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Sensitivity and noise of parallel fluxgate sensor with amorphous wire cores

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***Abstract*. Fluxgate sensors are vectorial magnetic field sensors suitable for the measurement of fields up to mT with maximum pT resolution. Due to their low weight, low power, and low cost, fluxgates are ideal sensors to monitor the Earth's field and measure its spatial deviations. The sensitivity of the sensor directly depends on the material and geometry of the core, and on the geometric parameters of the coils. Fluxgate is still the most sensitive room-temperature vectorial magnetic field sensor [1]. This work is devoted to the study of parallel fluxgate with multiple wire cores. The achieved sensitivity for a 35 mm long sensor is 12 mV/µT and the minimum noise was 25 pT/ √ Hz at 1 Hz for as-cast amorphous wires.**

Keywords— fluxgate; sensitivity; noise

I. Theoretical Background

The basic fluxgate sensor consists of the magnetic core, excitation coil, and pick-up coil (Fig. 1). An AC current into the excitation coil is used to drive the core into saturation. Characteristics of the core material are key to the performance of the fluxgate, but for improving sensitivity it is also needed to choose the right core and coil geometry [2]– [4].

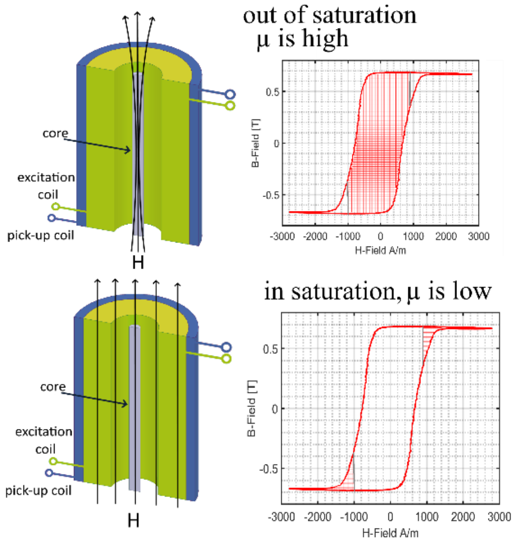

Fig. 1. Flux flow changes with the change of permeability

In this paper, we concentrate on wire-core fluxgate sensors, which generally have higher noise than the more popular ring-core fluxgates [2], but they keep several important advantages: they are spatially selective and so suitable for the detection of very small objects, their sensing direction is defined by the direction of the core and not the pick-up coil and their cross-field effect is very small [3]. In this paper, we discuss parallel-type fluxgate which does not require electric contact with the magnetic core [4].

The main disadvantage of the single-wire sensor is the large spurious voltage at the odd harmonics caused by the transformer effect from the excitation. This voltage can be more than 120 dB above the second harmonic voltage to be detected. However, single-wire sensors are still used as a part of gradiometers or multi-sensor devices such as torque transducers.

Double-core sensors of the Förster or Vacquier [5] type utilize two wire cores excited in opposite directions so that the excitation flux is subtracted and spurious voltage at the odd harmonics is ideally zero. Similar geometry is used for microfluxgates [6]. Compared to our previous research, which was using a permalloy core and a single excitation coil [7], in this study, we use amorphous wires and more complicated coil structures. We also calculate the sensitivity factor by FEM and optimize the geometry. The results are compared to the ring-core sensors made of the same material.

II. Measurements

A. Single-core sensor

The amorphous wire used as a core has a diameter of 0.12 mm and chemical composition $(Co_{94}Fe_{06})_{75}Si_{15}B_{10}$. The wire was manufactured by the Institute of Technical Physics, Iasi, Romania. Permalloy (Py) wires were 0.2 mm in diameter with chemical composition $Ni_{78}Fe_{15}Cu_{4}Mo_{3}$, manufactured by Elidis, Czechia. The parameters of the coils are presented in Table 1. Similar coils were used for Förster and Vacquier-type sensors (section IIb).

TABLE I. Parameters of coils

Parameters of coils	*Excitation coils (diam = 0.5 mm)*	*Excitation coils (diam = 0.35 mm)*
N excitation	400	625
N pick-up	200	300
D pick-up	1.3 mm	0.8
D winding wire	0.2 mm	0.09
l length	3.5 cm	3.5 cm

The excitation current source was HP 33120A and for demodulation was used lock-in amplifier SR865 2MHz. The experiments were held in Helmholtz coils generated 50µT field. Noise measurements were done in 6-layer permalloy shielding at a frequency of 1 Hz.

