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An angle sensor based on magnetoelectric effect

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ABSTRACT

Based on magnetoelectric effect, an angle sensor consisting of a magnetostrictive/piezoelectric laminate composite (MPLC), a multi-polar magnetic ring (MPMR), a modulation coil, and a shaft is presented. The MPLC and the modulation coil winded around it are the immobile parts of the angle sensor. The shaft and the MPMR fixed on it are the moving parts of the angle sensor. The modulation coil pro-applies an AC magnetic field to the MPLC which works at its resonance state. So the MPLC can dynamical and static detects the DC magnetic field produced by the MPMR. The theoretical analysis and experimental results demonstrated that the output signal of the angle sensor is influenced by the DC magnetic field. Thus, the amplitude of the output signal is used to measure the rotational angle, and the varying frequency of the amplitude has a linear relationship with the rotational speed. A resolution of 0.1° at a rotational speed of 10 rpm and the distance between the MPLC and the MPMR of 0.5 mm is achieved from this sensor, so a small step-change rotational angle of 0.1° can be clearly distinguished. In addition, for enhancing the performance of the angle sensor, the distance is much smaller much better. These characteristics show that the magnetoelectric effect can be successfully used in rotational parameters testing and make the angle sensor as a promising candidate device for rotational applications, such as robots, motors, revolving stage, etc.

1. Introduction

The magnetoelectric (ME) effect is a polarization response to an applied magnetic field, or conversely a magnetization response to an applied electric field [1]. The most important performance index of it is the ME coefficient that has got much attention from many researchers on how to enhance it. An equivalent circuit method [2–4], an elastic mechanics method [5,6], Green's function technique [7], and Hamilton's principle [8] have been used to construct the theoretical model of the ME effect. The influence of the shape demagnetizing effect has been discussed to optimize the theoretical model of the ME effect [9–11]. The self-biased effect has been investigated to remove the applied DC magnetic field which add complexity to device fabrication and could introduce additional noise [12,13].

According to the above results, the ME effect has been successfully demonstrated in the potential applications of magnetic sensors and energy harvesters. The ME effect can be directly used to harvest magnetic energy. But the magnetic energy which can be harvested is very uncommon in production and life. It usually has been used to harvest mechanical energy. For harvesting the vibration [14,15] and rotational [16,17] energy with the ME effect, some mechanical structures that can convert the mechanical energy to magnetic energy are essential. A cantilever beam with a magnetic circuit attached to the free end is the most usual choice. When the ME effect is directly used to detect magnetic field, the reported sensitivity is up to 10.12 V/Oe of a FeCuNbSiB/Ni/PZT composite [18]. A geomagnetic-field sensor based on Metglas/PZT laminates can perfectly servo to measure both the strength and the orientation of the earth's magnetic field [11,19,20]. As a variable magnetic field exits at the surrounding of a wire transmitted an AC current, so the ME effect also has been used to measure the current [21,22]. In addition, if a physical process can produce a magnetic field under the help of some necessary auxiliary mechanisms, ME effect also can be used to detect those physical parameters.

Rotational motion is one of the most common and important mechanical movement in people's life and production. Perceiving and measuring the rotational parameters like position, speed, and others are related to the operating performance and using security of those devices. To meet the demands of different devices, many kinds of angle sensors based on optical, electric, and magnetic principles have been developed. An optical grating encoder,

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famous for its high accuracy and resolution [23,24], has been widely used in many machine tools for precision manufacturing. But it is very strict to the working environment. Based on the concept of optical grating, according to the knowledge of magnetism and electricity, a magnetic grating and a capacitive grating have been developed and successfully used in magnetic encoders and capacitive grating transducers [25–27]. Compared with the optical grating encoder, the magnetic encoder with a simple construction has a good resistance to humid and dirty environments [25]. However, the grating structure is a double-edged sword. These encoders are usually larger and more expensive if higher accuracy in angular measurement is necessary [24,28]. Synchros and resolvers as angular sensors are widely spread nowadays in industrial applications. Although they have robustness and stable accuracy in unfriendly environments [29–32], the problem of large volume also could not be avoided.

