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Current Perspectives

A new method to determine magnetic properties of the unsaturated-magnetized rotor of a novel gyro

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ABSTRACT

A new method is proposed to determine magnetic properties of the unsaturated-magnetized, small and irregular shaped rotor of a novel gyro. The method is based on finite-element analysis and the measurements of the magnetic flux density distribution, determining magnetic parameters by comparing the magnetic flux intensity distribution differences between the modeling results under different parameters and the measured ones. Experiment on a N30 Grade NdFeB magnet shows that its residual magnetic flux density is 1.10 ± 0.01 T, and coercive field strength is 801 ± 3 kA/m, which are consistent with the given parameters of the material. The method was applied to determine the magnetic properties of the rotor of the gyro, and the magnetic properties acquired were used to predict the open-loop gyro precession frequency. The predicted precession frequency should be larger than 12.9 Hz, which is close to the experimental result 13.5 Hz. The result proves that the method is accurate in estimating the magnetic properties of the rotor of the gyro.

1. Introduction

Gyroscopes are widely used in navigation systems [1]. In recent years, MEMS vibration gyroscopes are boosting for their compact and low-cost [2], but their performances are hard to improve due to theoretical reasons, with currently reported [3] random bias drift about 0.01°/h. Rotational gyroscopes have the ability to achieve higher precision (the bias drift of ESG reached 0.0001°/h by the 1970s) [4,5], while existing rotational gyros are bulky and extremely expensive [6]. In this paper, a novel rotational gyro is discussed, which is small and has the potential to achieve higher precision relative to the MEMS gyros [7].

The rotor of the gyro has a disc whose outer radius is 5 mm, inner radius is 1.5 mm and thickness is 1 mm. It is made of 2J85 Grade FeCrCo material, which is a permanent magnetic material easy to machine and sufficient to meet the magnetic requirements of the gyro. The rotor is deliberately unsaturated magnetized to achieve a weak magnetic field, which makes it easier for the rotor to start rotating. However, this makes the magnetic parameters of the gyro rotor unknown and difficult to determine.

Magnetic parameters of the disc affect the axial driving torque and the radial constraint torque imposed on the rotor. The axial driving torque limits the maximum rotating speed of the rotor, which determines the significance of the gyroscopic effect. The radial constraint torque leads to signal couplings between different detection axes, thus its accurate estimation is critical for the gyro's signal decoupling. So, relatively precise determination of magnetic properties of the rotor is a prerequisite for the gyro analysis and signal processing.

The usual means of permanent magnet inspection can be classified as material testing or product testing. The former, by measuring the hysteresis curve, gets relatively complete technical parameters of a magnet, in order to determine the quality of a magnetic material [8–12]. This method is generally destructive and cannot be applied to the measurement of a magnetized magnet [13]. The latter, by measuring the open flux, the surface magnetic field distribution or magnetic moment of the product magnet, determine whether the magnet is identical or sufficiently close to a standard magnet. Flux meter, Gauss meter or Helmholtz coil and flux meter are generally used in the product testing. Product testing is simple and non-destructive, so it is widely used in the test of magnetized magnets [13]. The product testing methods can be applied to the measurement of an unsaturated-magnetized magnet, by comparing the target to a series of standard magnets; however, the production of unsaturated-magnetized standard magnets with known parameters is very difficult.

In this work, a new method is proposed to acquire magnetic properties of unsaturated-magnetized magnets based on magnetic

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field distribution and finite-element analysis (FEA). The method was proven successful in determining the magnetic parameters of a saturated-magnetized magnet (N30 Grade NdFeB). The method was applied to determine the magnetic parameters of the rotor of the gyro, which is unsaturated magnetized. And it is proven accurate by successfully predicting the open-loop precession frequency of the gyro using the magnetic parameters obtained through the method.

2. Theory and method description

A permanent magnet generates a magnetic field in the surrounding space, the distribution of which has certain features, associated with the magnetic properties of the magnet. According to Maxwell's equations, the three dimensional static magnetic field can be solved using [14]

$$\begin{cases} \nabla \times H(x,y,z) = J(x,y,z) \\ \nabla \cdot B(x,y,z) = 0 \end{cases}, \tag{1}$$

where $H(x,y,z)$ is the magnetic field strength, $B(x,y,z)$ is the magnetic flux density, and $J(x,y,z)$ is the conduction current density. For permanent magnet models, the conduction current density is zero. The equations are as follows.

$$\begin{cases} \nabla \times H(x,y,z) = 0 \\ \nabla \cdot B(x,y,z) = 0 \end{cases}. \tag{2}$$

For a permanent magnet, the following constitutive relationship between the magnetic flux density and magnetic field is applied:

$$\mathrm{B} = \mu_0 \mu_r H + \mu_0 M_p, \tag{3}$$

where μ_0 is the permeability of vacuum, μ_r is the relative permeability, and M_p is the permanent magnetization [14,15].

