce corresponding deflections and torsions, consequently generate associate strains, and finally convert to different piezoelectric voltage outputs. Though voltage analysis, the applied three-axis magnetic fields are obtained.

![Figure 1](image)

**Figure 1.** The illustration of (a) top view, (b) and (c) C-C’ cross-section view of the sensor when applying in-plane (X-axis) and out-of-plane (Z-axis) magnetic fields, respectively. Magnetization directions of nickel films are indicated by black arrows [3].

3. Fabrication and testing

Fabrication of the sensor is reported in our previous works [3], [7]. After the sensor is fabricated, two sensing areas are magnetized to different but specific directions [4] by applying a DC magnetic field of 3000 Oe [8]. The photographs of the sensor are shown in figure 2.

Figure 3(a)-(b) are the illustration and photograph of the test setup, respectively. The setup consists of a function generator, C-shape electromagnet, charge amplifier, voltage amplifier, and oscilloscope. The sensor, electromagnet, and charge amplifier are placed in a magnetic field shielding box. By the shielding, ambient magnetic noises is eliminated during testing. The testing procedure is described below. The function generator is used to provide a square-wave signal (3 Hz, 50% duty cycle) to the electromagnet to produce a DC magnetic field ranging from 1 to 20 guess. The charge amplifier and voltage amplifier are used to amplify voltage outputs generated by the sensor. Finally, the oscilloscope is used to record the amplified voltage outputs.
4. Result and Discussion
The voltage waveforms in sensing area A when applying X- and Z- axis magnetic fields of 20 gauss are shown in figure 4(a)-(b). The voltage waveforms in sensing area B when applying X-, Y-, and Z-axis magnetic fields of 20 gauss are shown in figure 4(c)-(e). The enlarged waveforms are shown in figure 4(f)-(j). When applying X- and Z- axis magnetic field to area A, the FDHM of the voltage outputs are 24.2, 1.0 millisecond. When applying X-, Y-, and Z- axis magnetic fields to area B, the FDHM of the voltage outputs are 22.2, 22.8, 0.9 millisecond.

![Figure 2. The photograph of the sensor [3].](image2)

![Figure 3. (a) Illustration (b) photo of test setup.](image3)
Figure 4. Voltage outputs in two sensing areas of the sensor under different axial magnetic fields: (a)-(b) voltage outputs in area A when applying X- and Z- axis magnetic fields. (c)-(e) voltage output in area B when applying X-, Y-, and Z- axis magnetic fields. (f)-(j) enlarged waveforms of (a)-(e).

Furthermore, we varied the applied magnetic field and obtain the results shown in figure 5(a)-(b). In figure 5(b), the sensitivities in linear regions of area A when applying X-axis and Z-axis magnetic fields are 0.03705 V/G in 2-20G and 0.08776 V/G in 3-20G, respectively. The sensitivities in linear regions of area B when applying X-, Y-, and Z- axis magnetic fields are 0.04097 V/G in 4-20G, 0.02613 V/G in 6-20 G, and 0.07525 V/G in 13-20 G, respectively. Finally, by comparing the FDHM and sensitivities, the direction and magnitude of these applied axial magnetic fields can be distinguished.

Figure 5. Sensing performance and sensitivity: (a) Voltage outputs in different area of the sensor under different axial magnetic fields. (b) Sensing sensitivities in linear regions of the voltage outputs.

5. Conclusion
We demonstrated a self-powered piezoelectric three-axis MEMS DC magnetic sensor. Experimental results show that the sensor can successfully senses three-axial DC magnetic fields and thereby will create more magnetic-field-sensing applications in the future.

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