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# MULTIWIRE CORE FLUXGATE

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**Abstract:** Fluxgate sensors with core made of multiple microwires are analyzed. We show that any study on sensors based on microwires should begin with detailed characterization of the magnetic properties of the wire, as they are dramatically changing within centimeters. Increasing the number of wires increases the sensitivity and lowers the sensor noise; by proper grouping into serioparallel configuration the current and power consumption can be optimized. The achieved sensitivity of 30 mV/μT and noise level is 0.34 nT/√Hz@1Hz for double- wire core with dipolar interaction.

**Keywords:** orthogonal fluxgate, multiwires, magnetic wires

## INTRODUCTION

Miniature precise low-power magnetic sensors are required for many applications including security, position sensing and compass [1]. High linearity, high temperature stability, low noise and low perming are needed. Although significant effort was invested into the development of new magnetic sensors, the only candidates for the precise applications are AMR sensors and fluxgates. Although some authors report magnetoresistors with 10 pT noise, however this is white noise measured at frequencies higher than of 100 Hz. The best noise values for magnetoresistors measured at 1 Hz are 200 pT/√Hz [2,3]. AMR sensors have other precision limits [4] and often cannot meet mentioned requirements, research effort is therefore invested into the miniaturization of fluxgate sensors.

Thin low-cost PCB fluxgate sensor can reach temperature offset stability of 0.2 nT/K [5]. The sensor size can be further reduced by using microtechnology [6]. Serious problem is to find proper material for the core of miniature fluxgates. Sputtered and electrodeposited permalloy do not possess required parameters. Microfluxgate sensor with amorphous sputtered Co85Nb12Zr3 shows promising properties: coercivity of 0.03 Oe, and the permeability of 10 000 was reported in [7].

Orthogonal fluxgates represent another approach to the miniaturization of fluxgate sensors. These almost forgotten sensors [8] reappeared recently; with wire core they have several advantages:
- low demagnetization factor which results in low crossfield error
- low power consumption
- no excitation coil is necessary since the excitation current flows directly through the wire

Sasada introduced fundamental mode of transverse fluxgate [9,10]. Some sensors have lower noise in this mode (which was not the case for our sensors), but in its simple mode fundamental-mode fluxgated exhibit high offset, which is changing with temperature [11]. Sasada offered in [11] an improved mode by periodical changing of the polarity of the excitation bias. This technique requires more complicated circuitry and it is in fact equivalent to fluxgate symmetrically excited by current waveform of complex shape. We may conclude that [11] confirmed that only deep saturation into both polarities guarantee operation with long-term offset stability. However in this study we consider only second-harmonic excitation, which for our sensors gave both higher sensitivity and lower perming compared to fundamental mode.

Single–wire transverse fluxgate sensors of 2nd harmonic type with amorphous cores were studied in [12]. Later it was shown that if the permeability tensor has non-zero off-diagonal component, sensor output can be detected from the voltage induced between the wire terminals, i.e. the fluxgate sensor has no coil at all [13].

Transverese fluxgate sensor can also be manufactured by planar technology [14].

One of the disadvantages of orthogonal fluxgate sensors with wire cores is relatively low sensitivity caused by low cross-sectional area [15]. Multiwire cores can solve this problem. In the first multiwire fluxgate sensor all wires were connected in parallel [16]. The authors of [16] observed non-linear increase of the sensitivity with increasing number of wires for very closely packed wire cores. They have observed only linear dependence for 5 mm distant wires. By replacing some of the magnetic wires with copper wires, they experimentally verified, that the effect cannot be explained by adding the influence of the excitation currents from the close neighboring wires. Also inactive magnetic wires do not significantly influence the sensitivity. The result was that the effect should be caused by ac magnetic interaction between the wires, but the origin of this interaction remained uncovered.

In this paper we further investigate that effect measuring also serial and antiserial combinations of the wires. Also more systematic study was needed as we found that the wire properties dramatically change within the same batch. We also considered magnetic interactions between the wires, which depend on their distance, and quality of the tuning circuit.

## THE EXPERIMENTS

We have made systematic study on core made of glass-covered amorphous Co68.25Fe4.5Si12.25B15 wire. The wire is 22 μm thick and the glass coating thickness is 2 μm.

