A miniature and ultralow power search coil optimized for a 20 mHz to 2 kHz frequency range

Eugene Paperno[a)] and Asaf Grosz[b)]
Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 84105, Israel

(Presented 12 November 2008; received 10 September 2008; accepted 21 November 2008; published online 10 March 2009)

We describe the design of a miniature search-coil magnetometer that is optimized in terms of resolution and power consumption for frequencies down to 20 mHz. Our aim is to come close to the size and resolution of fluxgate magnetometers, while reducing the power consumption by at least an order of magnitude. To reach this goal, we attach flux concentrators in the shape of thin disks to a ferrite core, employ an ultralow power, zero $1/f$ noise preamplifier, and finally optimize the diameters of the coil core and wire. The optimized search coil is of 54 mm length, 30 mm outer diameter, and includes 160 000 turns of a 50 μm copper wire. The coil resistance is 86 kΩ, the self-resonance frequency is 250 Hz, and the total weight is 210 g. Our experimental results are in close agreement with the theoretical calculations. For a power consumption of 5 mW, the coil resolution is 14 pT/$\sqrt{}$Hz at 1 Hz and reaches 350 fT/$\sqrt{}$Hz in the frequency range from 100 Hz to 2 kHz. For a power consumption of 0.17 mW, the coil resolution decreases only by 25%. As a result, the new search-coil magnetometer consumes power one to two orders of magnitude less than the commercial fluxgates having similar resolution and size. © *2009 American Institute of Physics*.
[DOI: 10.1063/1.3072718]

I. INTRODUCTION

The fluxgates and search coils are the most widely used magnetometers for space research,[1] magnetic anomaly detection,[2] geophysical prospecting,[3,4] etc. At low frequencies, from tens of millihertz to tens of hertz, fluxgates have better resolution than conventional search coils of comparable size. To provide similar resolution, a search coil should be almost 20 cm long,[5] while the length of fluxgates does not usually exceed a few centimeters.

On the other hand, a very important advantage of the search coils is that they are completely passive sensors: they do not require any internal energy source to convert magnetic field into electrical signal. The only power consumption associated with a search coil is that needed for signal processing.

Power consumption is a very important aspect for applications where magnetometers are powered by batteries and, especially, for those applications where the batteries should last for months or even years. Thus, it becomes very interesting to miniaturize a search coil without sacrificing too much its resolution and to benefit from much lower power consumption.

In this work, we describe a miniature search-coil magnetometer (see Fig. 1) that is optimized in terms of resolution and power consumption for frequencies down to 20 mHz. Our aim is to come close to the size and resolution [15 pT/$\sqrt{}$Hz at 1 Hz (Ref. 4)] of commercial fluxgate magnetometers, while significantly reducing the power consumption.

a)Electronic mail: paperno@ee.bgu.ac.il.
b)Electronic mail: grosz-t@zahav.net.il.

II. METHOD

To reach the goal, we limit the length and the diameter of the search coil (see Fig. 1) by 5.4 and 3 cm, respectively, employ a high-permeability ferrite core, attach to it flux concentrators in the shape of thin disks, employ a zero-drift, zero $1/f$ noise preamplifier, and finally optimize the diameter of the core and the wire.

A. Flux concentrators

It is shown in Ref. 6 that thin, but relatively wide, flux concentrators most effectively increase the flux density in a

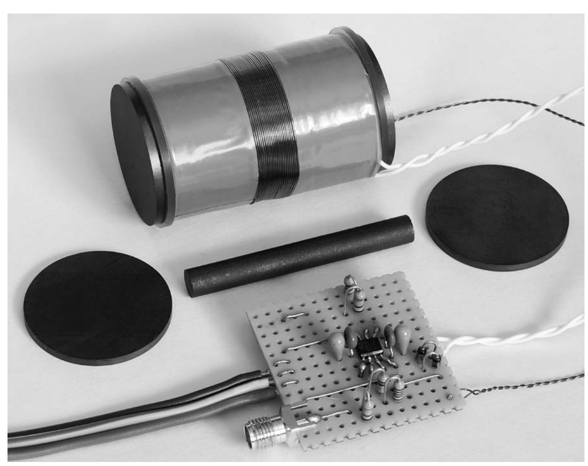

FIG. 1. Experimental model of the search-coil magnetometer. The core and the flux concentrators are also shown separately. The winding seen in the figure is the single-layer feedback coil. The electrostatic shield is not shown.