With the progress of technology and the development of multi-function in fusion, the characters of angular sensors such as small size, low power, and easy integration are playing an increasingly important role. Researchers have designed some magnetic angular sensors consisted of Hall sensors placed around a small radial magnetized ring or diametrically magnetized cylindrical or annular magnet [33–35]. Through fixing a magnetic ring on a rotational shaft, the purpose of producing a changing magnetic field can be realized. And then, an ME rotational parameter sensor consisting of a magnetostrictive/piezoelectric laminate composite (MPLC) and a multi-polar magnetic ring (MPMR) has been proposed to investigate the role of ME effect in rotational parameters detection [36]. Based on this sensor, the rotational speed can be measured by determining the frequency of the output signal and the rotational position can be detected by the phase discrimination. In this sensor, the ME effect is used to detect the AC magnetic field produced by the magnetic ring, so it is suitable only for dynamics testing.

In this paper, for realize dynamics and static testing by the ME effect, an angle sensor consisting of an MPLC, a MPMR, a modulation coil, and a shaft and its working principle shall be described in Section 2. The details of the experimental system and the manufacturing process of the proposed sensor shall be given in Section 3. The results of the proposed sensor in detecting the rotational parameters shall be discussed in Section 4. Conclusion shall be given in Section 5.

2. Analysis and design of the sensor

2.1. Sensor design

A schematic diagram of the proposed angle sensor based on the ME effect is shown in Fig. 1. It contains an MPLC, a modulation coil, an MPMR, and a shaft. The MPLC is a PZT8 layer laminated with a FeNi layer. The PZT layer is polarized in the thickness direction. The FeNi layer is magnetized along the longitudinal direction. The MPMR is a bonder permanent magnetic with multiple polars which are specified four polars in the following. The magnetic polars are magnetized along the radial direction. The magnetization in two neighboring magnetic polar are in opposite directions. The MPMR is attached on the shaft, so the magnetic field around the MPMR can include the rotational information. The MPLC is placed beside the MPMR. The MPLC and the MPMR have the same symmetry plane. The modulation coil is winded around the MPLC. It is used to pro-apply an AC magnetic field to the MPLC.

2.2. Working principle

Through loading an AC current to the modulation coil, an AC magnetic field can be applied to the MPLC. In order to have a good output performance, the frequency of the AC current is specified to equal the resonance frequency of the MPLC. The MPLC undergoes the magnetic field variations, and the AC magnetic field causes the magnetostrictive layer to generate stress. Then the stress is transmitted to the piezoelectric layer, which generates electrical signal. When the shaft is rotating, the MPMR applies an alternating magnetic field to the MPLC. Even the shaft rotates much fast such as 3000 rpm, the frequency of the alternating magnetic field is only 200 Hz which is far less than the resonance frequency of the MPLC. So compared with the AC magnetic field, the magnetic field produced by the MPMR can be regarded as a DC magnetic field detected by the MPLC. Under the function of the DC magnetic field, the output signal of the MPLC should be changed with the rotation of the shaft. That is to say, the DC magnetic field is related with the rotational parameters such as rotational speed and position. Thus, through detecting and analyzing the changing of the MPLC's output signal, the dynamics and static testing of the rotational parameters both can be realized.

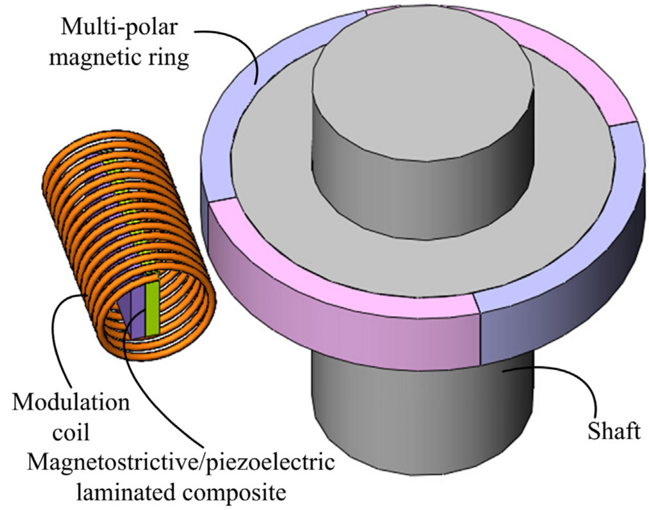

Fig. 1. (Color online) Schematic diagram of the proposed angle sensor.