The sensitivity of the single-core sensor can be increased by using multiple wires for the core [6], [7]. The measured sensitivities are shown in Figure 2 for several frequencies. Figure 3 shows the sensitivity factor $\mu_a N$ calculated for several values of material relative permeability $<\mu_r>$ averaged for the excitation cycle. The apparent permeability μ_a was calculated by 3D Finite-Element Modelling (FEM).

The gain of the sensitivity after increasing the number of wires is bigger at the lower frequencies: for 8 wires the sensitivity increases by a factor of 3 at 4 kHz, and only 2 at 32kHz. In Fig. 3 the gain increase has a factor of 3 for $<\mu_r>$=10 000, which is a realistic value for our case.

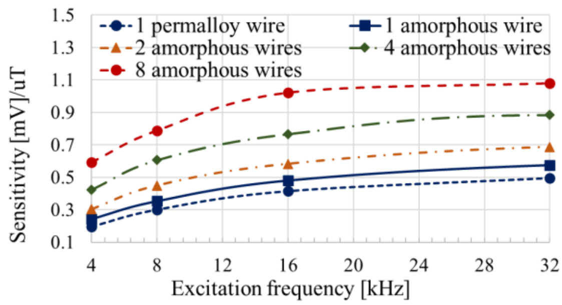

Fig. 2. Sensitivity of the single-core fluxgate on the frequency with different numbers of wires in the core (experimental results)

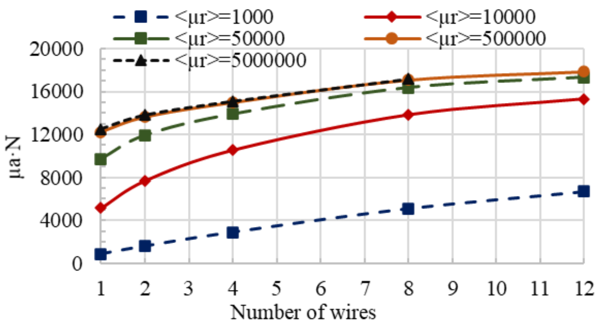

Fig. 3. Sensitivity factor as a function of the number of wires in the core for several values of average coil permeability (3D FEM simulation)

The simulations fit the experimental studies which indicate a possibility to use the model to predict the result for other geometries, from 1-meter long rod-core fluxgates for geophysical applications to nanowire fluxgates having millions of cores [8]. The increase in sensitivity with increasing the number of wires is non-linear due to the demagnetization. Therefore, using more than 8 wires in a single core does not bring significant improvement.

The noise comparison of single-core fluxgate sensor from permalloy and amorphous wires is shown in Fig. 4. Usage of amorphous wires could decrease the noise dramatically. An increasing number of wires inside the excitation coil leads to an increase in noise and also the increase of the demagnetization factor.

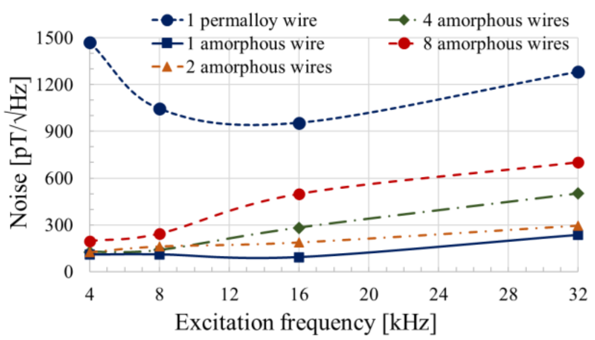

Fig. 4. Measured noise at 1 Hz for single-core fluxgate as a function of the excitation frequency with different numbers of wires in the core

One of the reasons is the small distance between the wires which causes that the noise in individual wires is correlated. In the following section we will show that splitting the excitation coil into a few of them so that each wire core has individual excitation coil can reduce the noise and increase the sensitivity.

B. *Förster and Vacquier sensors*

Classical Förster and Vacquier-type fluxgate sensors contain two cores. The excitation coils are always connected antiserially, the pick-up coils for the Förster sensor (Fig. 5) are individual for each core, while the Vacquier sensor (Fig. 6) has one common pick-up coil wound around both cores. Figure 7 shows a comparison of the sensitivity of the two types.