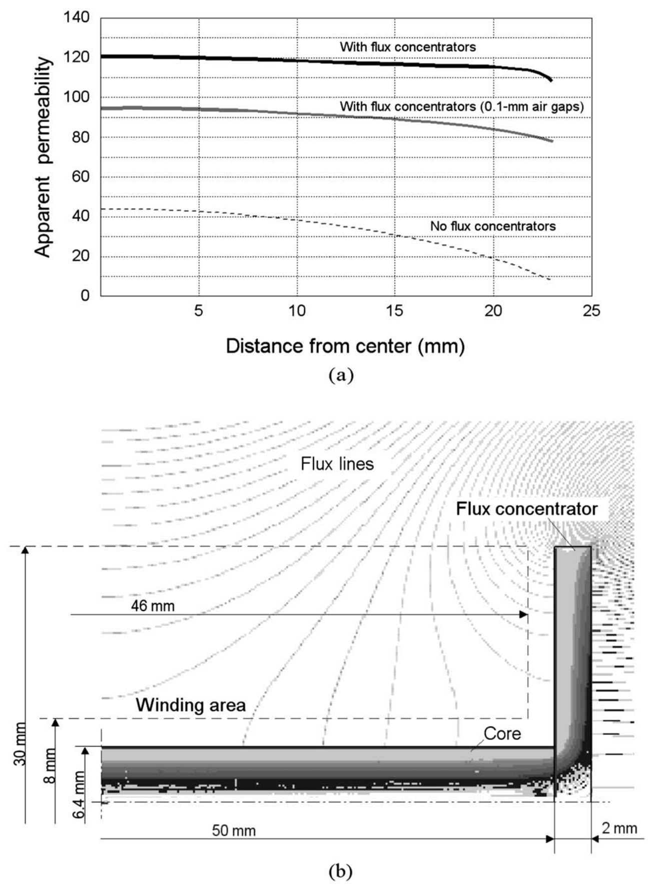

FIG. 2. Magnetic flux seen by the winding. (a) Apparent permeability along the core axis. (b) A magnetic flux within and about the search-coil core and the flux concentrators. Simulated with Maxwell SV. Note that only one-fourth of the search-coil cross section is shown.

miniature magnetic-core antenna. We have used this idea to increase the sensitivity of our search coil without increasing its total length too much.

We have used a commercially available MnZn ferrite core of 6.4 mm diameter and 50 mm length. The relative permeability of the core material (1000–2700 in the −50–100 °C temperature range) is high enough to provide nearly maximum apparent permeability of the core. Our simulations show that increasing the core temperature from −50 to 100 °C results only in a 6.5% change in its apparent permeability.

Figure 2 shows that adding very thin flux concentrators to the ferrite core increases more than threefold its average apparent permeability. One can also see from Fig. 2(a) that even wide, 0.1 mm air gaps between the flux concentrators and the core do not reduce considerably the flux density within the core.

It is also important to note that due to the wide concentrators, the magnetic flux density is more evenly distributed over the core length. We have also found that the flux crossing the winding area in the opposite direction [see Fig. 2(b)] is negligible compared to that inside the core. All this allows us to effectively use for winding the entire volume between the flux concentrators, excluding the volume occupied by the core and the reel.

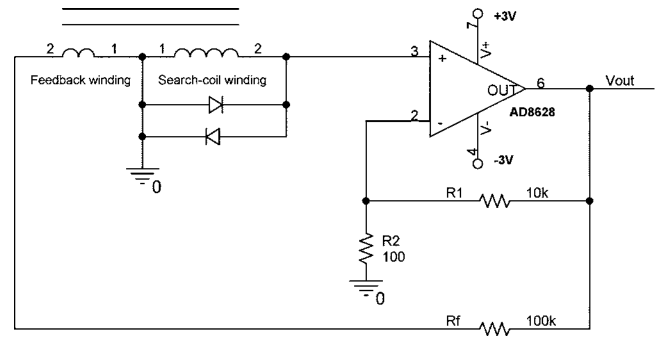

FIG. 3. Circuit diagram of the search coil and preamplifier.

