Compensation of the thermal drift in the sensitivity of fundamental-mode orthogonal fluxgates

Anton Plotkin, Eugene Paperno,[a] and Alexander Samohin
Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 84105, Israel

Ichiro Sasada
Department of Applied Science for Electronics and Materials, Kyushu University, Kasuga-Koen, Kasuga-Shi, Fukuoka 816-850, Japan

(Presented on 1 November 2005; published online 19 April 2006)

A method is suggested that reduces the temperature coefficient of the sensitivity of fundamental-mode orthogonal fluxgates by an order of magnitude. For the background magnetic fields greater than 20 μT, the method provides even better reduction, down to 100 ppm/°C, which is comparable with the temperature coefficient of conventional parallel-type fluxgates operated in closed-loop configuration. The fluxgate prototype has demonstrated a 20-fold reduction of the thermal drift in its sensitivity. The suggested method is solely based on the processing of signals generated by fundamental-mode orthogonal fluxgates in open-loop configuration and does not require any additional hardware. This makes the *open*-loop fundamental-mode orthogonal fluxgates competitive with closed-loop parallel-type ones in terms of both resolution and accuracy, while still keeping them simpler than the parallel fluxgates. © *2006 American Institute of Physics*.
[DOI: 10.1063/1.2164429]

I. INTRODUCTION

The main advantage of orthogonal fluxgates is their simplicity and small size compared to parallel-type fluxgates. An orthogonal fluxgate[1–4] (see Fig. 1) consists of a single magnetic core and a single pickup coil, while a parallel fluxgate[3,5] is usually built by a differential scheme and employs either two separate cores or a single ring core. It also employs an excitation coil, which is absent in the simplest orthogonal fluxgates.

Conventional fluxgates, either parallel or orthogonal, are usually operated in the second-harmonic mode.[5] The fluxgate core is excited with a periodic bipolar magnetic field and the output signal is detected at a frequency that is twice the excitation one.

The main disadvantage of conventional orthogonal fluxgates operated in the second-harmonic mode is their relatively large offset and inferior noise performance relative to the parallel fluxgates.[5]

Recently suggested fundamental-mode operation[1] of orthogonal fluxgates provides nearly zero offset and a very low, 10 pT/Hz$^{0.5}$, noise.[2] This makes fundamental-mode orthogonal fluxgates competitive in resolution with the state of the art parallel-type ones.

However, the accuracy of orthogonal fluxgates still remains below that of parallel fluxgates. The main factor limiting the accuracy of orthogonal fluxgates is the large temperature coefficient of their sensitivity (TCS): 5000–10 000 ppm/°C.

Such a large TCS restricts the applications of orthogonal fluxgates to those where high resolution is not needed or to those where the ambient field is virtually zero, such that in the closed-lop configuration.

Fluxgates with a large TCS are not effective in applications where a weak magnetic field should be measured against the background of a relatively large one, such as active shielding and magnetic tracking. Closed-lop configuration in these applications cannot be used due to the undesirable interference of the feedback field.

Another reason not to have a feedback loop in a much wider variety of applications is to reduce the power consumption. In this case, the dynamic range cannot be made large. However, there are many cases where relatively week, nanotesla to 40 μT (roughly the earth's magnetic field), fields to be assessed.

In the present work we suggest a method that reduces the TCS of *open*-loop fundamental-mode orthogonal fluxgates down to the level comparable with that of conventional closed-loop parallel-type fluxgates[3] (30–50 ppm/°C). The suggested method is solely based on the processing of signals generated by fundamental-mode orthogonal fluxgates in open-loop configuration and does not require any additional

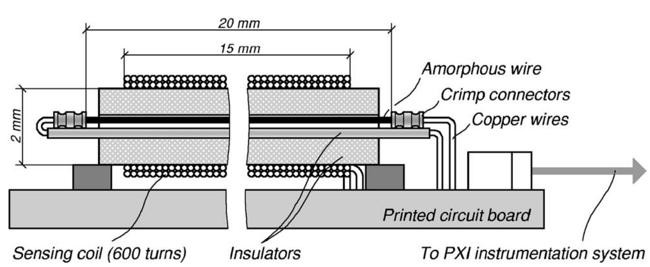

FIG. 1. Orthogonal fluxgate.