First of all we investigated homogeneity of the magnetic properties along the wire length. For this we developed ambulatory measurement setup to measure longitudinal hysteresis curves and also DC field sensitivity in simulated fluxgate mode (2nd harmonic response to the DC field in the direction of the wire). We observed huge changes of these properties within cm distance (Fig. 1), which means that each wire should be tested individually before being used for the sensor core. Big changes in the magnetization characteristics can be explained by local residual stresses [17]. Fig. 2 shows how the sensor characteristics change at different points of the wire length. One of the main factors affecting the change of the shape are residual mechanical stresses in the wire and local regions with induced anisotropy causing spatially changing off-diagonal components of the permeability tensor. We assume that some of the stresses can be caused by imperfect glass layer.

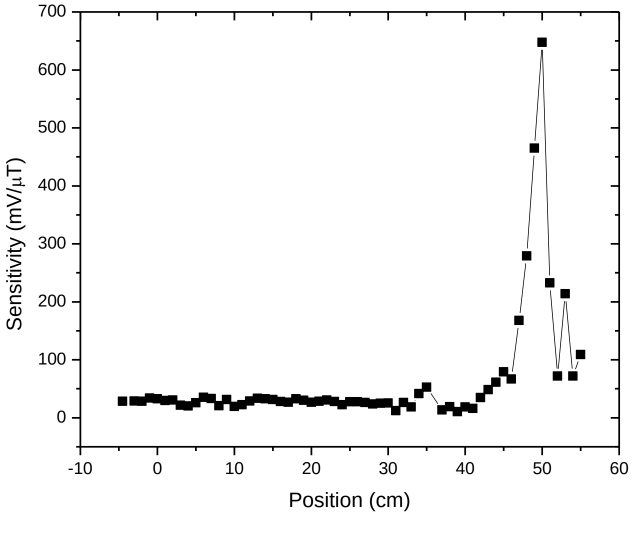

*Figure 1. Sensitivity profile along the 60 cm section of the amorphous wire*

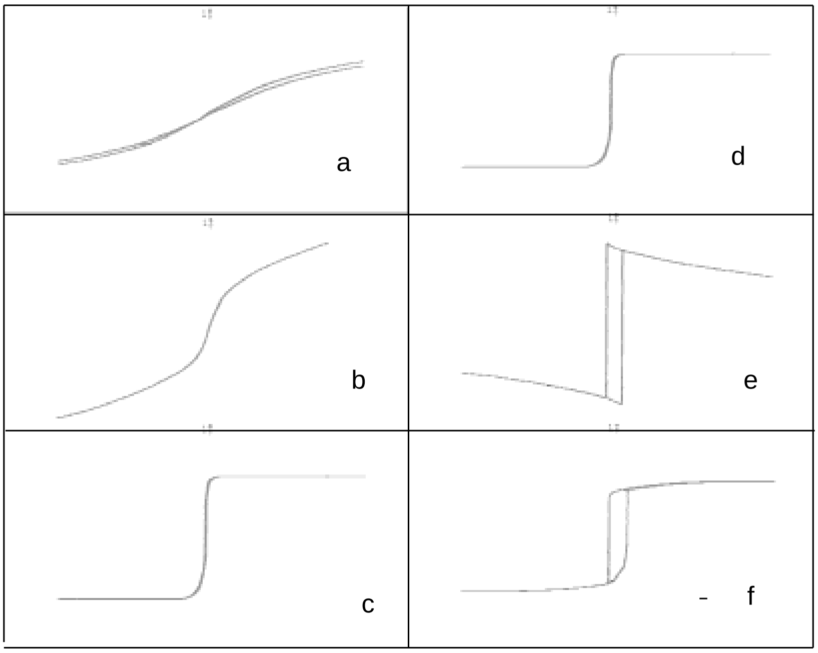

*Figure 2. Sensor characteristics (second harmonics voltage versus longitudinal external field at different points of the wire from previous figure.*

Later we cut 10 mm wire sections with similar characteristics and used them as the sensor cores. We changed the number of wires from 1 to 8 and their mutual distances (from direct contact with possible exchange coupling to 100 μm resulting in fully dipolar interaction). The electrical connection was either parallel, serial, antiserial or combined serioparallel. In general, parallel connected wires require large amplitude for the excitation current, which is very unpractical. On the other hand serial connection of higher number of wire cores may requirev high excitation voltage. It is possible to use current transformer in the excitation circuit, but we found more simple solution – group wires to serioparallel combinations to optimize the impedance to the excitation source.

We also investigated the frequency dependence of the sensitivity and compared it with models. The pickup coil always had 1015 turns. The excitation frequency was always tuned for maximum sensitivity - the resonance frequency depends on the parasitic capacitance and mean inductance of the pick-up coil (which depends on the excitation parameters). The typical tuning curve is shown in Fig. 3.

