PCB FLUXGATE GRADIOMETER MEASURING dB_x/dy

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In this paper, we investigated a dB_x/dy gradiometer formed by PCB fluxgate sensors stacked together with a gradiometric base of 20 and 10-mm, respectively. We discuss several possible arrangements of the gradiometer with the emphasis to a common compensating coil wound around the two sensors, which can be in a novel configuration also used for as a gradient pick-up coil. The 1-Hz noise power spectral density of the 20-mm-base gradiometer was found as 3.7 nT/m/√Hz and it increased to 8.2 nT/m/√Hz when reducing the gradiometer base to 10 mm.

Keywords: fluxgate sensor, printed circuit board, pulse excitation, gated integrators, signal extraction, magnetometer

1 INTRODUCTION

Fluxgates made with printed-circuit-board technology (PCB) have potentially low noise and temperature drift to fulfil the requirements for a small-size tensor gradiometer for satellite projects such as LISA [1]. Their advantage for this application is that they are flat (<1mm) and thus allow forming dB_x/dy type gradiometer easily.

Measuring a dBx/dy gradient can be advantageous in many other application situations. In [2], the authors used two fluxgate sensors in dB_x/dy configuration to suppress the environmental noise and increase the sensitivity in magnetorelaxometry-based detection of nanoparticles. An array of CMOS-integrated dB_x/dy fluxgate gradiometer for the purpose of NDT was presented in [3].

1st-order gradients with PCB sensors and 1-mm gradiometric base were already measured in a device developed for the detection of magnetic markers [4]. The short gradiometric base allowed for high spatial resolution, however, it degraded the noise performance (in the order of 10 nT_{RMS}/m/√Hz @1Hz).

2 THEORETICAL ASPECTS

2.1. Gradient sensitivity, noise

The arrangement of a dB_x/dy gradiometer is evident, Fig.1 – two sensors with a sensitive axis in x-direction are placed in a distance d (gradiometric base) to measure the dB_x/dy component of the magnetic field – the most straightforward solution with fluxgate sensors is to use two phase-sensitive detectors (PSD's) and subtract their outputs.

Let us have two sensors A and B, with sensitivities S_A and S_B, gradiometric base of d, and a gradient field with values B_{xA} and B_{xB} in a distance d. Then, we can write for the gradient (derivative approximation for small d)

$$\frac{d(B_x)}{dy} = \frac{B_{xB} - B_{xA}}{d} . \tag{1}$$

The voltage output of the two sensors sensing the two field values of B_{xA} and B_{xB} is then

$$\Delta V = B_{xB} S_B - B_{xA} S_A \tag{2}$$

The sensitivity to gradient can be then expressed as

$$S\left[\frac{d(B_x)}{dy}\right] = \frac{B_{xB} S_B - B_{xA} S_A}{B_{xB} - B_{xA}} d . \tag{3}$$

The sensors need to be astatized, *ie* the sensitivities matched, in order to suppress homogeneous field response and increase gradient sensitivity. Then, using one field sensitivity S, we can write for sensitivity on gradient

$$S\left[\frac{d(B_x)}{dy}\right] = \frac{\left(B_{xB} - B_{xA}\right) S}{B_{xB} - B_{xA}} d = Sd \tag{4}$$

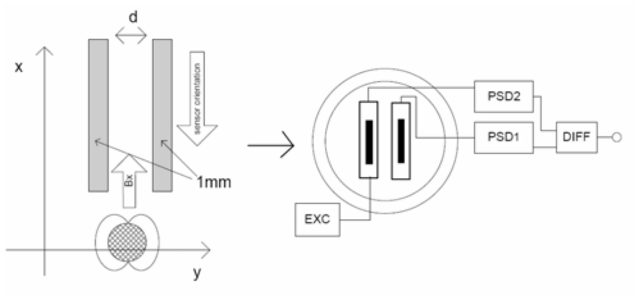

Fig. 1. Configuration of a fluxgate sensor measuring dBx/dy – layout and block diagram of simplest signal-processing

It is obvious that for short gradiometric bases, the sensitivity is low, and consequently the field noise is high. The gradient noise depends on the noise values of individual sensors B_N and correlation between them. If there is no correlation, we can write (in field units)

$$N\left[\frac{d(B_x)}{dy}\right] = \frac{\sqrt{\left(B_{NB}{}^2 + B_{NA}{}^2\right)}}{d} . \tag{5}$$

For matched sensors, the gradient noise is given by

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$$N\left[\frac{d(B_x)}{dy}\right]=\frac{\sqrt{2}\cdot B_N}{d}. \quad (6)$$

From (6), we can see that the equivalent gradient noise increases with decreasing the gradiometric base d.

