Sensors and Actuators A 273 (2018) 232–239

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Packaged angle-sensing device with magnetoelectric laminate composite and magnetic circuit

Zhiyi Wu[a,*], Leixiang Bian[b], Sheng Chen[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 30 November 2017
Received in revised form 23 February 2018
Accepted 25 February 2018
Available online 27 February 2018

Keywords:
Angle sensor
Magnetoelectric effect
Magnetic circuit
Piezoelectric transformer

ABSTRACT

A packaged angle sensor consisting of four PZT/FeGa/PZT magnetoelectric (ME) laminate composites, four magnetic accumulation arcs, a magnetic accumulation (MA) ring, a multi-polar magnetic ring (MPMR), a shaft, and necessary shells is fabricated and characterized. The ME laminate composite with a slim shape is placed between the MA arc and the MA ring. The MPMR fixed on the shaft is used to apply a magnetic field associated with angle information to the ME laminate composites. Under the role the MA parts, the magnetic field applied to the ME laminate composites can be enhanced about 7 times. With the increasing of the rotational speed, the frequency of the sensor's output signal is increased linearity, which can be used to measure the rotational speed. The amplitude of the output signal is increased as well and finally reached a stable value of 45.3 Vpp. In order to realize static test without the participation of an excitation coil, one of the ME laminate composites has been used as a piezoelectric transformer. In experimental, a resolution of 0.2° and a favorable stability with a standard deviation in population of ~40 μVpp are achieved from this sensor. These characteristics show that the packaged sensor can be successfully used in rotational parameters testing and has the potential to establish self-powered wireless angle-sensing devices.

1. Introduction

Nowadays, many kinds of angle sensors based on optical, electric, and magnetic principles have been developed to monitor the operating performance and using security of rotational devices in people's life and production. An optical grating encoder, famous for its high accuracy and resolution [1,2], 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, magnetic grating encoders and capacitive grating transducers have been developed and successfully replaced the optical grating encoder in some area [3–5]. Compared with the optical grating encoder, the magnetic encoder with a simple construction has a good resistance to humid and dirty environments [3]. 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 [2,6]. Synchros and resolvers as angular sensors are widely spread in industrial applications. Although they have robustness and stable accuracy in unfriendly environments [7–10], 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 [11–13].

The magnetoelectric (ME) effect is a polarization response to an applied magnetic field, or conversely a magnetization response to an applied electric field [14]. The ME effect has been successfully demonstrated in the potential application of magnetic sensors [15–19] and energy harvesters [20–23]. The reported sensitivity is up to 10.12 V/Oe of a FeCuNbSiB/Ni/PZT composite, which is much higher than that of Hall sensors [15]. So, for investigating the role of the ME effect in rotational parameters detection, an ME rotational parameter sensor consisting of a magnetostrictive/piezoelectric laminate composite (MPLC) and a multi-polar magnetic ring (MPMR) has been proposed [24]. Based on this sensor, the rotational speed can be measured by determining the

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

https://doi.org/10.1016/j.sna.2018.02.042

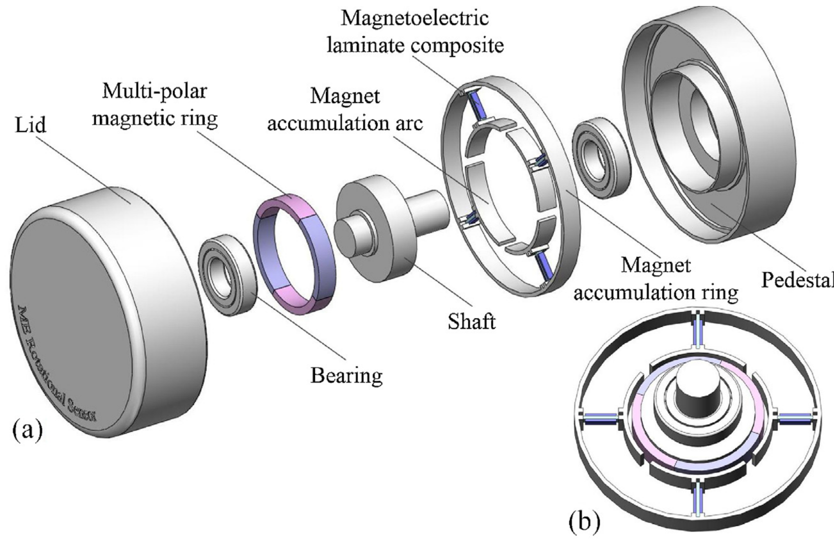

Fig. 1. Schematic view of the packaged sensor. (a) Explosion view of the proposed sensor. (b) Assembly diagram of the proposed sensor.