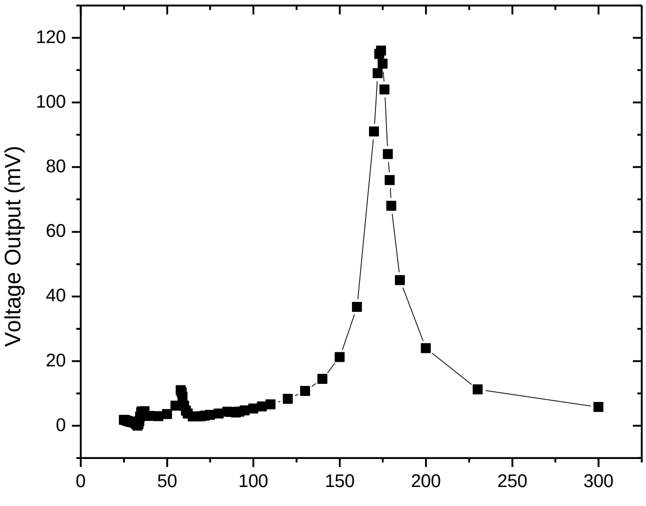

*Figure 3. Frequency dependency of sensitivity: Iexc = 20 mA rms, external field = 8.6 uT*

An example of the measured sensitivity curves is shown in Fig. 4: two wires (T1A and T1B were used individually (single-wire cores) or closely together, either in parallel or antiserial connection. The results show that the sensitivities for double cores are more than twice the sensitivity of single-wire sensors. We explain this fact by increasing of the quality of the tuning circuit due to larger cross-section of inserted ferromagnetic material. The frequency characteristics of the sensitivity shows that with the exception of highest frequencies the sensitivity of parallel and antiserially connected cores are the same. The important advantage of antiserial connection is that the amplitude of spurious voltage at the excitation frequency is lower and thus the signal processing is much easier. Disadvantage of parallel connection is that it requires double excitation current.

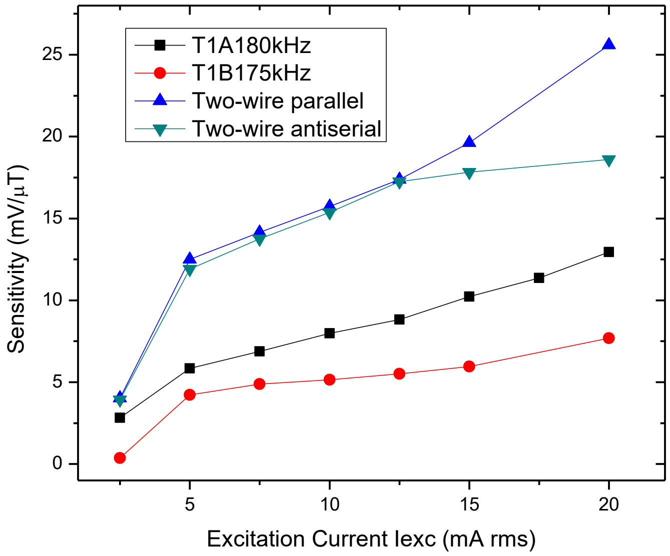

*Figure 4: Sensitivity using T1A and T1B as cores for tuned fluxgate sensor: single-wire versus closely mounted double-wires (either connected in parallel or antiserially). The indicated excitation current flows through each wire.*

We have measured the noise and sensitivity of our sensor demonstrators also for changing distance between the wires. The lowest noise of 0.34 nT/√Hz@1Hz (1.2 nT rms in 30 mHz .. 10 Hz range) was achieved for core made of antiserially connected wires with dipolar interaction (Fig. 5). The noise in the time domain and short-term (10-minute) offset stability at constant temperature are shown in Fig. 6. Distance between the wires was approximately 100 µm and excitation current was 20 mA rms. With the excitation current reduced to 10 mA the noise increased to 0.52T nT/√Hz@1Hz. These are values competitive to AMR sensors.