B. Zero-drift preamplifiers

Conventional search-coil preamplifiers consume too much power and have too large $1/f$ noise to meet our requirements. In this work we employ for the first time, to the best of our knowledge, zero-drift operational amplifiers to design the search-coil preamplifier (see Fig. 3).

Such operational amplifiers have only recently become commercially available and possess absolutely zero $1/f$ noise and consume ultralow power. We have tested two of them: the AD8628 and the OPA333. The AD8628 has a 22 nV/$\sqrt{\text{Hz}}$ voltage noise, 5 fA/$\sqrt{\text{Hz}}$ current noise, and 5 mW power consumption. The OPA333 has a 55 nV/$\sqrt{\text{Hz}}$ voltage noise, 100 fA/$\sqrt{\text{Hz}}$ current noise, and 85 μW power consumption.

C. Optimization of the diameter of the core and the wire

The search-coil resolution can be found as follows:[1,5]

$$B_{\min} = \frac{e_n}{2\pi f N S \mu_{\text{app}}}, \tag{1}$$

where $B_{\min}$ is the noise equivalent magnetic induction (the spectral density of the smallest magnetic field that could be detected beyond the noise), f is the frequency, N is the number of turns, S is the cross section of the core, μ_{app} is the core apparent permeability[1]

$$\mu_{\text{app}} = \frac{\mu_r}{1 + \mu_r H_D \cdot d^2/D^2}, \tag{2}$$

where μ_r is the relative permeability of the core material, H_D is the demagnetizing factor, d is the core diameter, D is the diameter of the flux concentrators. e_n in Eq. (1) is the voltage spectral density of the magnetometer total noise,

$$e_n = \sqrt{4kTR + e_{\text{amp}}^2}, \tag{3}$$

where $4kTR$ is the voltage spectral density of the coil thermal noise, k is the Boltzmann constant, T is the absolute temperature, R is the coil resistance, and e_{amp} is the voltage spectral density of the amplifier total noise referred to its input.[5,7] Equation (2) was used in Ref. 1 for cone-shaped flux concentrators. Our numerical calculations, done with the help of Maxwell SV, as well as our experiments have shown the applicability of Eq. (2) to the disk-shaped flux concentrators. The difference between the analytical results and that ob-

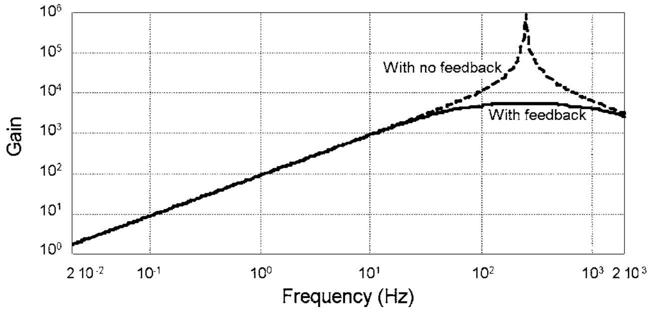

FIG. 4. Search-coil frequency response.

tained both numerically and experimentally was within 10%.

The aim of the optimization is to find the values of N and S that minimize B_{min} in Eq. (1) for a given search-coil size, type of preamplifier, and minimum acceptable wire diameter. Our simulations are solely based on analytical Eqs. (1)–(3), and this helps us to find the best coil configuration. Other works, for example,[1] do not optimize all the coil parameters regarding some of them as fixed factors.

We have found that any core material with permeability greater than 1000 bring the sensor resolution near to its maximum value, provided of course that the core diameter was optimized. For the preamplifiers mentioned in Sec. II B, the optimized search coil includes 160 000 turns of a 50 μm copper wire. The coil resistance is 86 kΩ, the self-resonance frequency is 250 Hz, and the total weight is 210 g. A magnetic feedback was used to flatten the coil response (see Fig. 4) and increase the magnetometer stability. The feedback coil (see Fig. 1) was wound with 23 turns of a 0.31 mm copper wire.

III. EXPERIMENTAL RESULTS

All the measurements were performed inside a magnetic shield using a calibrated solenoid to apply the external field. The experimental results we have obtained are in close agreement with our theoretical calculations and simulations except for the frequency range near the resonance. We assume that this disagreement near the resonance is caused by the incompleteness of the simplified coil model.

