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An angle displacement sensor using a simple gear

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ABSTRACT

This paper presents an angle displacement sensor that consisting of a specified gear, permanent magnets, pairs of tunnel magnetoresistance (TMR) magnetic sensors, and a shaft. The shaft and the gear fixed on it move together with the object under measurement. TMR magnetic sensors with the permanent magnet behind it are placed beside the gear. The gear is made up with high magnetic permeability, which constitutes the magnetic circuit with the permanent magnet. With the rotation of the gear, an alternating magnetic field with displacement information is generated. Pairs of TMR sensors separated by 90° electrically angle and applied with sine and cosine voltages respectively are used to perceive the changing magnetic field. So, the angle displacement detection can be realized by analyzing the output signals of TMR sensors. That is, the phase shift of the signals is proportional to the displacement and the phase detection can be realized by serve high frequency time pulses as standard. Thus, the displacement is measured by counting the time pulses. Finite element stimulation and experiment are performed using a prototype of the angular sensor. The proposed scheme is proven to be feasible. The proposed angle displacement sensor can reach up to ±5″ stability with 0.1° resolution.

1. Introduction

Rotational motion is one of the most common and important mechanical movement in people's life and production, such as industrial applications, vehicles, household appliances, even toys, and so on [1,2]. Position measuring is related to the operating performance and using security of those devices. To meet the demands of different devices, many kinds of angle sensors are currently available in the market, such as grating, encoder, resolver, and capacitance sensors [3–5]. Grating and optical encoder have the advantages of high precision and resolution. However, they cannot work in a harsh environment [3,6]. The inductosyn and resolver as angular sensors are widely spread in industrial applications nowadays. Although they have robustness and stable accuracy in unfriendly environment, the problem of large volume also could not be avoided [7–9]. With the progress of technology, 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 round a small radial magnetized ring or diametrically magnetized cylindrical or annular magnet [10–12]. In order to detect the absolute position, the magnet usually has one North and South magnetic pole and even eccentrically mounted, which limit that those sensors difficult to achieve much high resolution. In addition, Hall sensors have been successfully used in the gear position and speed measurement [13,14], and so does giant magnetoresistance (GMR) and anisotropic magnetoresistance (AMR) sensors [15,16]. The magnetic sensors are taken as sensing element to measure the speed or position of gear. However, this method is unsuitable for universal rotating component. At the same time, this method has guiding significance to the design of angular sensors with small size and high precision. Furthermore, the TMR sensor has several performance advantages over the conventional magnetic sensor, such as higher sensitivity, lower power consumption, and wider range of magnetic field detection [17,18].

In this paper, we attempt to design an angle displacement sensor that consisting of a specified gear, permanent magnets, and tunnel magnetoresistance (TMR) magnetic sensors. The proposed packaged angular sensor is widely applied in all kinds of rotating component. What's more, it can achieve small size, easy integration, and also has the convenience of keeping high resolution.

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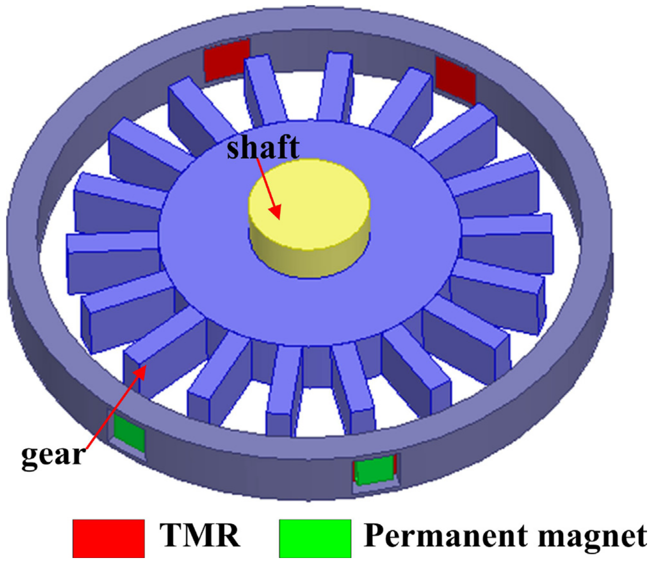

Fig. 1. Structure diagram of the sensor.

2. Analysis and design of the sensor

2.1. Sensor design

The schematic of the proposed angle displacement sensor is shown in Fig. 1. The sensor contains a gear, a shaft, pairs of TMR sensors, and permanent magnets. The gear is made of permalloy. A pair of TMR sensors are supposed to be separated by 90° electrically angle. The gear is fixed on the shaft. The TMR sensor and the permanent magnet behind it are placed beside the gear. The gear, TMR sensors, and permanent magnets have the same symmetry plane.

2.2. TMR sensor characteristics

The design of TMR sensors are based on spintronics. Fig. 2 shows its structure, there are a pinned layer which has a fixed magnetization direction and a free layer, where the magnetization changes with the external field [19]. Also, the pinned layer and the free layer are separated by a thin barrier layer, usually made from Al_2O_3 or MgO. The resistance of such a tunnel junction is varied with the external field.