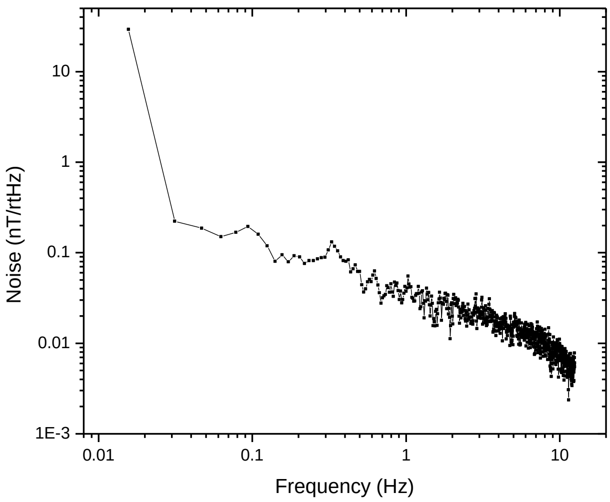

*Figure 5. Noise for two-wire core with dipolar interaction excited antiserially*

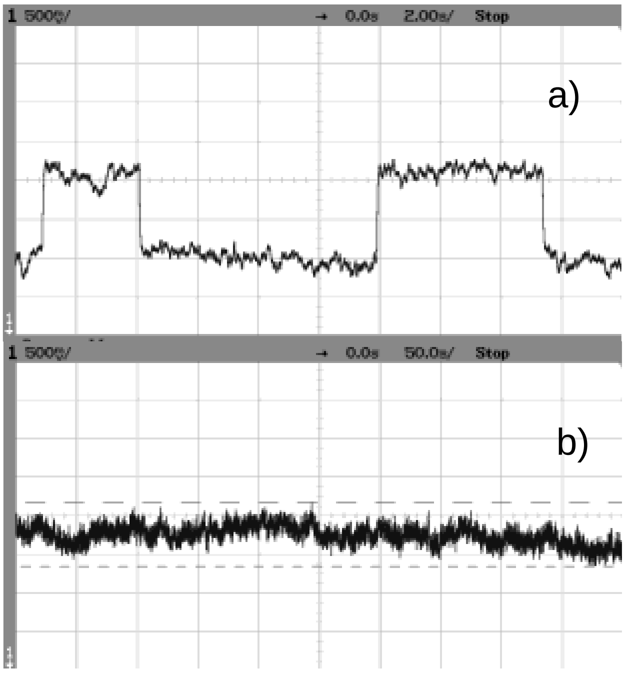

*Figure 6. Noise of the same sensor in the time domain:*
*a) response to 10 nT field step, b) 10-minute stability (same y scale 5 nT/div)*

The sensitivity of the same sensor as a function of the excitation current rms value is shown in Fig. 6. The sensitivity was calculated over the range of 34 A/m (lower curve) and 7 A/m (upper curve). The results show that even with the maximum value of the excitation current the core is still not saturated. We also observed that in this case the noise decreases with increasing of the excitation level proportionally to the increase of the low-field sensitivity.

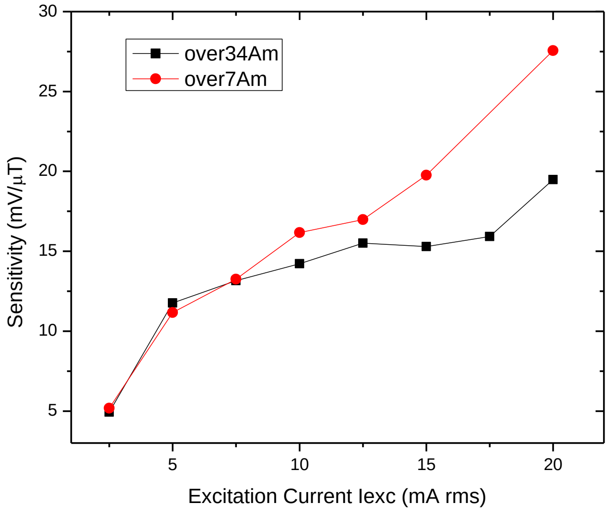

*Figure 7. Sensitivity over two field ranges for core made of two antiserially connected wires with 100 µm distance*

## CONCLUSIONS

The sensitivity of orthogonal fluxgate sensors with wire core can be increased by using multiple wire core. Sensitivity of such system depends on the demagnetization factor, but it is also strongly dependent on the quality factor of the tuned output circuit. In our experiments presented in this paper we always tuned the pick-up coil by changing the excitation frequency, as this leads to best sensitivity and lowest noise. We have shown that both serial and antiserial connection of the wires is possible and the necessary excitation current is reduced compared to paralell connection. Moreover the antiserial configuration lowers the spurious voltage at the sensor output. The limitation for the number of serially connected wires is the generator voltage. The achieved noise level of 0.34 nT/√Hz@1Hz shows that these sensors can be a serious competitor to AMR magnetoresistors. The achieved 5 nT stability is sufficient for precise compass.

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