When the MPLC works in the *L-T* mode, based on the equivalent circuit method, the resonant ME coefficient (α_V^{reson}) of the MPLC can be given as [4]

$$\alpha_V^{reson} = \frac{\partial V}{\partial H} = \frac{8Q_{mech}}{\pi^2}\frac{n(1-n)td_{31p}d_{33m}}{\varepsilon_{33}^T[n(1-k_{31p}^2)S_{11}^E+(1-n)S_{33}^H]} \quad (1)$$

where, Q_{mech} is the mechanical quality factor; S_{11}^E, S_{33}^H are the elastic compliance coefficients at constant electric field strength and constant magnetic field strength; d_{31p} and d_{33m} are the piezoelectric and piezomagnetic coefficients; ε_{33}^T is the dielectric permittivity at constant stress; k_{31} is the electromechanical coupling coefficient of piezoelectric material; n is the thickness ratio of the magnetostrictive layers; and t is the thickness of the piezoelectric material, respectively.

The modulation coil winded around the MPLC likes a solenoid. The length of it is just a little longer than that of the MPLC. The magnetic field pro-applied to the MPLC is not a uniform magnetic field, and the magnetic field's math formulas of the solenoid are not suitable for this situation. So when the modulation coil carries a sinusoidal AC current with the magnitude at the MPLC's resonance frequency (f_{reson}), the average pro-applied magnetic field (H_{mc}) in the MPLC should be simply expressed as

$$H_{mc} = H_{MC}\sin(2\pi f_{reson}t) \quad (2)$$

where, H_{MC} is the magnitude of H_{mc} and t is time.

According to Eqs. (1) and (2), the output voltage (V_{out}) of the MPLC can be expressed as

$$V_{out} = \alpha_V^{reson} H_{mc} = \frac{8Q_{mech}}{\pi^2} \frac{n(1-n)td_{31p}d_{33m}}{\varepsilon_{33}^T[n(1-k_{31p}^2)S_{11}^E + (1-n)S_{33}^H]} H_{MC} \sin(2\pi f_{reson} t) \quad (3)$$

Hence, whether the shaft rotates or not, the MPLC will always have an output signal at the function of the modulation coil.

With the rotating of the shaft, the magnetic field applied to the MPLC by the MPMR is variable. This situation has been discussed in Reference [36]. It shows that the relationship of the average magnetic field along the longitudinal direction in the magnetostrictive layer (H_{mr}) and the rotational angle (θ) has a good sinusoidal property. Hence, H_{mr} can be simply expressed as

$$H_{mr} = H_{MR} \sin(\theta) = H_{MR} \sin(NSt) \quad (4)$$

where, H_{MR} is the magnitude of H_{mr}, N is the number of magnetic polars, and S is the rotational speed, respectively.

And then, the frequency (f_{rota}) of H_{mr} can be written as

$$f_{rota} = \frac{N}{2\pi} S \quad (5)$$

Then, S can be got as

$$S = \frac{2\pi f_{rota}}{N} \quad (6)$$

Compared with f_{reson}, f_{rota} is very slow, such as only 200 Hz even when S equals 3000 rpm. That is to say, H_{mr} just like a DC magnetic field detected by the MPLC.

According to Eq. (3), V_{out} is positively connected with d_{33m}. But at the same time, d_{33m} will be changed under different magnetic bias field just like H_{mr} in this situation [9]. With the increasing of the magnetic bias field, d_{33m} has a peak value. When the value of the magnetic bias field is lower than that value which lets d_{33m} reach its peak value, d_{33m} can keep a linear relation with the magnetic bias field. So when the value of H_{mr} is appropriate, V_{out} is directly proportional to H_{mr}. Hence, with the rotating of the shaft, the angle information can be determined by measuring the amplitude of V_{out} and the rotational speed is related with the variable frequency of the V_{out}'s amplitude.

