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Single-core fluxgate gradiometer with simultaneous gradient and homogeneous feedback operation

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A novel configuration of a single-core gradiometer, utilizing both homogeneous and gradient feedback operation, is presented. The fluxgate gradiometer comprises of a standard pick-up/feedback coil and an additional gradient pickup/feedback coil with two separate electronic blocks. The 40-mm-long gradient coil is concentric and coaxial with the homogeneous pickup/feedback coil: the gradient coil assembly was slipped over an already existing race-track fluxgate sensor. The gradient coil works as a pick-up coil and it also generates the compensating field which well approximates a first-order gradient field with zero spatial-mean value. Together with the compensating field from the homogeneous feedback coil, it is thus always possible to measure in two independent feedback loops the homogeneous and gradient field components. The 1/f gradient noise is 4 nT/m/$\sqrt{\text{Hz}}$ @ 1 Hz, and it can be further improved by separating the gradient feedback and compensating coil. © *2012 American Institute of Physics*. [doi:10.1063/1.3676238]

I. INTRODUCTION

A common type of magnetic gradiometer with fluxgate sensors uses two separate sensor heads, either using two single-axis sensors,[1] or two orthogonal triplets.[2] In both of these cases, the fluxgate sensors typically work in a compensating feedback. The so-called gradiometric base, which is the distance between individual sensor heads, affects resolution and noise when measuring the magnetic field difference and it also defines the rate of approximation of the measured value to the magnetic field gradient. The gradient base is however limited to certain minimum distance (usually tens of centimeters), which is determined mainly by mutual interaction of feedback-compensated sensors.

If the gradiometer is used for suppressing of interfering fields during measurements of weak, point-like sources (e.g., magnetic nanoparticles in medicine), the excessive length of the gradiometric base does not allow to efficiently suppress close sources of interference.[3] Also, it is difficult to measure the magnetic field gradient with a good rate of approximation in the presence of higher-order gradients or if the gradient is weak (i.e., when the reading of the distant sensor is buried in noise). In addition, the angular deviation between the sensor heads results in gross measurement error, and therefore very stable fixture of the sensors is required.

A so-called "single-core" fluxgate gradiometer, i.e., a gradiometer using a single fluxgate sensor and two or more pick-up coils along its core, allows to shorten the gradiometric base. These gradiometers measure the axial gradient of magnetic field and they have been introduced in 1960s.[3] The single-core gradiometer principle was since then used in a rod-type fluxgate gradiometer[4] with separate signal processing blocks, and a race-track type was presented with the pick-up coils antiserially connected.[5] As these gradiometers were operated in an open-loop, their parameters were unstable with temperature and time. In this paper, we introduce a gradient feedback using a special gradient coil. It allows, together with the standard homogeneous feedback, to create a single-core fluxgate gradiometer/magnetometer with promising parameters.[6]

II. SINGLE CORE GRADIOMETER THEORY

If the uniaxial first-order gradient field is measured by two separate and coaxial fluxgate elements of length l, originating at the coordinates L_1 and L_2, respectively, as shown in Fig. 1, we can write[3]

$$\frac{\partial H}{dx} = \frac{dH}{dx} \cong \frac{dH}{L_2 - L_1} = \frac{\int_{L_1}^{L_1+l} H(x)dx - \int_{L_2}^{L_2+l} H(x)dx}{l(L_2 - L_1)}. \quad (1)$$

If the two fluxgate elements are joined together so that the coils share one common fluxgate core ($L_1 + l = L_2$), the single-core gradiometer is established (Fig. 1). Equation (1) is valid also for this case.

The distance $(L_2 - L_1)$ is the "gradient base," d. It is evident that the approximation is approaching the derivative definition only for a very short gradient base. Assuming that each of the two pickup coils is measuring an average of the magnetic field (its integral over the coil length l) with a sensitivity S [V/T] and outputs a voltage V, we can write

$$\frac{1}{d}\left(\frac{V_1}{S_1} - \frac{V_2}{S_2}\right) = \frac{dH}{dx}. \quad (2)$$

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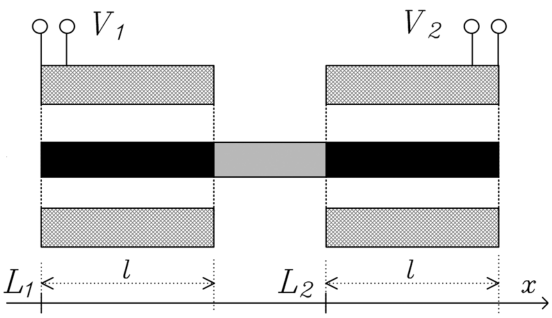

FIG. 1. The coaxial fluxgate gradiometer—two separate core elements, or a single-core type if the two cores are joined.

