Multiwire Parallel Fluxgate Sensors

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Fluxgate sensors with straight wire or rod cores are used in NDT, portable gradiometers and sensor arrays and for the detection of small objects. We show that their sensitivity at the voltage output mode depends on the excitation parameters, properties of the core material and geometry, pick-up coil length, but only slightly on the pick-up coil diameter. This finding allows to design multiwire cores with large wire pitch, which decreases their magnetic interactions and thus reduces demagnetization and correlation of their noise. As a result, using *N* wires theoretically increases sensitivity *N*-times, which is not achievable with dense cores. We have demonstrated this tendency for N up to 8 and one type of permalloy wire.

Index Terms—**fluxgate sensors, magnetic field sensors, demagnetization.**

I. Introduction

SOME of the early parallel fluxgate sensors had cores made of straight magnetic wires and this design is still used in many devices, including portable gradiometers and low-cost sensor arrays in magnetoelastic torque meters [1]. In this paper we will deal with fluxgates of parallel type, which have the same direction of the excitation field and the measured field. The other type is transverse fluxgate, which is excited by current flowing through the wire [2]. The magnetic core of parallel type open-core fluxgates typically consists of crystalline permalloy wire with diameter of around 0.2 mm.

While straight wire-core fluxgates usually do not achieve the low noise and high offset stability of ring-core fluxgate sensors made of thin tape, they have very small demagnetization due to their slim shape. This brings several advantages which keep these sensors on the market [3]:

1. their sensing direction is precisely defined by the direction of the sensor core
2. they have excellent spatial selectivity which is important for the detection of magnetic particles [4, 5]
3. High sensitivity allows decreasing the core length
4. The large shape anisotropy gives them low crossfield error [6].

There are also important disadvantages of straight-wire-based sensors: sensor cores with open ends are usually noisier and their offset is less stable with temperature and time than the closed-core sensors. The open rods are more difficult to saturate, so these sensors are also consuming more energy and are more susceptible to perming effects (i.e. offset change after a shock of a large field).

The fluxgate sensitivity depends on magnetic characteristics of the core, excitation parameters and geometry of the core and the windings. The sensitivity of ring-core and race-track fluxgate sensors is well understood and described in literature both for voltage output [7-9] and current (short-circuited output) [10], while we are not aware of specific study on the sensitivity of the straight-wire-cored fluxgate sensors. We offer such study it in this paper for the case of voltage output.

The existing straight-wire-core parallel fluxgate sensors are of the basic two types: single and double wire sensors.

A. Single-wire Sensors

Sensors with a single open core are utilized for magnetometers using time-domain detection - the device described by Sonoda and Ueda [11], Blazek [12] and Ando [13] being typical examples - and it is often used for auto oscillation or magnetic multivibrator (or self-oscillating) sensors, such as in [14]. Multiple single-coil fluxgates with a wire core can also be connected in series to measure the field gradient or to provide averaging of the measured magnetic field. This is used in magnetoelastic torque sensors manufactured by Methode. Single cores are also used for some fluxgate-based sensors of electric current [15] . The main problem of the single-core fluxgates is large spurious voltage at their output which is caused by a large mutual inductance between the excitation and output winding. This spurious voltage at the excitation frequency and odd harmonics, it can oveload the processing electronics and together with some nonlinearity in the measuring chain, it can create 2nd harmonic signal, which is falsely interpreted as sensor offset.

B. Double-wire Sensors

The large part of the spurious signal is eliminated in the double-core sensor consisting of wires excited in opposite directions, so that their output without field is near zero. Advanced double-rod sensor with a common pick-up coil (Vacquier type) was developed by Moldovanu et al. for the INTERBALL satellite instrument [13] and later tested with various kinds of core materials [14]. Foerster [15] used two individual identical pick-up coils connected serially; such a configuration allows easier adjustment of the sensor balance by moving the cores with respect to their coils. A 50-cm long fluxgate of this type with 10-pT resolution was constructed for a geophysical observatory [16].

Multiple wires have been used for the cores of transverse fluxgates. It was found that the sensor performance is strongly affected by the magnetostatic coupling between the wires which depends on their distance [17]. Demagnetization factor of the core made of several microwires was studied in [18].

In this paper we analyze the possibility to use multiple straight wires or rods in the cores of parallel-type fluxgate.

The idea is obvious, but as far as we know it has been neither described in the literature or applied in the industry. The paper is based on measurements on model cores made of permalloy wires. The model can be upscaled for magnetic rods and downscaled for bundles of microwires and arrays of nanowires.