[a]Electronic mail: paperno@ee.bgu.ac.il

hardware. This makes the open-loop fundamental-mode orthogonal fluxgates competitive with the closed-loop parallel-type ones in terms of both resolution and accuracy, while still keeping them simpler than parallel fluxgates.

II. ORTHOGONAL FLUXGATE

The orthogonal fluxgate (see Fig. 1) was fabricated with a Co-based amorphous wire (AC-20-type made by Unitika) of a 120 μm diameter and 20 mm length. The sensing coil was wound with 600 turns of a 50 μm copper wire.

The excitation electric current was applied directly to the fluxgate core. The external field was applied along the core with a calibrated solenoid.

A National Instruments PXI modular instrumentation system was used to apply the external magnetic field, excite the fluxgate core, and process the fluxgate output.

The fluxgate was placed in a magnetic shield and heated with hot airflow. In order not to heat the shield, it was thermally isolated from the fluxgate and the air manifolds.

III. FUNDAMENTAL-MODE OPERATION

The fundamental mode[1] differs from the second-harmonic one[4] in adding a flipping dc bias to the ac excitation [see Fig. 2(a)] and detecting the fluxgate output at the ac-excitation fundamental rather than at its second harmonic.

The flipping dc bias causes corresponding flipping of the fluxgate transfer characteristic [see Fig. 2(b)]: the fluxgate sensitivity changes its sign, but the offset remains unchanged.[1] Thus, theoretically offset-free measurements

$$V_{\text{diff}}(H_a,T) = \frac{V_p(H_a,T) - V_n(H_a,T)}{2}, \quad (1)$$

can be extracted [see Fig. 2(c)], where $V_p(H_a,T)$ and $V_n(H_a,T)$ are the averaged amplitudes of the fluxgate response corresponding to two successive polarities of the dc bias, H_a is the applied field, and T is the temperature of the fluxgate core.

Figures 2(b) and 2(c) show that both the slope and the offset of the fluxgate transfer characteristics are affected by temperature. We attribute this effect to the temperature dependence of the fluxgate core anisotropy.

In order to better illustrate the behavior of the offset-free transfer characteristic $V_{\text{diff}}(H_a,T)$, we show in Fig. 2(d) its relative deviations from the idealized linear, temperature-independent transfer characteristic $V(H_a)=1.5\times10^3 H_a$ that corresponds to the maximum measured value (1.5 mV/μT) of the fluxgate sensitivity.

The relative deviations of the $V_{\text{diff}}(H_a,T)$ transfer characteristics from the ideal one are caused by both the inherent nonlinearity of the core magnetization and by temperature. The maximum deviation caused by the heating alone is about 98×10^3 ppm. This corresponds to an about 6500 ppm/°C TCS.

IV. COMPENSATION METHOD

It is important to note that the $V_{\text{diff}}(H_a,T)$ characteristic is a two-dimensional function. To compensate its tempera-