3. Experimental design

In order to investigate the influence of the space between the MPLC and the MPMR, a sensing head consisting of the MPLC, the modulation coil, and some auxiliary mechanisms is designed and fabricated, as shown in Fig. 2. The auxiliary mechanisms made of duralumin include a specified cylindrical holder, a Φ15 mm round tube, and a coil cover. Those auxiliary mechanisms are fabricated by high-speed wire electrical discharge machining (WEDM). The MPLC is intermediate simply-supported by a specified cylindrical holder. The modulation coil with 235 turns is winded around a Φ15 mm round tube by an enameled wire with the diameter of 0.1 mm. The MPLC with bilayer structure is consisted of PZT8 and FeNi. PZT8 (China Electronics Technology Group Corporation No. 26 Research Institute, China) is used as the piezoelectric material with dimensions of $12^L \times 6^W \times 0.8^H$ mm^3, electrodes are distributed in the two largest surfaces. The FeNi plate (Chongqing Instrument Materials Research Institute, China) is commercially supplied to have dimensions of $12^L \times 6^W \times 1^H$ mm^3. The sample is bonded together with the PZT8 layer and the FeNi layer by epoxy adhesive. The sample is cured at 80 °C for 4 h under load to provide a strong bond between layers. The resonance frequency of the MPLC is about 172 kHz. The

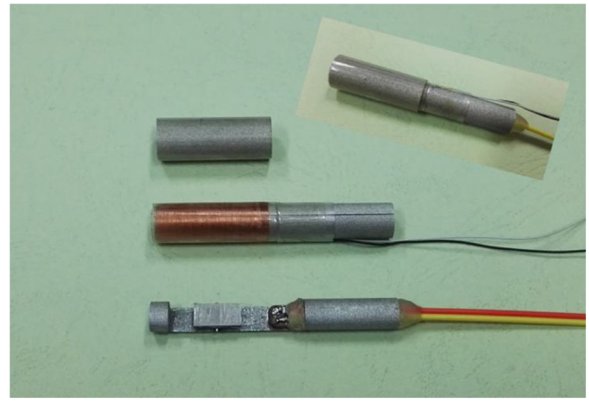

Fig. 2. (Color online) Structure of the sensing head consisting of the MPLC, the modulation coil, and some auxiliary mechanisms.

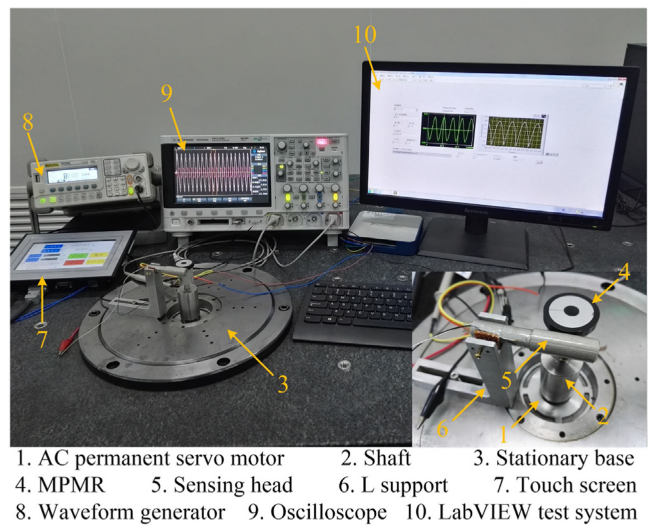

Fig. 3. (Color online) Experimental system.

MPMR is a four poles bonder permanent magnet with dimensions of D30–26 × 5 mm^3.

The experimental setup used to measure the characterization of the proposed sensor is shown in Fig. 3. As shown in the subgraph of Fig. 3, the MPMR is fixed on a shaft which is rigid coupled with a 750W AC permanent servo motor (Fuji Electric (China) Co., Ltd., China). The motor is mounted on a carbon steel stationary base, which is able to bind the very small magnetic flux leakage of the motor. The sensing header is fastened at an L support beside the MPMR. Through moving the L support, the space (d) between the sensing head and the MPMR sides can be adjusted. The control system of the motor takes PLC as the control nucleus, touch screen as human-computer interface, it makes the system friendly watched, easily operated and handled. A function signal generator (DG1022U Function/Arbitrary Waveform Generator, Rigol Technologies Inc., China) is used to apply a sinusoidal signal with 172 kHz and 10 Vpp to the modulation coil. With the rotating of the shaft, the output signal of the proposed sensor is monitored by an oscilloscope (InfiniiVision DSO-X2024A Digital Storage Oscilloscope, Agilent Technologies, U.S.A.). In addition, a LabVIEW test system based on a data acquisition card (NI PCI-6259 High-Speed M Series Multifunction Data Acquisition, National Instruments, U.S.A.) is established.