2.1 Alternative sensor arrangements for measuring the dB_x/dy type gradient

The disadvantage of the arrangement in Fig. 1 is the large common-mode field seen by both sensors when recovering small horizontal gradients. Although feedback-compensating mode of both sensors can be used, there are disadvantages: short gradiometric bases (tens of mm) cannot be used because of mutual coupling of the compensating fields of respective sensors, and, the signal processing chain still has to have large dynamic range to recover the gradient reading. This was verified with the PCB sensors used in [4].

With the use of a common coil, wound around the two sensors (Fig. 3), new ways to measure the dB_x/dy gradient are possible.

As seen in Fig. 3(a), the output of one sensor can be used to field-compensate its reading with the help of the common coil. In this case, the second sensor senses only the field gradient as most of the common large field is compensated by means of the common coil.

The circuit in Fig. 3(b) adds the possibility to compensate for the homogeneous (average) part of the field. Outputs of the two PSD's are summed (yielding the homogeneous part), this signal is the control signal of the feedback loop. The ½ part of the averaging term is simply part of the feedback-loop gain, so the PSD outputs can be taken directly without any correction for it. The difference between the two sensors is then the dB_x/dy gradient.

Finally, we introduce an original approach of using a common pick-up coil - as seen in Fig. 3(c). The two sensors are excited in opposite directions: in this manner the common flux cancels and only differential flux due to the field gradient can be sensed by the common pick-up coil. The disadvantage of this approach is the large air flux decreasing the sensitivity; however, this configuration is particularly suited for Vacquier sensors: by switching the polarity of the excitation coils, measuring both homogeneous field and dB_x/dy gradient would be possible with no additional wiring.

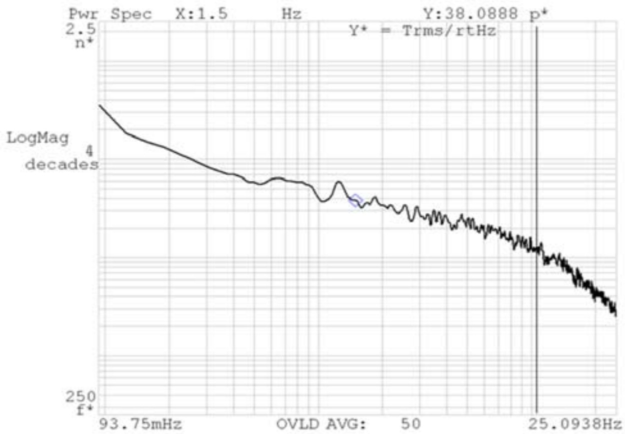

Fig. 2. Noise of individual PCB fluxgate sensor used in the gradiometer.

3 EXPERIMENTAL RESULTS

3.1 The used sensors and their arrangement

We used PCB fluxgate sensors with race-track core, which are a direct development of the sensors presented in [5]. The overall dimensions of each of the sensors are 35x16x1 mm, the sensor core is an amorphous material of Vacuumschmelze, type 6025F. We used this material because of its perspective for low noise; however large excitation current had to be used because of the low permeability of the material (up to 3.6 A p-p with 25% duty-cycle in pulse mode). The sensor noise is shown in Fig. 2 – the 1/f dependence is evident and for frequencies above 20 Hz, the field noise is below 10 pT.

To form the gradiometer, two of the PCB sensors were arranged with a gradiometric base of 20 and 10-mm, respectively (Fig. 1). The larger gradiometric base was chosen to verify the noise parameters; 10-mm base was used together with the common pickup/compensating coil.

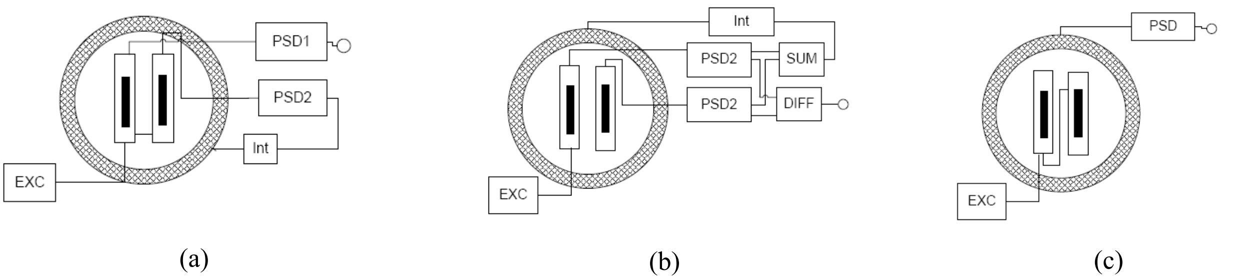

Fig. 3. Special cases of gradiometric arrangement with one common coil – compensating the field sensed by one fluxgate sensor (a), compensating the homogeneous field (b) and serving as pick-up coil for sensors with reversed excitation (c)