If the gradiometer is perfectly astatized, i.e., if the two sensitivities are known or equal, the gradiometer output can be rewritten to a simple equation

$$(V_1 - V_2) = S \cdot d \cdot \frac{dH}{dx}. \tag{3}$$

III. THE GRADIENT FEEDBACK

We introduce a gradient-feedback loop, compensating the measured first-order-gradient field. The use of two flux-locked feedback loops in the two pick-up coils would be possible, but they would influence each other and finally the gradiometer output would be difficult to interpret. Suitable coils are already used in MRI,[7] but we found them difficult to manufacture. We thus designed a gradient coil of different type: it consists of equidistant sections of equal width, where the number of turns N in the respective sections almost linearly decreases to the coil center and, after reversing the winding direction in the middle, again increases to the coil end (Fig. 2). The coil bobbin could be easily manufactured by lathe-turning.

In order to increase simplicity and also geometrical stability, this coil is also used as a gradient-pickup coil. For calculating the theoretical output, the Eq. (1) is now rewritten

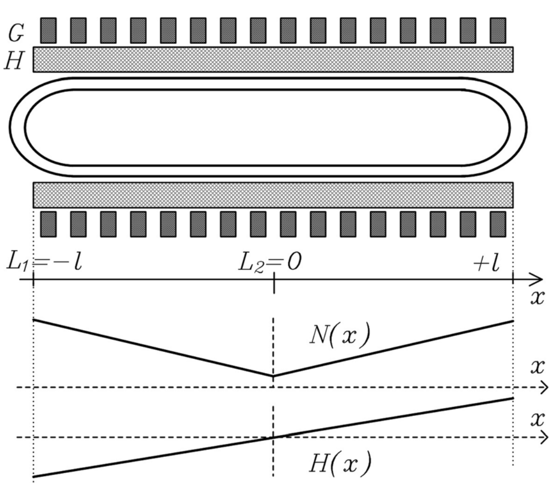

FIG. 2. The single-core gradiometer with homogeneous (H) and gradient feedback coil (G). The number of turns of gradient coil $N(x)$ and gradient field $H(x)$ are shown.

according to Fig. 2, $L_1 = -l$, $L_2 = 0$ and the gradient base $d = (L_2 - L_1) = l$. We further assume that the sensitivity between $\langle -l,0\rangle$ and $\langle 0,l\rangle$ (depending on the number of turns) is a linear function of the position, thus, we can define its spatial derivative $dS(x)/dx = \pm s$. Analogically if the measured field H is only a linear function of x, $\partial H(x)/\partial x = dH(x)/dx = g$. The output voltage V of the gradient pickup coil can be then written as

$$\begin{aligned} V &= \frac{1}{l^2}\left[\int_{-l}^{0} S(x)H(x)dx - \int_{0}^{l} S(x)H(x)dx\right] \\ &= \frac{1}{l^2}\left[\int_{-l}^{0} (-sx \cdot gx)dx - \int_{0}^{l} (sx \cdot gx)dx\right], \end{aligned} \tag{4}$$

and after simple calculation and substitution for $g = \partial H(x)/\partial x$ the output can be rewritten as

$$V = \frac{2}{3} \cdot \frac{\partial H}{\partial x} \cdot s \cdot d. \tag{5}$$

The number of turns of the gradient coil was determined by optimizing the linear series with finite element modeling (FEM) in the *Flux3D* software package in order to obtain best linearity. The 40-mm long gradient coil consisted of 20 sections—the section width was 0.2 and the pitch 1.8 mm. The gradient coil diameter was 10 mm, the coil sections with twice 65, 42, 35, 29, 24, 20, 16, 11, 7, and 3 turns were wound with 0.056 mm diam copper wire (Fig. 3). The gradient coil constant was determined by the FEM analysis as 1.38 $(\mathrm{T.m^{-1}}).\mathrm{A^{-1}}$, and was later verified experimentally by calibrations.

The coil support was swept over an existing tape-wound race-track fluxgate sensor with homogeneous feedback and separate pick-up and feedback coils.[8] The dual electronics is a common type with an integrating regulator in the feedback loop. Both electronics share the same reference signal, however the phase adjustment is done separately: we found it necessary in order to keep the feedback loops stable.

The single-core gradiometer is usually influenced by core inhomogenities, causing false response to homogeneous fields even after careful astatization.[5] We observed that the simultaneous use of a homogeneous feedback loop decreased this effect by keeping the core in zero-average field.

IV. GRADIOMETER PARAMETERS

A coil system producing coaxial gradient and homogeneous field was used for the calibrations. The rectangular

FIG. 3. The fluxgate gradiometer shown with 1-cent coin.