II. Experimental Setup

Our model cores consists of of 36 mm long, 0.2 mm diameter Permalloy wires with chemical composition Ni78Fe15Cu4Mo3. The wires were annealed for 3 hours in a dry hydrogen atmosphere at 1080 °C to obtain near-zero magnetostriction. The wires are kept inside the glass tube to protect them from mechanical stress. Five experimental sensor types were designed:

S1: Single-core sensor: both excitation coil and pick-up coil are wound directly on the glass capillary or on cylindrical bobbins of various diameters (Fig. 1 a, 2).

V(1+1): Double-core sensor of Vacquier type: the same excitation coils are connected antiserially. The cores are inserted into the larger glass pipe serving as a bobbin for pickup coil around both cores. (Fig. 1 b)

F(1+1) Double-core sensor of Förster type: excitation coils are connected either antiserially or serially, but each core has its own pickup coil. These pickup coils are connected serially or antiserially (Fig. 1 c)

Ln: n-wire core sensor with individual excitation coils and one large common pick-up solenoid using honeycomb array made by 3D printing..

L(n+n): two n-wire sensors connected antiserially

The parameters of selected sensors and measured sensitivity values are shown in Table 1.

FIG. 1 HERE

Tab. 1 HERE

Fig. 2 shows examples of the measured fluxgates. The multiwire type has a 3D printed honeycomb bobbin which allows insertion of different configurations of wires in glass capillaries. Fig. 3 shows examples for dense and loose positioning of 8 wires inside the honeycomb.

FIG. 2 HERE

FIG. 3 HERE

III. The effect of the pick-up coil geometry

The effect of the pick-up coil diameter and length is shown on single-wire fluxgate in Fig. 4. Flux line „a“ returns back inside pick-up turns 1 and 2 and does not cross pick-up turn 3; therefore it does not contribute to the flux of these coils. Line „b“ contributes only to 2, „c“ contributes to 2 and 3 and „d“, „e“ contribute to all 1,2,3.

From that we may conclude that with the given number of turns, the pick-up coil should be short and slim to maximize the sensitivity. However, also other design aspects should be considered: shorter coil has higher capacitance and very short coil with the same number of turns also cannot be physically slim.

FIG. 4 HERE

Using 2D FEM simulation we calculated the pick-up coil flux as a function of pick-up coil diameter D for several material permeabilities. The wire diameter was always $d = 0.2$ mm and the field source was the excitation coil with internal diameter of 1.1 mm. . Figure 5 shows result for the long pick-up coil. Displayed are relative values Φ_{pick}/Φ_{exc} where Φexc is the total flux of the excitation coil and Φ_{pick} is the total flux of the pick-up coil. The flux of the pick-up coil decreases with increasing diameter as intuitively expected for fluxgate sensors. This dependence is very similar regardless the wire permeability. The sensitivities measured on single-wire fluxgate sensors are marked for comparison. Both simulated and measured sensitivity values change only by about 20% in this large range of diameters. This is very different from currrent-output fluxgate, which shows much steeper decrease of sensitivity. This finding is fundamental for the design of multicore fluxgate.

FIG. 5 HERE

As mentioned, shorter pick-up coil with the same number of turns located in the central part of the core is more sensitive. The reason is that some of the flux lines (type b in Fig 1) do not cross end turns of the long coil. In order to examine this effect quantitatively we calculated by 2D FEM the relative flux for the short pick-up coil as a function of its position (Fig. 6). In the same figure we show the measured values of the relative sensitivity of fluxgate with short coil, which roughly fit with the simulation.

FIG. 6 HERE

We also calculated the total flux of pick-up coil as a function of its length l (Fig. 7). In this case the results depend on the wire permeability, but it is clear that the end parts of the pick-up coil do not contribute much to the sensor sensitivity. The reasonable length of the pick-up coil is 60 to 80 % of the core length. However, for the relative permeability of the core material μ_r = 10 000, the increase of sensitivity caused by shortening of the pick-up coil is only 25 %. Similar effect was observed for ring-core and race-track fluxgates [10] and also for the cored induction sensor [22].