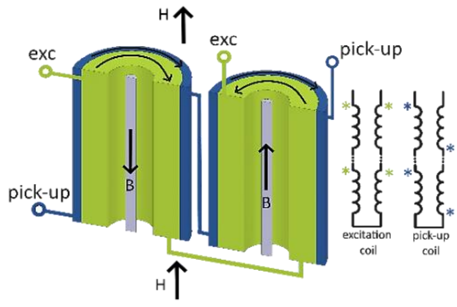

Fig. 5. Förster type 1+1 construction

The Vacquier type sensor has slightly higher sensitivity at higher frequencies, which can be explained by stronger parametric amplification caused by parasitic capacitances of the pick-up coil [1]. The higher noise for the Vacquier sensor could be explained by the fact that the cores are closer, and their noise is, therefore, more correlated.

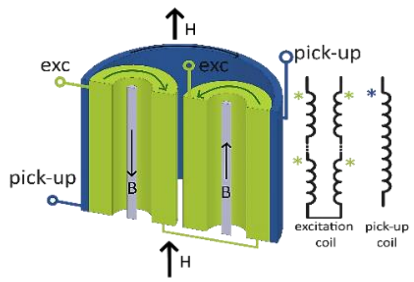

Fig. 6. Vacquier type 1+1 construction

The difference in sensitivity is small (Fig. 7), so the selection of the sensor type depends on the application: the Förster design is more convenient for sensor arrays such as gradiometers or torque meters. The Vacquier design is more compact, and it is used for field sensing and non-destructive testing.

N+N stands for the number of excitation coils divided into 2 antiserially connected parts. The coils in each part are connected serially. Each excitation coil has single amorphous wire core.

Sensitivity of fluxgate sensors is in general increasing with frequency, but the limitations are eddy currents in the core and self-capacitance of the pick-up coil. Due to the non-linear resonance effects, the frequency characteristics are non-linear such as in Fig. 8. Frequency dependence of the noise is even more complicated as shown in Fig. 9: the local noise maximum at 32 kHz may be explained by interplay between the pick-up coil self-resonance and possible magnetoelastic core resonance.

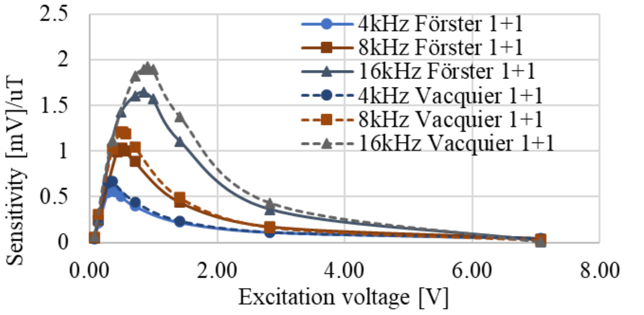

Fig. 7. Sensitivity of Förster 1+1 and Vacquier 1+1 sensors , f_{exc} = 4-16kHz, diameter of excitation coil 0.5mm

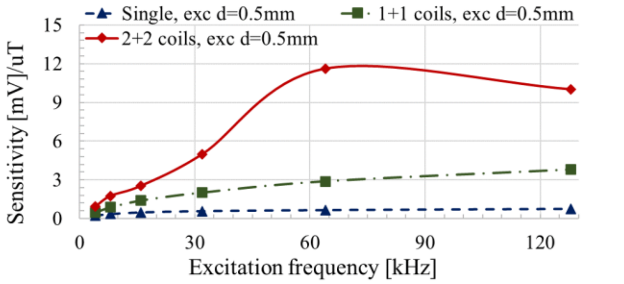

Fig. 8. Förster 1+1, Förster 2+2, and single-type sensor sensitivity measurements as a function of excitation frequency. The excitation amplitude was always adjusted for maximum sensitivity.