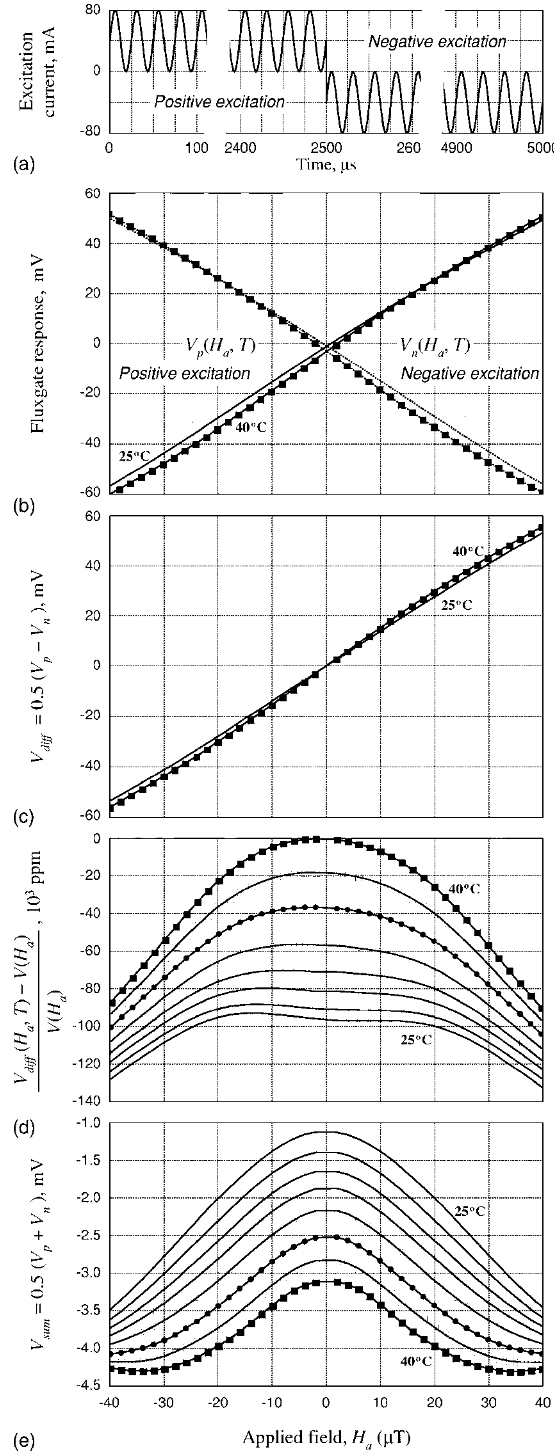

FIG. 2. The effect of temperature on the fluxgate characteristics. (a) Waveform of the excitation current. (b) The transfer characteristics obtained for different polarities of the excitation current. (c) The offset-free transfer characteristics. (d) Relative deviations of the offset-free characteristics from the idealized one, $V(H_a)=1.5\times10^3 H_a$, that corresponds to the maximum measured value (1.5 mV/μT) of the fluxgate sensitivity. (e) The $V_{\text{sum}}=0.5(V_p+V_n)$ characteristics. (1 μT=10 mOe)

ture dependence and nonlinearity, one more independent fluxgate transfer characteristic, $V=f(H_a,T)$, is needed.

This characteristic can be obtained as follows:

$$V_{\text{sum}}(H_a,T) = \frac{V_p(H_a,T) + V_n(H_a,T)}{2}. \quad (2)$$

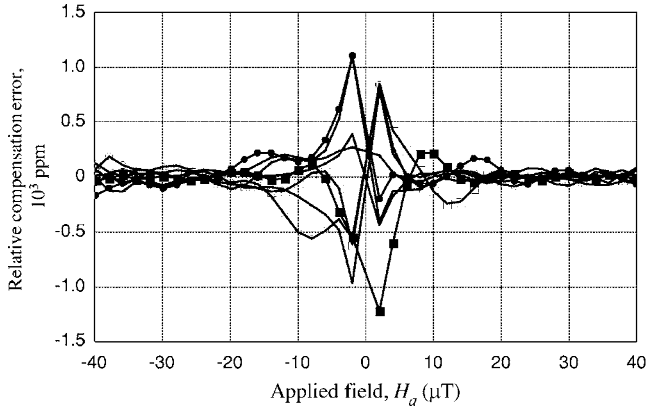

FIG. 3. Relative compensation error as a function of the applied field and temperature.

It is interesting to note that compared to the offset-free characteristic $V_{\text{diff}}(H_a,T)$, the $V_{\text{sum}}(H_a,T)$ characteristic [see Fig. 2(e)] carries information about the fluxgate offset, which can be measured as $V_{\text{sum}}(0,T)$.

Analyzing the behavior of the $V_p(H_a,T)$ and $V_n(H_a,T)$ characteristics in Fig. 2, one can conclude that a unique pair of V_{diff} and V_{sum} corresponds to each pair of H_a and T. This means that there exists a unique transfer characteristic that converts the measured V_{diff} and V_{sum} values into the applied field

$$\hat{H}_a(V_{\text{diff}},V_{\text{sum}}) = \sum_{i=0}^{n}\sum_{j=0}^{m} a_{ij}V_{\text{diff}}^{i}V_{\text{sum}}^{j}. \tag{3}$$

To find the polynomial coefficients a_{ij} in (3), we have measured values of H_a, V_{diff}, and V_{sum} signals at different temperatures [see Figs. 2(d) and 2(e)] and then have solved a system of $n\times m$ independent equations.