The space distribution of magnetic field around a magnet can be determined through finite-element (FE) modeling based on the above theories. The strongest magnetic field at a certain distance from the surface of magnets can be measured by a Gauss magnetometer, as is shown in Fig. 1. By adjusting the measuring distance, the peak magnetic flux density distribution curve can be acquired. The magnetic parameters of a magnet can be represented by this magnetic field distribution curve. And the magnetic field distribution of a parameters-known magnet can be solved by FEM. So, the parameters of the measured magnet can be determined by comparing the results of FE modeling and the measurement.

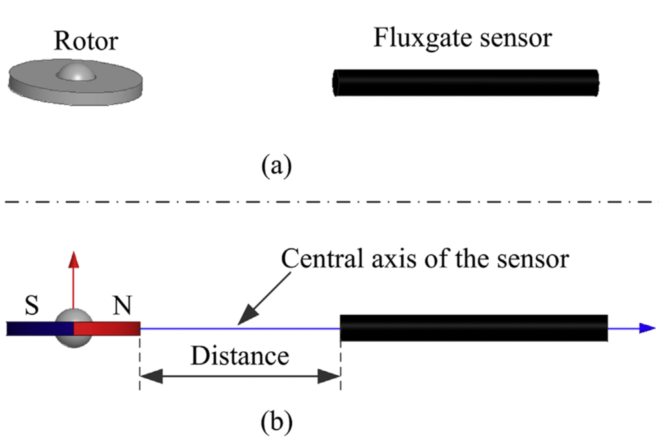

Fig. 1. Schematic diagram of the strongest magnetic field distribution measurement, (a) the 3D view and (b) the side view.

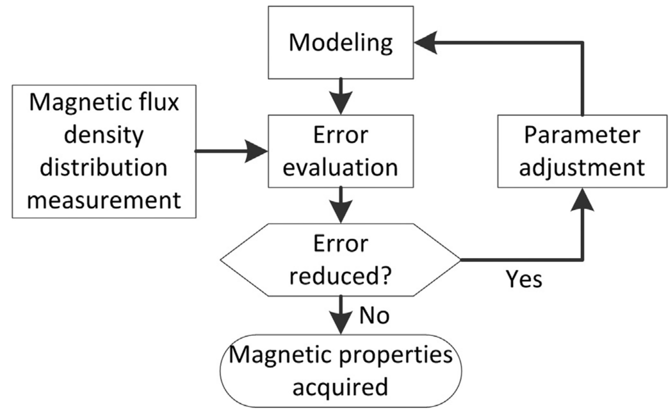

Fig. 2. Flow chart of magnetic properties acquisition.

A rough procedure of the acquisition of magnetic properties is shown in Fig. 2. First, we build a static magnetic model, using a set of initial parameters, and get its flux density distribution results through FEA. The error between the FEA results and the measurement results is evaluated as the root mean squared error (RMSE). If the error of this model is smaller than last one, adjust the parameters and repeat the procedure again; if the error of this model is larger than last one, then clearly the estimated value of magnetic properties should be between the last two model parameters. The RMSEs for the FEA results are calculated according to Eq. (4).

$$err = \sqrt{\frac{\sum_{i=1}^{i=n} (S_i - M_i)^2}{n}}, \tag{4}$$

where n is the measured position point number, S_i ($i = 1, 2, \ldots, n$) are the simulation results, M_i ($i = 1, 2, \ldots, n$) are the measurement results, and err is the RMSE.

The dichotomy is used in the choosing of parameters, in order to improve efficiency, and to reduce the parameter selection range until the desired accuracy is met. By increasing FEA meshing density and the solution precision, the accuracy of this magnetic parameter estimation method can be further improved.

3. Experiments and results

The method was first applied to the parameters-known saturated-magnetized magnet to verify the correctness of the method itself. Then it is used to obtain magnetic properties of the unsaturated-magnetized rotor of the gyro.

3.1. Verify the method using well known magnet.

In order to test the method, a cubic saturated-magnetized N30 Grade NdFeB magnet was chosen. The parameters of N30 are well known, and it is a linear permanent magnetic material, whose properties can be set by the coercivity, *Hc*, and the remnant flux density, *Br*, making it easy to calculate and clear to compare with the measurement results.

The measurements were carried out at room temperature, using a Gauss meter which has a precision of 10 nT. During the measurement, the central axis of the sensor was kept to coincide with the magnetization direction of the magnet by adjusting the orientation of the magnet to find the strongest flux density at a certain distance. The magnet was moved to different distances along the central axis of the sensor, and the maximum flux densities there were measured.

FEA models were built according to the measurement