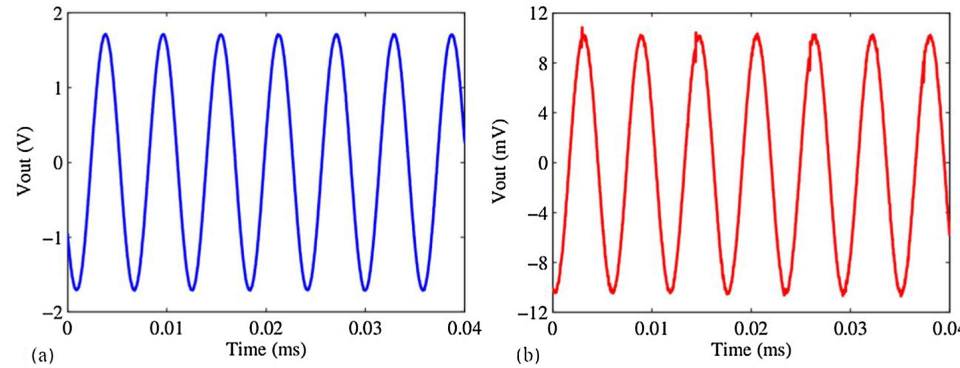

Fig. 4. (Color online) The output signal of the proposed sensor with d = 0.5 mm: (a) the maximum situation of the output signal with the MPLC opposites the interface of two polars and (b) the minimum situation of the output signal opposites the N or S polar.

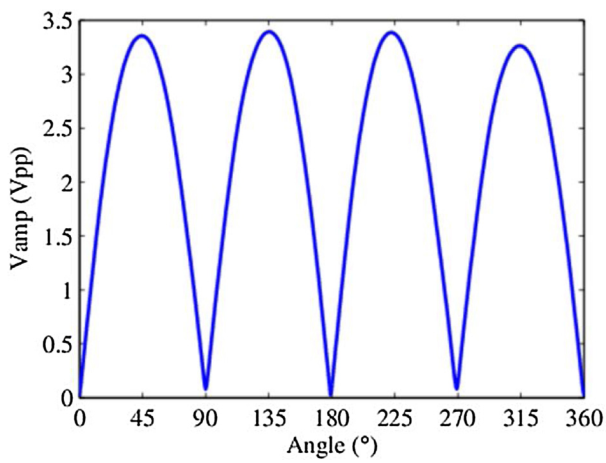

Fig. 5. (Color online) The relationship between V_{amp} and the rotational angle.

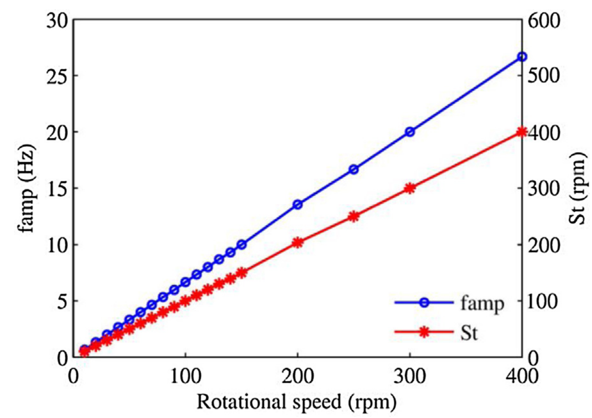

Fig. 7. (Color online) The relationship between the frequency of Vamp and the rotational speed.

4. Results and discussion

Fig. 4 shows the output signal of the proposed sensor with d equals 0.5 mm. Theoretical analysis makes know that the value of V_{out} is influenced by the varying of H_{mr}. As shown in Fig. 4(a), when the MPLC opposites the interface of two polars, H_{mr} reaches the maximum value. Then, the amplitude of the output signal (V_{amp}) can be up to 1.7 V. When the MPLC opposites the N or S polar, H_{mr} is almost zero which leads V_{amp} is only 10.5 mV, as shown in Fig. 4(b). These results demonstrate the theoretical analysis that through measuring V_{amp}, the angle information can be determined.

