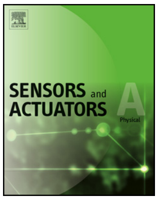
Sensors and Actuators A 279 (2018) 113–119

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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



Miniature orthogonal fluxgate sensor in rotation magnetization mode: Modeling and characterization

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ARTICLE INFO

Article history:
Received 27 June 2017
Received in revised form 14 May 2018
Accepted 15 May 2018
Available online 16 May 2018

Keywords:
Fluxgate
NiFe
Magnetic sensor
Orthogonal fluxgate
Electroplating
Noise analysis

ABSTRACT

Orthogonal fluxgates operated with a dc bias can achieve lower noise levels by suppressing Barkhausen jumps. We constructed and mathematically modeled a small orthogonal fluxgate consisting of a NiFe electroplated Cu wire, surrounded by a pick-up solenoid. A large dc current was applied through the wire to keep the core in constant saturation. This ensures that the main permeability modulation mechanism is magnetization rotation. Several output parameters were analyzed: sensitivity, noise and the perming error amplitude, all with respect to two input parameters, constant and alternating excitation field component. A good agreement between the experimental data and the theoretical model was found, with higher deviations appearing when the excitation field was not high enough to saturate the core and domain wall movement becomes relevant. Measured sensitivities were highly dependent on the excitation amplitudes, but mostly in the hundreds of V/T, and noise levels of about 0.75 nT in the 0.1–10 Hz range were found. As for the perming, the sensor zero readout can vary about 20 μT if subjected to magnetic shocks of up to 4.8 mT.

1. Introduction

Measuring the magnetic field is key feature to a wide range of technologies like navigation systems, magnetic-based medical diagnostics [1,2], data storage, magnetic ink reading and space exploration [3].

Fluxgates are widely used as vectorial magnetometers. But with the invention of magnetoresistors, lots of fluxgate use cases were taken. Magnetoresistors are usually smaller, cheaper and consume less power. However fluxgates can achieve better resolution and are less affected by temperature changes [4]. Lately, the research has been focused in reducing the size of the sensors without loosing their good sensitivity and resolution, a well-known drawback effect of shrinking the core.

Recently, there has been an increasing interest for orthogonal fluxgate devices where the excitation and the observed fields are orthogonal. Although when operated with symmetrical excitation the noise levels for these type of sensor are generally higher than for parallel sensors, this situation can inverted by applying a constant bias excitation current [5–8]. A strong dc component makes the core less susceptible to Barkhausen jumps, irregular domain wall motion due to magnetization pinning sites. This bias moves the core magnetization state away from the low field region where the wall movement is the dominant magnetization mechanism.

Orthogonal fluxgates also allow an easy way to couple the excitation field and the ferromagnetic core and thus a recurring geometry is seen: a ferromagnetic wire surrounded by a solenoid. The permeability of the wire is modulated by the tangential generated field produced by passing an electric current through the wire. Notice, however, that it is impossible to fully saturate a simple ferromagnetic wire as the field produced in the center is zero.

In this work we present a simple orthogonal minifluxgate using Cu wire electroplated with NiFe as the sensor's core. By adding a large enough dc bias excitation to keep the core in permanent saturation, the main permeability modulation mechanism is expected to be magnetization rotation, free from Barkhausen noise. The non-ferromagnetic substrate avoids the low excitation regions in the wire center, which is crucial to keep the whole core in permanent saturation. A similar approach can be found in [9]

The aim of this work is to characterize in details the described sensor and compare it to the results expected from a simple theoretical model based solely on the magnetization rotation. A wide set of input and output parameters was mapped out: constant exci-

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https://doi.org/10.1016/j.sna.2018.05.027

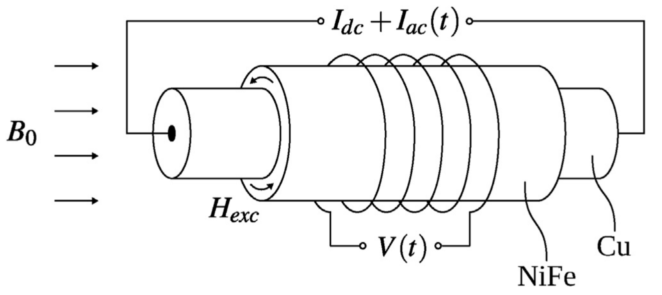

Fig. 1. Sensor scheme. An excitation current with two components ($I_{dc} + I_{ac}$) passes trough the compound wire generating the excitation field H_e. Because of the permeability modulation done by H_e, the flux gating phenomena, a signal ($V(t)$) caring the external field (B_0) information appears in the pick-up solenoid.

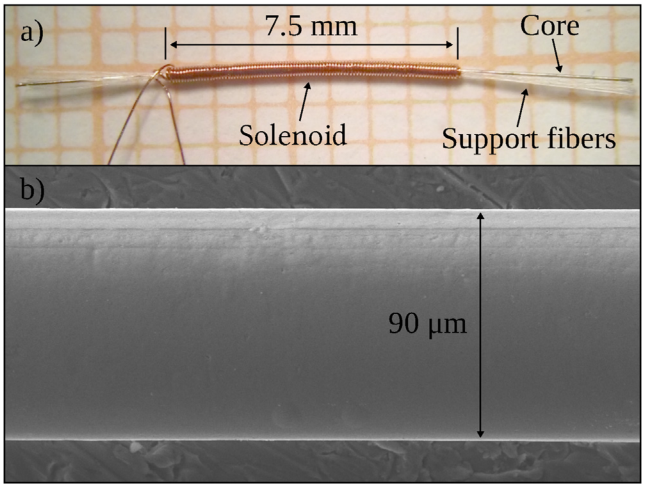

Fig. 2. (a) Optical image of the core wire with the surrounding solenoid. A two layer solenoid with 200 turns total was used. The clear fibers were added to support the axial load during the winding process. (b) Scanning electron microscopy (SEM) image of the electroplated wire.

tation field amplitude, alternating excitation field amplitude and sensitivity. We also included performance relevant parameters: noise and perming.