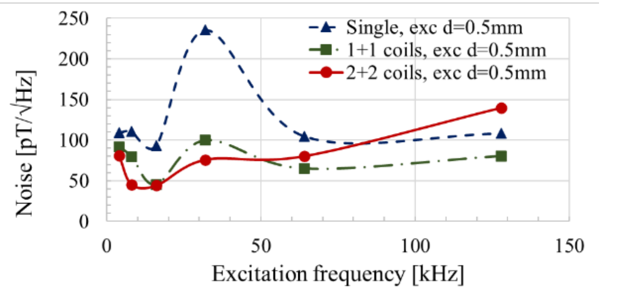

Fig. 9. Noise at 1 Hz for for Förster 1+1, Förster 2+2, and single-type sensor as a function of excitation frequency

We have also studied the sensitivity and noise dependence on the distance between the cores for a sensor of the 1+1 Vacquier type. The results of the measurements are shown in Figures 10 and 11. For a larger distance between the cores, the sensitivity is higher, and the noise is lower. This effect was also observed in simulations, and it can be explained by the magnetostatic interaction between the cores.

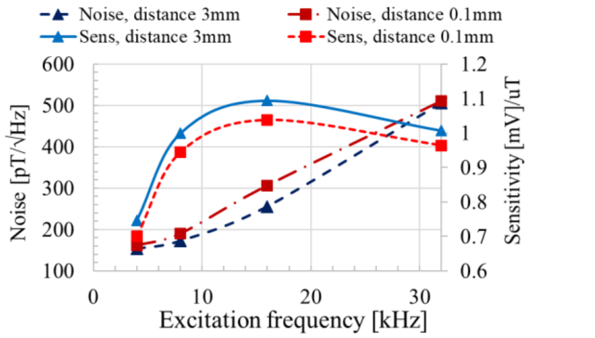

Fig. 10. Sensitivity and noise at 1 Hz as a function of the distance between wires in Vacquier sensor

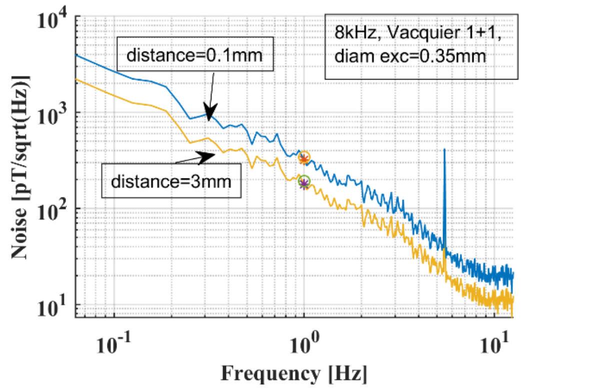

Fig. 11. Noise spectrum as a function of the distance between wires, Vacquier 1+1,

C. *Vacquier n+n*

Fig. 12 shows characteristics of a single core sensor and Vacquier sensors with different parameters. The increase in sensitivity vs. the number of wires is non-linear. Vacquier 2+2 consists of 4 excitation coils and 4 cores, the single sensor has 1 excitation coil and 1 core with the same parameters. If we compare the results for a Single core and a Vacquier 2+2 at 4 kHz, then the increase in sensitivity will be more than 4 times – 20 mV for a Single core sensor and 120 mV for a Vacquier sensor. The possible explanation is again resonance tuning of the sensor output by parasitic capacitance.

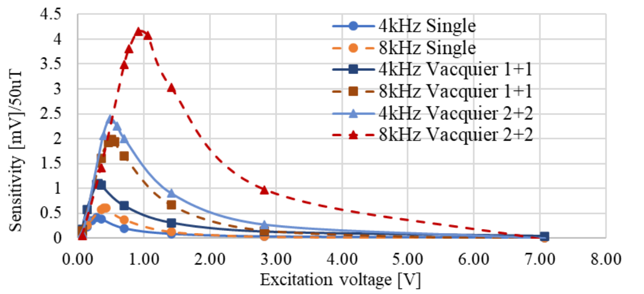

Fig. 12. Sensitivity vs. excitation voltage for Single and Vacquier sensors, exc. coil diam = 0.35mm, Fexc = 4 kHz -16 kHZ

Sensitivities in wider frequency range are are shown in Fig. 13 and the noise as a function of the excitation frequency is shown in Fig. 14. In case of Vacquier sensors we do not observe local noise maximum, which we explain by larger distance between the cores and the pick-up coil. Here we observed minimum noise of 25 pT for Vacquier 2+2 sensor excited at 32 kHz.