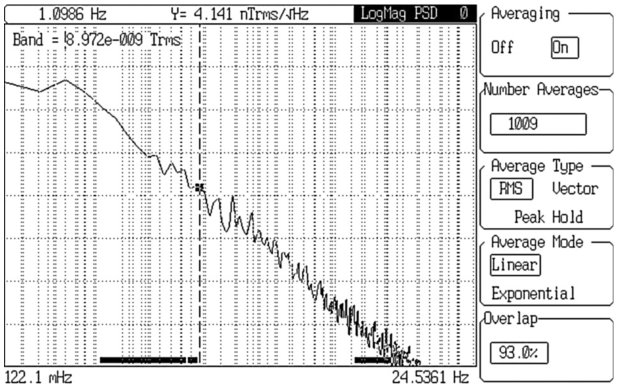

FIG. 4. Noise spectral density of the gradiometer.

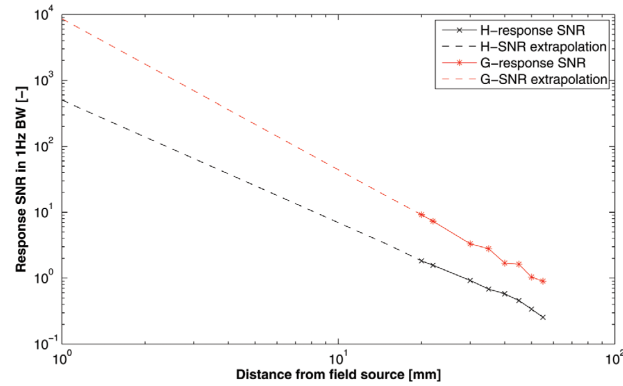

FIG. 5. (Color online) The SNR in 1-Hz bandwidth for homogeneous and gradient readings for a dipole source in an unshielded environment (in log-log scale).

4-coils system[9] assured high field homogeneity. The gradient coil of Maxwell-pair type shared the outer two coil supports of the homogeneous system. During calibration, the gradiometer was positioned to the geometric center of the coils, thus not influencing homogeneous reading by applied gradient field. A quasistatic field (4 Hz) was used for the calibrations.

The sensitivities of the gradiometer were determined as 0.17 $V{\cdot}\mu T^{-1}$ and 0.163 $V{\cdot}(\mu T{\cdot}m^{-1})^{-1}$ and agreed with the coil-constants of both feedback-loop coils. The sensitivity of homogeneous reading on gradient field was found as negligible, but the parasitic sensitivity of gradiometric reading on homogeneous field was significant - 0.2 $(nT.m^{-1}){\cdot}nT^{-1}$. However, as this dependence was found to be linear and the homogeneous field value is measured simultaneously, it should be possible to compensate for this effect.

The noise of the gradiometer was measured in a 6-layer Permalloy shielding can, the noise spectral density is shown in Fig. 4. The 1-Hz noise of 4 $nT{\cdot}m^{-1}/\sqrt{Hz}$ is higher than expected, and should not be influenced by the 10 $pT/\sqrt{Hz}$ "homogeneous" noise of the magnetometer which was used to build the gradiometer. The sensitivity to gradient of 14 $V{\cdot}(T{\cdot}m^{-1})^{-1}$ means that the noise level is already influenced by the electronic noise. Further increasing the sensitivity by increasing the number of turns is, however, possible only when splitting the gradient coil to separate feedback and pickup coils, since its coil constant is already very high: for 1 $nT.m^{-1}$ field gradient, a current of only 0.7 nA is needed.

V. EXPERIMENTAL RESULTS

The gradiometer performance was verified with a 22-turn, 9-mm diam and 3 mm long coil representing a dipole-like source, in an unshielded laboratory environment. The 20-Hz, 50 μA_{rms} coil current resulted in a dipole moment of approximately 0.07 $\mu A.m.^2$ The fluxgate sensor was positioned coaxially to the source and the distance was increased in 5-mm steps from the minimum distance of 20-mm required for true $1/r^3$ field dependence. The signal-to-noise ratio (SNR) was measured for both the homogeneous and gradient output in a 1-Hz bandwidth. Figure 5 shows that the SNR ratio of 10 could be maintained for more than doubled distance in the case of gradiometric output. The power-law extrapolation of the results (Fig. 5, dashed trace) confirms the feasibility of the gradiometer for measuring the response of weak, point-like sources in an unshielded environment.

VI. CONCLUSION

We have presented a single-core gradiometer with both homogeneous and gradient feedback operation, with a gradient base of 40 mm. The linear parasitic sensitivity to homogeneous fields, which is inherent to single-core fluxgate gradiometers, can be reduced by knowing both the homogeneous and gradient field value. The gradiometer noise of 4 $nT{\cdot}m^{-1}/\sqrt{Hz}$ maintains 1/f character over the whole 20-Hz frequency range and it can be further lowered by, e.g., separating the gradient pickup and feedback coil into two coils of different number of turns, allowing to gain on sensitivity. We confirmed that the gradiometer is feasible for measurements of weak point-like sources where minimum sensor distance is required, i.e., in magnetorelaxometry of magnetic nanoparticles.[10] Further suppression of the unshielded, environmental noise could be achieved by simultaneous numerical corrections of the gradient output signal for parasitic sensitivity to homogeneous fields.

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