2. Sensor description

A cylindrical core fluxgate was constructed by electroplating a ferromagnetic core on a conducting wire, and winding a solenoid around it, as shown schematically in Fig. 1. A 15 mm long, 45 μm diameter copper wire was used as substrate. After the NiFe deposition a total diameter of 90 μm was achieved.

The NiFe electroplating bath contained $NiSO_4$ (0.7 mol/l), $FeSO_4$ (0.03 mol/l), $NiCl_2$ (0.002 mol/l), H_3BO_3 (0.4 mol/l) and sodic saccharine (0.016 mol/l) [10]. Due to the substrate geometry, in order to achieve the $Ni_{80}Fe_{20}$ alloy, it was necessary to use a current density of about 50 mA/cm^2, what is larger than the 14 mA/cm^2 normally necessary for flat substrates. Energy Dispersive Spectroscopy (EDS) was used to measure the final composition.

Special care was required when winding the solenoid to avoid mechanically stressing it. A dedicated winding machine was developed for that. Fibers were also added to support the axial load during the processes. Fig. 2 shows the result: a two layers 200 spires solenoid with 7.5 mm length.

Finally, the sensor was mounted in a PCB taking special care to avoid the heat of a welding process that can change the core's magnetic properties. The electrical contacts were made by electroplating Cu over the pads with the wire extremities positioned on top of it for long enough so copper layer was able to join the parts. This process provided a good connection without the need for heat.

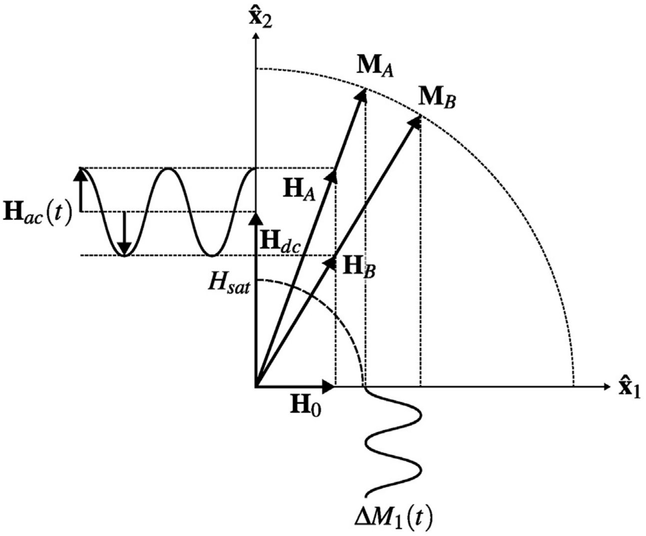

Fig. 3. Permeability modulation vectorial scheme. To measure the external field H_0 in the $\hat{x}_1$ direction, the ferromagnetic material is excited with a continuous component $\mathbf{H}_{dc}$ and an alternating one $\mathbf{H}_{ac}$, both in the $\hat{x}_2$ direction, orthogonal to $\hat{x}_1$. To guarantee permanent saturation, the excitation fields amplitudes must respect $H_{dc} - H_{ac} > H_{sat}$ where the last one is the saturation field. The permeability in the 1 direction, defined as $\mu_1 = B_1/H_1$, varies because $B_1 = \mu_0(H_1 + M_1)$, and M_1 varies. Consider an external field H_0 and the states where $\mathbf{H}_{ac}$ is at the extremes, A and B. From A to B the magnetization rotates increasing its projection on to the $\hat{x}_1$ axis. Overlooking some details (taken into account in the algebraic part of the model) we got between the points $\Delta\mu_1 = \mu_0(1 + \Delta M_1/H_0)$.

3. Theoretical model

3.1. Permeability modulation mechanism

Before going to the quantitative part, observe the permeability modulation scheme shown in Fig. 3. The key aspect is that the sensor's core is kept in permanent saturation due to a constant excitation field H_{dc} while an alternating excitation field H_{ac} swings the magnetization direction, just by magnetization rotation, leading to a measurable signal in the horizontal direction ($\mathbf{x}_1$) proportional to low external fields.

3.2. Output signal theoretical model

A simple relation of the output signal with the sensor parameters can be achieved by considering the following assumptions: a core with only shape magnetic anisotropy (with alignment restriction discussed below); the permeability modulation is done by magnetization rotation only; a spatially homogeneous excitation and external fields. The results were made more general by taking into account the sensor actual geometry in the end only.

The **H** field inside the core can be written as

$$\mathbf{H} = \mathbf{H}_0 + \mathbf{H}_e + \mathbf{H}_d, \tag{1}$$

where $\mathbf{H}_0$ is the external field, $\mathbf{H}_e$ the excitation field and $\mathbf{H}_d$ the demagnetizing field. The latter takes the form

$$\mathbf{H}_d = -\overline{D}\mathbf{M}, \tag{2}$$

where $\overline{D}$ is the demagnetizing tensor and **M** the magnetization. For an arbitrary shape, $\overline{D}$ depends on the position, being uniform only for ellipsoids. If the coordinate axis is aligned with its main axis, the tensor representation is diagonal, and its non-zero values are the demagnetizing factors associated with the corresponding direc-