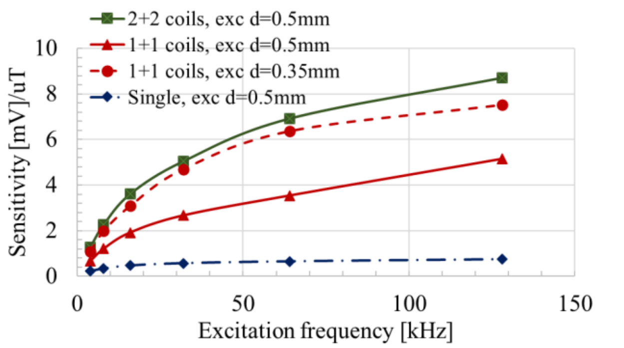

Fig. 13 Sensitivity vs. excitation frequency voltage for Single and Vacquier sensors

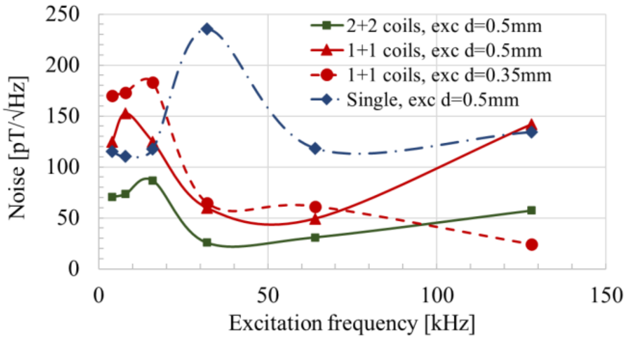

Fig. 14 Noise at 1 Hz for Vacquier1+1, Vacquier 2+2, and single-core sensor

III. Ring-core Sensor

For the measurements of magnetic properties of amorphous material and also for comparative purposes, a ring-core sensor was built from the same $(Co_{94}Fe_{06})_{75}Si_{15}B_{10}$ amorphous wire. The sensor is shown in Fig. 15. Number of turns of the excitation coil is 250, the pick-up coil is 2000, and 16 turns of magnetic wire in the magnetic core. The diameter of the magnetic wire is 0.12 mm, and the diameter of the toroid is 24 mm. Optimum excitation parameters were 13.7 kHz and 10 V. The measured sensitivity is 75 mV/μT and the minimum noise is 115pT/√Hz

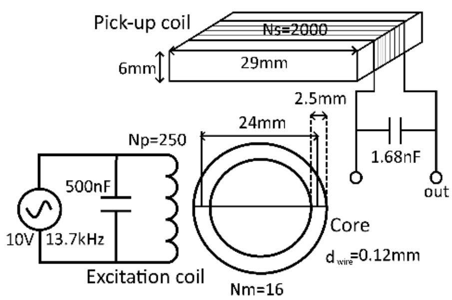

Fig. 15 Settings of measurements of the ring-core sensor

The measured B-H loop of the ring core is depicted in Fig. 16. The coercivity is 12.7 A/m. Coercivity measured for the rod-type sensor is 24 A/m.

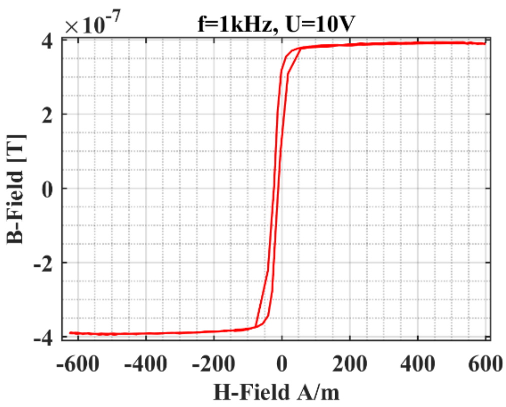

Fig 16 B-H. loop of ring-core sensor based on amorphous wire measured at 1 kHz

IV. Conclusions

The sensor design and the core material selection have a significant influence on the performance of wire-core fluxgate sensors. The sensitivity estimated by FEM simulations has a good fit with the experiments. Replacing permalloy wires with amorphous wires increases the sensitivity and reduces the noise by more than 5 times. Using amorphous material brings also benefits in an easier sensor fabrication process due to its resistance to external mechanical influences, while classical crystalline permalloy wires must be annealed in the final form.

The sensitivity could be increased by a factor of 10 to 120 μV/nT and the noise can be reduced to 25 pT by using a multiwire configuration. This noise level is significantly better than 350 pT reported in [5] and 1.5 nT in [9].

Acknowledgment

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