Fig. 5 describes the relationship between V_{amp} and the rotational angle with d equals 0.5 mm. It has 4 periods in the range of 360°, which is determined by the number of polars. The crests and troughs of the waveform correspond to the interface of two polars and N or S polar, respectively. The consistency of V_{amp} in different period reflects the quality of the MPMR. In a period, V_{amp} is directly or inversely proportional the rotational angle, the rate of which can be enhanced by increasing the number of polars. For optimizing the performance of the proposed sensor, another sensing header could be augmented and placed on the other side of the MPMR.

The frequency of H_{mr} is directly proportional to the rotational speed. With the raising of the rotational speed, the frequency of H_{mr} is always much lower than 172 kHz. So the rotational speed has no influence to the value of V_{amp}, only can altering the frequency of V_{amp} (f_{amp}), as shown in Fig. 6. The linear relationship between f_{amp} and the rotational speed is shown in Fig. 7. According to Eq. (6), the testing result of speed (S_t) with different rotational speed can be calculated as shown in Fig. 7. The S_t also is linear directly proportional to the rotational speed. The slope of the line is about 1, that is to say, the rotational speed can be accurately test by f_{amp}.

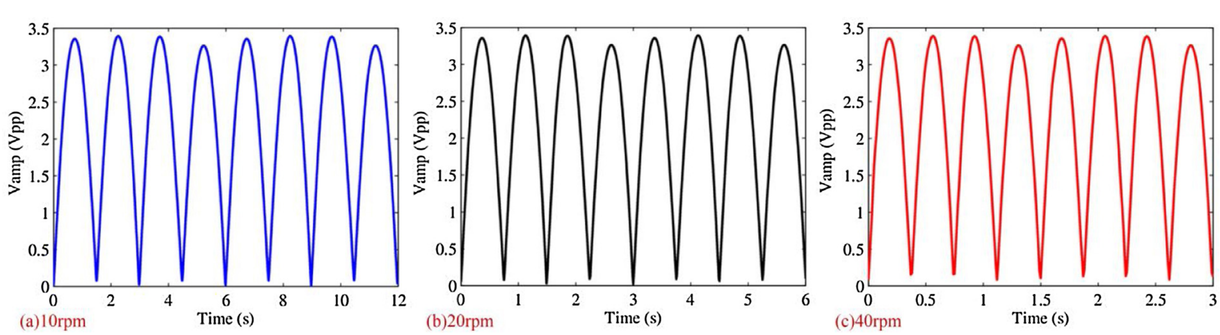

Fig. 6. (Color online) Vamp under different rotational speed: (a) 10 rpm, (b) 20 rpm, and (c) 40 rpm.

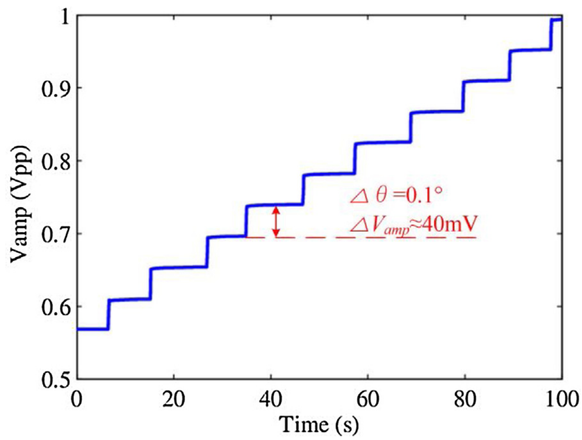

Fig. 8. (Color online) The resolution of the proposed sensor.