FIG. 7 HERE

IV. The effect of the excitation parameters

The fluxgate sensitivity depends on the the frequency and amplitude of the excitation current, as well as on its shape. In our study the sensor was excited from the generator with internal resistance of 50 Ω. Due to the low inductance of the excitation coil, this is similar to current source. The typical measured sensitivity values plotted in Fig. 8 correspond well with the elementary fluxgate theory: for given frequency, the sensitivity is increasing with excitation amplitude, reaches the maximum and slowly decreases. The sensitivity increases with frequency (until it reaches limit given by eddy currents and hysteresis losses). The excitation level for the maximum sensitivity is increasing with frequency [1, 23]. These rules do not take into the account the parametric amplification which at higher frequencies can be caused by parasitic capacitance of the pick-up coil. Many fluxgates also use resonance excitation circuit; that solution reduces the excitation power, but introduces strong non-linearity [24]. For open-core fluxgates these resonant effects are usually not important due to low quality factor of the sensor coils.

FIG. 8 HERE

V. Effect of the core geometry and Multiwire sensors

The sensor sensitivity depends on the core geometry which affects its effective demagnetization factor. With fixed core diameter d the sensitivity can be increased by increasing the core length l. However, for most practical applications l is limited. It is possible to increase core area by using a stack of several wires, however the sensitivity increase is limited by demagnetization. The effective way to decrease the demagnetization factor is to decrease the magnetostatic coupling between the wires by increasing their distance. In order to do that one should use larger pick-up coil diameter. This is possible because as shown in Section 3, increasing the pick-up coil diameter reduces the sensitivity only very slightly. In order to verify this assumption we made 3D FEM model in Ansys and calculated relative sensitivity as a function of number of wires and their permeability. The results of this simulation are shown in Fig. 9 for the maximized wire distances (wire positions as shown by + marks in Fig. 3). In the same Fig. 9 we show sensitivities measured on sensors L1 to 8. The measured values fit well with the curve for μ_e = 10 000. It should be noted that the apparent permeability of fluxgate core is time-dependent and the effective permeability μ_e is its avegage value.

By increasing the number of wires in the core from 1 to 8 (sensor L1 vs L8 in Table 1) the sensitivity is theoretically increased by a factor of 8, if the wire distance (pitch) is large enough to avoid magnetostatic interacion. In our case the achieved sensitivity increase was only 6.

For each configuration or the sensor core, we found the optimum working point (excitation frequency and amplitude) to maximize the sensitivity and minimize the noise. In general the excitation amplitude for minimum noise was 10 to 20 % higher than the amplitude for maximum sensitivity.

FIG. 9 HERE

According to the theory, the noise is reduced by the factor of $\sqrt{N}$ for independent noise sources. We have observed general decrease of noise with increasing of the wire number and with increasing of wire distance. However, the decrease was significanly lower than $\sqrt{N}$. Fig.10 shows typical noise spectra of the measured sensors and their cross-spectrum. The noise has 1/f character, drop at higher frequencies is caused by low-pass filter of the lock-in amplifier with 30 ms time constant. Even for distance of 5 mm between two wires the noise correllation is still high which explains that the achieved noise reduction was less than $\sqrt{N}$. Comparing an L1 with an L8 fluxgate, the measured noise level decreases by a factor of 0.53 (instead of $1/\sqrt{8}$ = 0.35 which is theoretical value for independent noise sources).

FIG. 10 HERE

VI. Conclusions:

We have shown that the sensitivity of the straight-wire-core fluxgate with voltage output depends only very slightly on the diameter of the pick-up coil. This opens up the possibility to design multi-wire fluxgate with loose core.

The sensitivity of the multiwire fluxgate is increasing with the wire pitch. This is caused by the fact that with increasing wire distance their magnetostatic interaction is decreasing, which results in lower demagnetization This initial study was limited to the single diameter and Permalloy material for the core wire. The achieved noise was 150 pT√Hz at 1 Hz, which is acceptable for many applications such portable gradiometers, position and torque sensors, and detection of small objects. For the mentioned applications the straight wire core has significant advantages. We plan to improve the noise properties by application of arrays of amorphous or nanocrystalline microwires.