To evaluate the compensation errors, we have computed in Fig. 3 the relative difference between the computed according to (3) and measured values of the applied field H_a. We have found that $n>7$ and $m>9$ do not help decrease the compensation errors.

Comparing the results of Fig. 2(d) and Fig. 3, one can see that the suggested method reduces the fluxgate TCS by an order of magnitude. For the background fields greater than 20 μT, the TCS is reduced still further: by a factor of 65, from 6500 ppm/°C down to 100 ppm/C.

To illustrate the effectiveness of the method, we have detected a squarewave magnetic field of a 10 nT amplitude against a 10 μT background field and compared in Fig. 4 the results obtained with and with no compensation. Figure 4 demonstrates a 20-fold reduction of the thermal drift in the fluxgate sensitivity.

V. CONCLUSIONS

The suggested method reduces the TCS of fundamental-mode orthogonal fluxgates by an order of magnitude. For the background fields greater than 20 μT, the method provides even better reduction, down to 100 ppm/°C. This is comparable with the TCS of conventional closed-loop parallel-type fluxgates. The fluxgate prototype has demonstrated a 20-fold reduction of the thermal drift in its sensitivity.

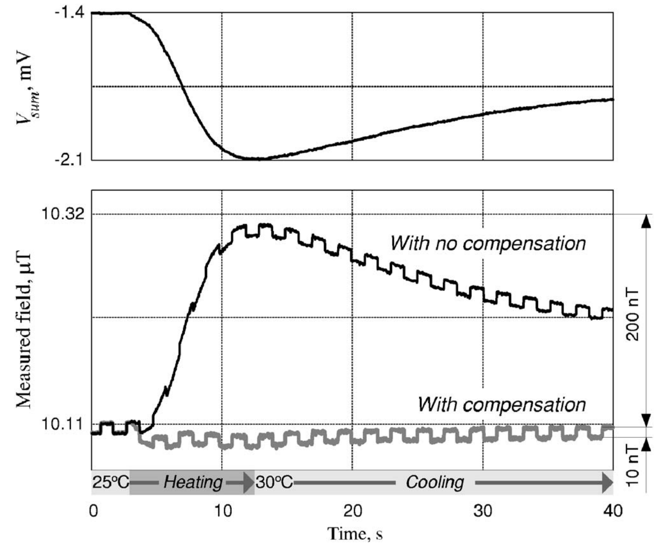

FIG. 4. Example of the compensation of the thermal drift in the fluxgate sensitivity.

The suggested method is solely based on the processing of signals generated by fundamental-mode orthogonal fluxgates in open-loop configuration and does not require any additional hardware. This makes the open-loop fundamental-mode orthogonal fluxgates competitive with the closed-loop parallel-type ones in terms of both resolution and accuracy, while still keeping them simpler than parallel fluxgates.

The main factor limiting the effectiveness of the temperature compensation appears the aftereffect and the fluctuations of the fluxgate core properties with time.

The employment of more stable core materials and more advanced fitting methods[6] would improve the temperature compensation effectiveness.

The advantages of fundamental-mode orthogonal fluxgates combined with the inherent simplicity of the orthogonal fluxgate mechanism make them very promising for the construction of miniature and inexpensive, low-power, high-resolution, stable magnetometers.

ACKNOWLEDGMENTS

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

[1]I. Sasada, J. Appl. Phys. **91**, 7789 (2002).
[2]E. Paperno, Sens. Actuators, A **116**, 405 (2004).
[3]P. Ripka, Sens. Actuators, A **106**, 8 (2003).
[4]T. M. Palmer, Proceedings of the Institution of Electrical Engineers, **100**, Pt. II (London, 1953), pp. 545–550.
[5]P. Ripka, Sens. Actuators, A **33**, 129 (1992).
[6]J. M. D. Pereira, P. M. B. S. Girão, and O. Postolache, IEEE Instrum. Meas. Mag. **4**, 26 (2001).