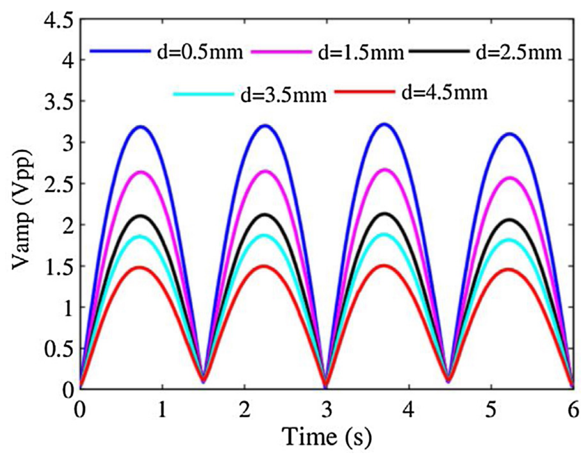

Fig. 9. (Color online) Vamp under the different distance between the MPLC and the MPMR with rotational speed equals 10 rpm.

Fig. 8 plots the resolution of the proposed sensor to small rotational angle variations around 6° at which the proposed sensor has a large rate of change, as shown in Fig. 5. V_{amp} goes through a step-change by adjusting the motor. It is clear that the rotational angle changes ($\triangle\theta$) as small as 0.1°, which is limited by the control system of the motor, can be easily distinguished with the changes of V_{amp} ($\triangle V_{amp}$) nearly equals 40 mV. We estimate that a much higher resolution could be further tested by optimized the motor's control system. Otherwise, the resolution also can be enhanced by replacing the PZT layer with a PMNT one, or by using other complex configurations.

In the following, the influence of the distance between the MPLC and the MPMR on the output characters of the proposed sensor has been studied. Fig. 9 describes that the values of V_{amp} are changed under different distance. Taking the maximum value of V_{amp} ($V_{\max}$) as example, there is a nearly linear relationship between $V_{\max}$ and the distance, as shown in Fig. 10. $V_{\max}$ decreases with the raising of the distance. Hence, in order to obtain high performance of the proposed sensor, the distance should be small enough. As the variation of the distance is adjusted by manual operation, so the existing of a little fluctuation in the line is inevitable.

5. Conclusion

In this work, an angle sensor based on magnetoelectric effect has been designed, fabricated, and functionally characterized. The angle sensor is composed of a magnetostrictive/piezoelectric laminate composite, a four polars magnetic ring, a modulation coil, and a shaft. The modulation coil preloads an AC magnetic field to the laminate composite which can give out a signal at the same frequency of 172 kHz. So, the laminate composite can dynamics or static detect the magnetic field produced by the magnetic ring. The theoretical analysis and experimental results demonstrated that the output signal of the angle sensor is influenced by the magnetic field produced by the magnetic ring. The output signal is the same under different rotational speed. The maximum and minimum values of the output signal are corresponding to the laminate composite opposites the interface of two polars and the N or S polar, respectively. So the amplitude of the output signal has been used to measure the rotational angle. And the varying frequency of the amplitude has a linear relationship with the rotational speed. A resolution of 0.1° at a rotational speed of 10 rpm is achieved from this sensor, so a small step-change rotational angle of 0.1° can be clearly distinguished. In addition, the role of the distance between the laminate composite and the magnetic ring has been tested. With the increasing of the distance, the output performance of the angle sensor should be reduced. These characteristics show that the magnetoelectric effect can be successfully used in rotational parameters testing and make the proposed angle sensor as a promising candidate device for rotational applications, such as robots, motors, revolving stage, etc.

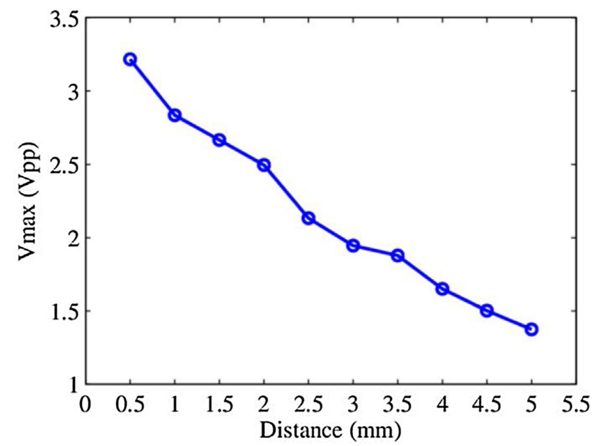

Fig. 10. (Color online) The relationship between the maximum value of Vamp and the distance.

Acknowledgments

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