Therefore, the output signal of the linear TMR sensor is proportional to the magnetic field. The TMR sensor MMLH45F (Multidimension Technology Co, Ltd, China) was taken used in this wok.

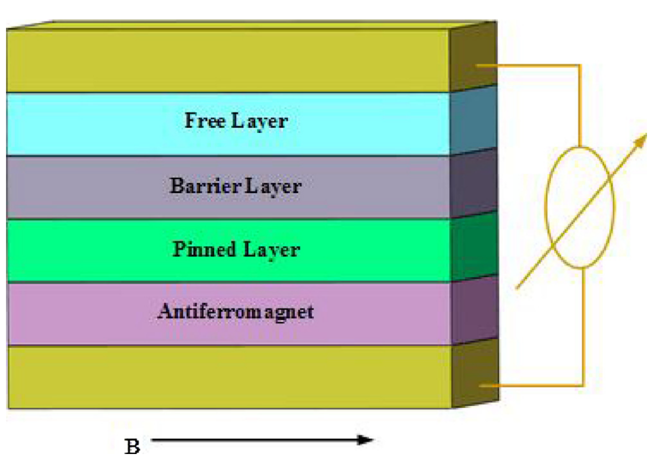

Fig. 2. Magnetic tunnel junction basic structure of the TMR sensor.

Table 1
Comparison of sensor specifications.

	TMR	AMR	GMR
Supply voltage(V)	<7	<10	<10
Typical Bridge resistance(KΩ)	80	0.14	8
Sensitivity(mV/V/Oe)	12	0.1	2
Field range (Oe)	0.001–200	0.001–10	0.1–30

Table 1 presents the detail specifications of this TMR sensor, the typical VA100F3-GMR sensor (SpinIC. Inc, China), and KMZ10CM-AMR (Measurement Specialties Inc, America) at room temperature. By contrast, the TMR sensor has higher sensitivity, lower power consumption, and wider range of magnetic field detection.

2.3. Working principle

When the gear is rotating, an alternating magnetic field produced by the common function of the magnetic gear and permanent magnets. A pair of TMR sensors spaced 90° electrical angle to perceive orthogonal magnetic field. What's more, they are applied with sine and cosine voltage respectively. Then, the TMR sensor's output electrical signal with phase shift is proportional to displacement. Thus, through count time pulses of phase discrimination between the output signal and a standard signal, the angle displacement can be measured.

The analytical formula of the magnetic field produced by permanent magnets cooperate with a rotation gear may be complicated [20]. Thus, the finite element analysis is adopted to solve the magnetic field. Fig. 3 shows the distribution situation of the magnetic flux of the TMR rotational displacement sensor. The magnetic field in the red dotted bordered rectangular is nearly uniform along the horizontal direction. So the magnetic field doesn't have the tangential components, as shown in Fig. 3(a). In the Fig. 3(b), the magnetic force line distributes between neighboring two gear teeth when the permanent magnet opposites to the slot of the gear. Thus, the magnetic field can provide the tangential components to the TMR sensor. This is to say, the tangential magnetic components applied to the TMR sensor is alternated under the gear turning, which is demonstrated in Fig. 4. The relationship between the average magnetic field along the tangential direction of the gear rotation (H_m) and rotation angle (θ) are sinusoidal wave. Hence, consideration of the periodic change in the magnetic field, H_m can be simply expressed as

$$H_m = H_A \sin\left(\omega_h\theta\right) = H_A \sin\left(\frac{2\pi}{z}\theta\right) \tag{1}$$

where H_A is the magnitude of the, H_m, ω_h is the changing frequency of magnetic field, z is the tooth pitch of gear.

When sine and cosine AC excitation signals V_{Ae}, V_{Be} are input into the pairs of TMR sensors, the standing wave signals V_A, V_B with amplitudes modulated by the angle θ are got. Adding two standing waves together, the traveling wave signal V_s can be expressed as

$$\begin{aligned} V_s &= V_A + V_B = \frac{SV_{Ae}H_{Am}}{R_0} + \frac{SV_{Be}H_{Bm}}{R_0} \\ &= \frac{SA_m\cos(\omega_e t)H_m\sin(\omega_h\theta) + SA_m\sin(\omega_e t)H_m\cos(\omega_h\theta)}{R_0} \\ &= k\sin(\omega_e t) + (\omega_h\theta) = k\sin(\frac{2\pi}{T}t + \frac{2\pi}{Z}\theta) \end{aligned} \tag{2}$$

where S is the sensitivity of TMR sensors, A_m, T, and ω_e are the magnitude, period, and angular frequency of AC excitation respectively, and k is a constant coefficient.

According to Eq. (2), the amplitude of traveling wave remains unchanged as long as it is determined by excitation and sensor structure. The frequency of traveling wave is determined by the