3.2 Gradient noise with 20-mm gradient base

We measured the gradient noise by recalculating the field noise by the factor of 1/*d*. The noise was measured in a 6-layer Permalloy shield with Agilent 3570A FFT signal analyzer. The sensors worked in open loop, similar results were obtained for either subtracting outputs of two PSD's (Fig. 4), or for directly subtracting the sensor's output voltages at the lock-in amplifier input. Feedback-compensating mode of both sensors was not used, because of evident mutual influence of the feedback fields. The combined noise spectra of the gradiometer in the range of 100 mHz up to 200 Hz are shown in Fig. 4, showing the noise of 300pT_{rms}/m/√Hz at 200 Hz and 3.7 nT_{rms}/m/√Hz @ 1Hz. As for astatization of the sensors, their open-loop sensitivities were matched by tuning each sensor output voltage.

3.3 Gradient noise 10-mm base and a common compensating coil

In this measurement, the sensors were arranged according to Fig. 3(a). The gradient compensating coil was fed by an integrator consisting of AD8671 operational amplifier and a second SR-830 lock-in amplifier with Fast-X output served as null-detector in the feedback loop using the second sensor. The common coil was wound around both sensors with 200-turns and 30-mm diameter. The gradient response was taken from the first sensor, whose output was demodulated again with SR830. The gradient noise was measured as 8.2 *n*T_{RMS}/m/√Hz @ 1 Hz, thus we can conclude that the noise performance scaled approximately with decreasing the gradiometric base and was not further deteriorated by the compensating feed-back-loop.

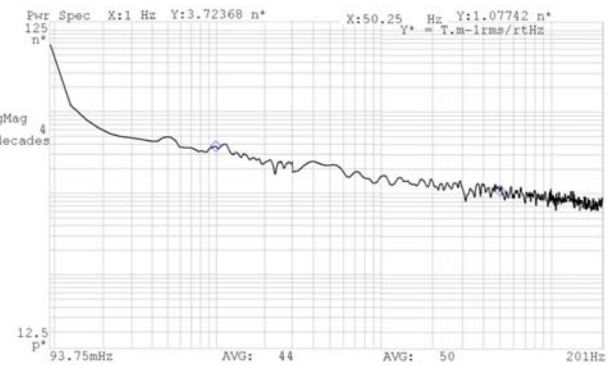

Fig. 4. dB_x/d*y* gradient noise – two PSD outputs subtracted by analog circuitry

3.4 Other configurations

We investigated the novel setup as described in Fig 3(c). The gradient sensitivity was determined by an indirect method – first, the sensitivity of the respective sensor in homogeneous field with that coil was obtained, then it was recalculated to gradient sensitivity according to (4). However, the noise degradation was too high in comparison to other setups (in the order of one magnitude). It was caused by the low sensitivity of the device – preamplifier noise of the lock-in amplifier was dominating (with 5nV/√Hz white noise of the detector, we need a sensitivity of at least of 0.5 V/T/m to reach 10 nT/m/√Hz gradient noise). In the future work, response of Vacquier sensors should be investigated, as they allow much higher coupling of the pick-up coil to the differential flux caused by field dBx/dy gradient, increasing the sensitivity of the sensor.

4 CONCLUSIONS

PCB sensors can perform well when arranged to a dBx/dy type gradiometer, taking the advantage from their flat design minimizing the mutual coupling of the external field-dependent flux (the used core is only one 25um sheet of amorphous material). For a gradiometer with 20-mm-base we measured 1-Hz noise power-spectral density as low as 3.7 nT/m/√Hz. Such noise is directly comparable to that of flat-coil SQUID gradiometer presented in [6] with an area of 200 mm^2, which is similar to the occupied area of the PCB gradiometer head. We also presented a novel configuration of the gradiometer with only one pick-up coil, which should be particularly suitable for Vacquier sensor designs – however those were not investigated in this work. Gradiometer astatization is another important factor and thus the feasibility of each setup to suppress the parasitic homogeneous field response should be further investigated. A highly-homogeneus coil arrangement has to be used to provide negligible field gradient in *y*-direction.

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