For the AD8628 amplifier, the magnetometer noise (see Fig. 5) almost linearly decreases with frequency from 1 nT/$\sqrt{}$Hz at 20 mHz to 1.4 pT/$\sqrt{}$Hz at 10 Hz. At frequencies from 100 Hz to 2 kHz, it reaches 350 fT/$\sqrt{}$Hz.

At 1 Hz, we have obtained a 14 pT/$\sqrt{}$Hz resolution at power consumption of as low as 5 mW. We have also found that using an OPA333 preamplifier instead of an AD8628 decreases the power consumption down to 0.085 mW but increases the magnetometer noise by 50%, up to 21.3 pT/$\sqrt{}$Hz at 1 Hz. This is because of the higher noise of the OPA333. To reach a better resolution at some expense of power consumption, we used two OPA333 connected in parallel.[7] This connection doubles the total power consumption but decreases the voltage noise of the preamplifier by a factor of $\sqrt{2}$. As a result, it is possible to reach a 0.17 mW power consumption, while increasing the magnetometer

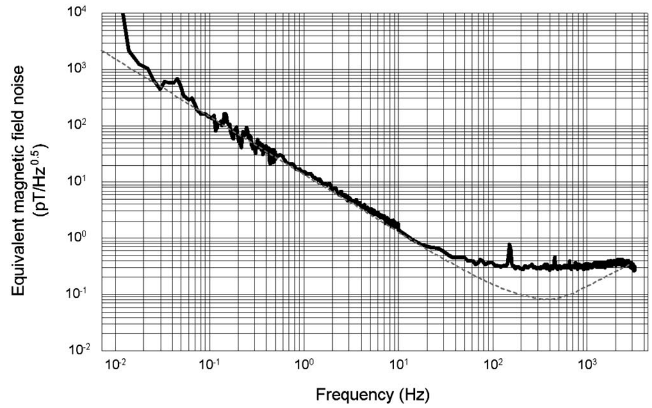

FIG. 5. Equivalent magnetic field noise of the search-coil magnetometer: the solid line represents the measurements and the dashed line represents the theoretical response.

noise only by 25%, from 14 to 17.5 pT/$\sqrt{}$Hz at 1 Hz. The magnetometer nonlinearity errors measured for the entire frequency range in Fig. 5 was below 1%.

IV. CONCLUSIONS

An attempt has been done to develop an ultralow power search-coil magnetometer with both the size and resolution approaching that of commercially available fluxgates. In order to increase the flux inside the coil core and most effectively use its length for winding, very thin, disk-shaped flux concentrators were attached to the core. The employment of standard, disk-shaped flux concentrators not only helps us to keep the coil length short but also allows us to assemble the magnetometer from commercially available parts. In order not to decrease the search-coil resolution at low frequencies, a zero-drift, zero $1/f$ noise preamplifier was used. The magnetometer resolution was optimized for frequencies down to 20 mHz. The resolution obtained at 1 Hz matches that of commercially available fluxgates,[4,8] while the power consumption has been decreased by an order of magnitude for the preamplifier employing an AD8628 operational amplifier and by two orders of magnitude for the preamplifier employing two OPA333 connected in parallel.

ACKNOWLEDGMENTS

This work was supported in part by the Analog Devices, Inc., National Instruments, Inc., and Ivanier Center for Robotics Research and Production Management.

[1]C. Coillot, J. Moutoussamy, P. Leroy, G. Chanteur, and A. Roux, Sens. Lett. **5**, 167 (2007).
[2]A. Sheinker, A. Shkalim, N. Salomonski, B. Ginzburg, L. Frumkis, and B.-Z. Kaplan, Sens. Actuators, A **138**, 105 (2007).
[3]V. Korepanov, R. Berkman, L. Rakhlin, Y. Klymovych, A. Prystai, A. Marussenkov, and M. Afanassenko, Measurement **29**, 137 (2001).
[4]Lviv, Center of Institute of Space Research, LEMI-019 and LEMI-118, available at http://www.isr.lviv.ua/.
[5]H. C. Séran and P. Fergeau, Rev. Sci. Instrum. **76**, 044502 (2005).
[6]K. Abe and J. Takada, IEICE Trans. Commun. **90-B**, 123 (2007).
[7]W. M. Leach, Proc. IEEE **82**, 1515 (1994).
[8]Bartington Instruments, Mag-01MS, available at www.bartington.com.