Acknowledgment

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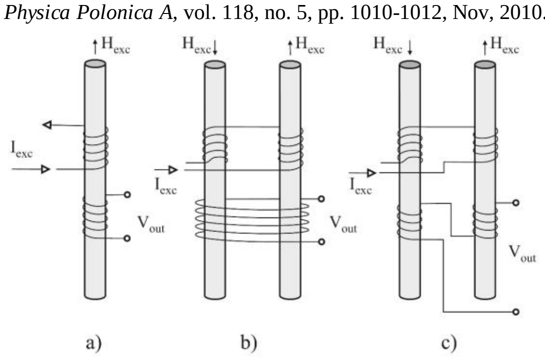

Fig. 1. Fluxgate sensors with wire cores a) single, b) Vacquier, c) Foerster

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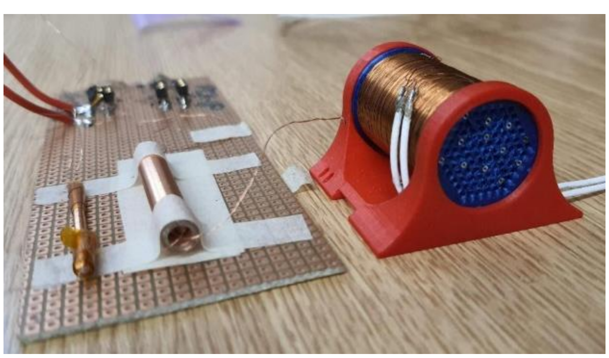

Fig. 2. Experimental fluxgate sensors: S1 single core, V2 Vacquier, Ln multiwire

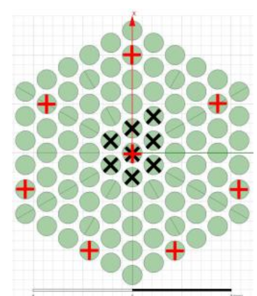

Fig. 3. multiwire sensors with 8 wires with distance (pitch) of 1 (**x**) and 4 (**+**)

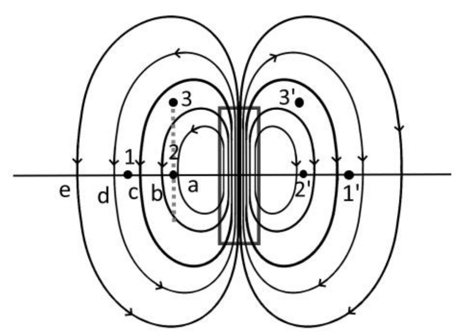

Fig. 4. Single-wire fluxgate: with flux lines a,b,c,d,e and three different pick-up turns 1, 2, and 3

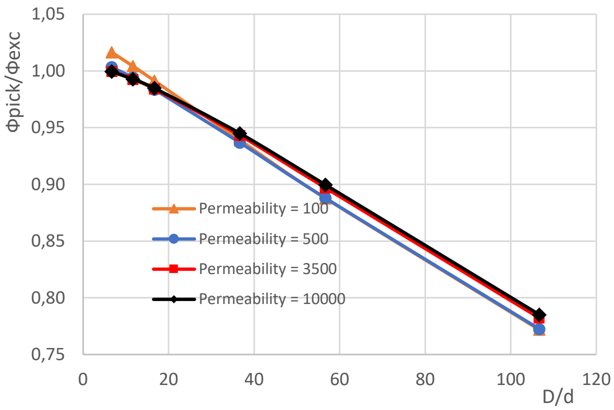

Fig. 5. Relative flux of the long pick-up coil as a function of its relative diameter – values calculated by 2D FEM

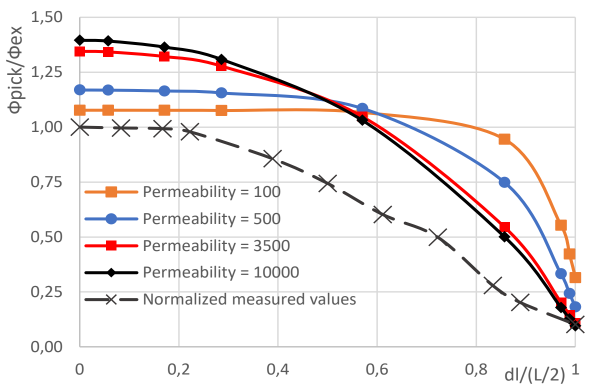

Fig. 6. Relative flux of the very short pick-up coil as a function of its relative position – calculated by 2D FEM for several values of relative permeability. Lower trace (**x**): measured relative sensitivity of short coil.

