Sensors and Actuators A 262 (2017) 108–113

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

An angle sensor based on magnetoelectric effect

Zhiyi Wu [a,*], Leixiang Bian [b], Shuxian Wang [a], Xuyun Zhang [a]

[a] Engineering Research Center for Mechanical Testing Technology and Equipment of Ministry of Education, Chongqing University of Technology, Chongqing, 400054, China

[b] School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing City, 210094, China

ARTICLE INFO

Article history:
Received 25 October 2016
Received in revised form 25 March 2017
Accepted 27 April 2017
Available online 24 May 2017

Keywords:
Angle sensor
Magnetoelectric effect
Magnet fields
Resonance

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,

* Corresponding author.
E-mail address: wuzhiyi_xiaohai@163.com (Z. Wu).

http://dx.doi.org/10.1016/j.sna.2017.04.049

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.

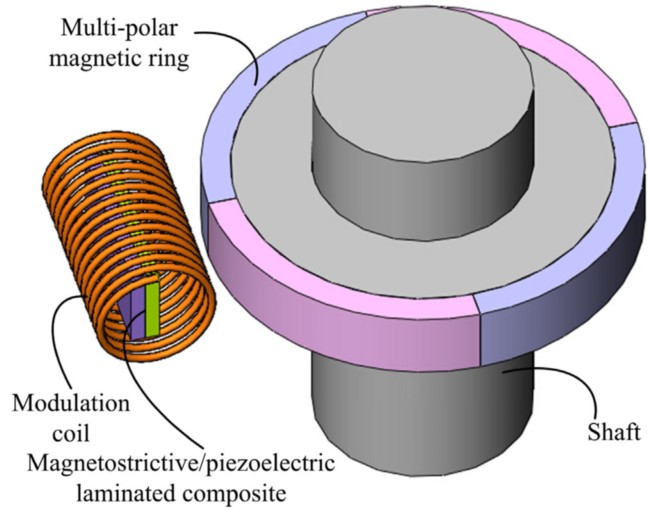

Fig. 1. (Color online) Schematic diagram of the proposed angle sensor.

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

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