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. For realize dynamics and static testing by the ME effect, a modulation coil winded around the MPLC is used to pro-apply an AC magnetic field to the MPLC which works in the resonance state [25]. However, the existence of the coil leads to the increasing of the sensor's volume and the requirements for assembly. Moreover, the piezoelectric transformer laminated with the magnetostrictive layer has been used to sensing the magnetic field [26], which offers significances for removing the coil. In addition, for improving the performance of the sensor, necessary encapsulation and magnetic circuit design should be considered.

In this paper, a packaged angle sensor consisting of four PZT/FeGa/PZT ME laminate composites, four magnetic accumulation (MA) arcs, a MA ring, a MPMR, a shaft, and necessary shells is fabricated and characterized. The effect of the magnetic circuit made up of MA parts in enhancing the magnetic field has been discussed. The relationship between the proposed sensor's output signal and the rotational parameters has been analyzed. The methods of measure rotational speed and position are given and discussed. This paper also probes into the angle-sensing performance of the PZT/FeGa/PZT ME laminate composite used as a composite piezoelectric transformer.

2. Analysis and design of the sensor

2.1. Sensor design

A schematic diagram of the proposed packaged angle sensor is shown in Fig. 1. It contains four ME laminate composites, four MA arcs, a MA ring, a MPMR, a shaft, two bearings, a pedestal, and a lid, as shown in Fig. 1(a). The ME laminate composite with a slim shape for decreasing the demagnetic field [27,28] is placed between the MA arc and the MA ring. The magnetostrictive (M) layer is embedded into the U-shaped slots of the MA parts to reduce the magnetic flux leakage [29]. Four MA arcs, four M layers, and the MA ring compose a closed magnetic circuit. The MPMR fixed on the shaft is used to apply a magnetic field associated with angle information to the ME laminates. The two bearings are fixed on the two sides of the shaft to connected with the pedestal and the lid. These details are plotted in Fig. 1(b).

2.2. Working principle

When the shaft is rotating, with the role of the magnetic circuit, the MPMR applies an enhanced alternating magnetic field to the MPLC. The MPLC undergoes the magnetic field variations, and the alternating magnetic field causes the M layer to generate stress. Then the stress is transmitted to piezoelectric (P) layer, which generates electrical signal. The alternating magnetic field is related with the rotational parameters such as rotational speed and position. Thus, through detecting and analyzing the output signal of the MPLC, the rotational parameters can be measured.

2.2.1. Analysis of the magnetic circuit

The role of the magnetic circuit is analyzed through the simulation results of Maxwell 16.0. Without the help of the magnetic circuit, no matter what is the relationship between the M layer and the MPMR, only a little magnetic force lines pass through the M layers along their length direction, as shown in Fig. 2. The magnetic force lines distribution of the proposed sensor with magnetic circuit are described in Fig. 3. Fig. 3(a) shows that when the M layers opposite the interface of two poles, the magnetic force lines only converge in the MA arcs. In Fig. 3(b), When the M layers opposite the N or S pole, almost all the magnetic force lines are pass through the M layers along their length direction. The magnetic field applied to the four M layers have the same amplitude. The numerical results of the effect of the magnetic circuit are shown in Fig. 4. From it, under the role of the magnetic circuit, the average magnetic field along the longitudinal direction (H_{al}) in the M layer is enhanced about 7 times. The relationship between H_{al} and the rotational angle (θ) can be regarded as a triangle wave. Considering the frequency-doubling effect of the magnetostrictive materials, the mathematical expression of H_{al} in a cycle can be approximately expressed as

$$H_{al} = H_A T\left(\theta\right) = \begin{cases} \dfrac{H_A}{\pi/4}\theta \ \left(0 \le \theta \le \dfrac{\pi}{4}\right) \\ 2H_A - \dfrac{H_A}{\pi/4}\theta \ \left(\dfrac{\pi}{4} \le \theta \le \dfrac{\pi}{2}\right) \end{cases} \quad (1)$$

Where H_A is the amplitude of the H_{al}, which is about 70 Oe in this situation.