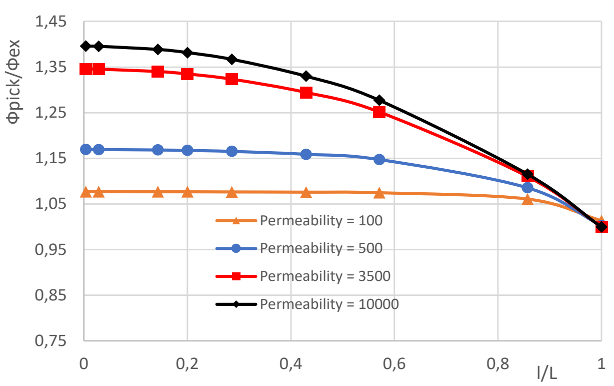

Fig. 7. Relative flux of a pick up coil as a function of its relative length – values calculated by 2D FEM for constant number of turns

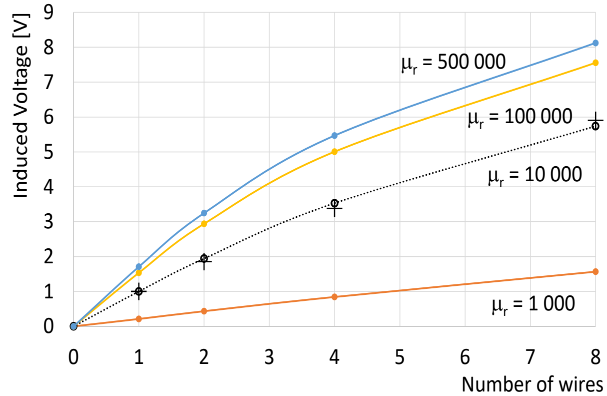

Fig. 9. Relative sensitivity of L1 to L8 sensors as a function of number of wires in the core. Calculated by FEM for several values of effective permeability. Values marked + are measured relative sensitivities.

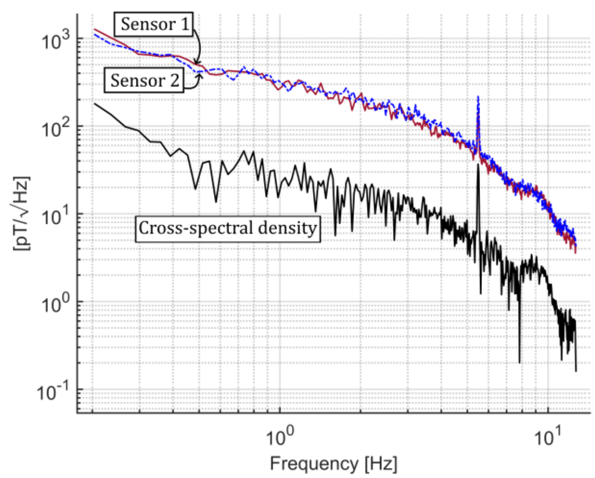

Fig. 10. Noise PSD and cross-spectral density of two single-wire sensors in 5 mm distance

TABLE I
SENSITIVITY OF THE TESTED WIRE-CORE FLUXGATE SENSORS AT 4 KHZ EXCITATION

sensor	D/d	D	N pick	Max sens (mV/47 μT)	at Vexc (V)
S1-1.5	7.5	1.5	220	10.1	0.91
S1-2.15	10.75	2.15	235	10.6	0.77
S1-11	55	11	235	9.4	0.91
V(1+1)	17.5	3.5	235	24	1
F(1+1)	7.5	1.5	470	28.6	1.05
Ln … large pickup coil					
1 wire			514	21	1.8
2 w	90	18	514	39	2.2
4 w			514	71	2.8
8 w			514	124	4.5

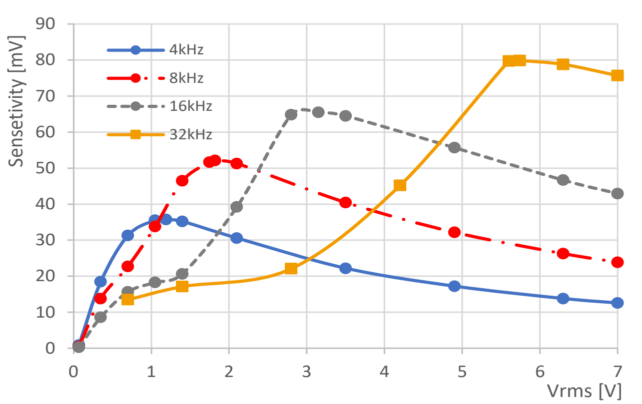

Fig. 8. Sensitivity of sensor V(1+1) as a function of excitation amplitude, excitation frequency is a parameter

D is the magnetic wire diameter, D is the diameter and Npick is number of turns of the pickup coil