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Noise investigation of the orthogonal fluxgate employing alternating direct current bias

Eyal Weiss[1,2,a)] and Eugene Paperno[1]
[1]Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel
[2]Applied Physics Division, Soreq NRC, Yavne 81800, Israel

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Alternating dc bias enables eliminating offset in orthogonal fluxgates operated in fundamental mode. However, the alternating dc bias reversals increase the fluxgate magnetic noise. It is shown in this work that the excess magnetic noise is related to the dynamics of the magnetic domains in the fluxgate core. The alternating dc bias reverses the fluxgate core magnetization causing nucleating domains and generating an intensive magnetic noise. To suppress the excess noise, two methods are suggested. The first method is based on eliminating the adequate parts of the fluxgate output appearing right after each dc bias reversal. The second method is based on introducing idle intervals between the dc bias reversals and subsequently eliminating the corresponding idle samples in the fluxgate output. Both methods suppress one and the same noise attributed to the domains relaxation dynamics and, hence, lead to similar results. In both cases, the fluxgate noise has been reduced down to its value in the excitation mode, where the dc bias is constant, and there are no reversals in the fluxgate core magnetization. The second method, however, has an advantage of lower power consumption due to the absence of both the ac and dc excitations during the idle intervals. Reducing the excess noise in the alternating dc bias mode, paves the way for developing a low-noise orthogonal fluxgates with practically no offset.
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I. INTRODUCTION

Fluxgates gates are probably the most practical precision magnetometers due to their high sensitivity, relatively low power consumption, and high stability.[1,2] The simplest fluxgates are those of orthogonal type: they comprise a single magnetic core and a pick-up coil. There are no excitation coils; the excitation electric current is applied directly to the core. The main advantages of orthogonal fluxgates are their simplicity and small size compared to parallel fluxgates that are built by a differential scheme and employ either two separate cores or a single ring core, a pick-up coil, and either two or one excitation coil, depending on the number of cores.

Conventional parallel and orthogonal fluxgates are operated in second-harmonic mode[3,4]: 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.

Orthogonal fluxgates can also be operated in fundamental mode, where either a constant[5–7] or alternating[8,9] dc bias is added to the ac excitation. Fundamental mode operation doubles the fluxgate sensitivity, significantly reduces noise, in the case of a constant dc bias, and enables the compensation of offset, in the case of an alternating dc bias. A constant dc bias keeps the fluxgate continuously saturated, and magnetization varies mostly by coherent rotation.[3,4] Practically no magnetic noise is generated in this case, and the fluxgate sensitivity threshold reaches 10 pT/$\sqrt{\text{Hz}}$ at 1 Hz.[5–7] An alternating dc bias flips the fluxgate transfer characteristic but leaves its offset unchanged, thus, the offset can be compensated by subtracting the fluxgate outputs corresponding to the different polarities of the dc bias.[8–11] It has been observed, however, that the alternating dc bias substantially increases the fluxgate noise.

In this work, we investigate the origin of the excess noise in orthogonal fluxgates with an alternating dc bias and suggest methods for its reduction down to the level of that in the orthogonal fluxgates with a constant dc bias.

II. EXPERIMENTAL SETUP

The fluxgate prototype (see Fig. 1) comprises a U-shape Co-based amorphous wire (AC-20 type made by Unitica), with a 120 μm diameter and 50 mm in length, and a sensing coil, with 180 turns of a 45-μm copper wire. The excitation

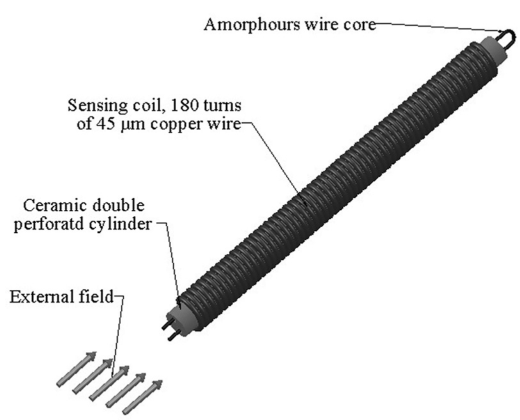

FIG. 1. Orthogonal fluxgate employing an amorphous wire.

[a)]Electronic mail: eyal_we@soreq.gov.il.

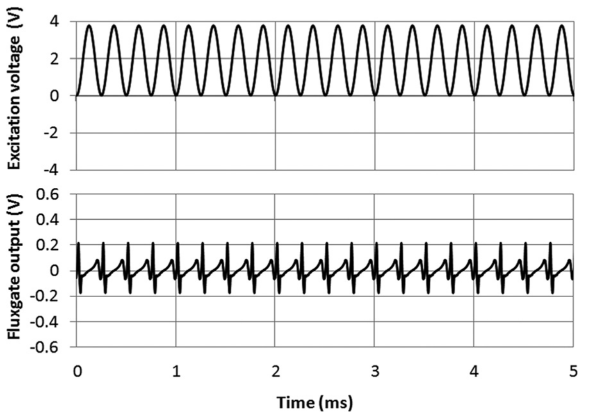

FIG. 2. Excitation with a constant dc bias: the excitation waveform (top) and the fluxgate output (bottom). The dc bias has a 1.9 V magnitude, and the ac excitation part has a 1.9 V amplitude and a 4 kHz frequency (0.25 ms period).

current is applied directly to the wire, and the fluxgate output is measured at the sensing coil terminals.

The fluxgate core is excited by a TTI TG4001 arbitrary function generator. The external magnetic field is applied by a calibrated solenoid. The fluxgate and the solenoid are placed inside a three-shell magnetic shield to reduce the ambient magnetic noise. The fluxgate output is amplified by a low-noise INA103 instrumentation amplifier and sampled with an NI PXI-4461, 24 bit, 204.8 ksps data acquisition module. The excitation is synchronized with the acquisition module clock. All the measurements are postprocessed in LabView.

The fluxgate excitation modes with a constant and alternating dc biases are shown in Figs. 2 and 3. The ac part of the excitation voltage has a minus cosine waveform to smooth the transitions during the dc bias reversals. The amplitude of the ac excitation current is 80 mA and the dc bias current value is 40 mA. The ac excitation fundamental is set at 4 kHz, with a period of $t = 0.25$ ms, and the period of the alternating dc bias is set at $T = 20t$ (see Fig. 4).

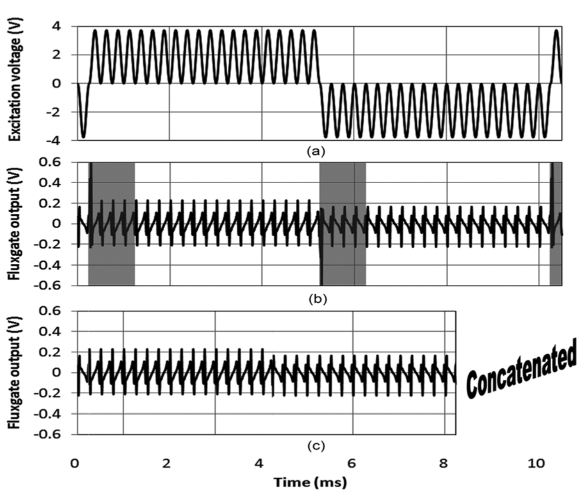

FIG. 3. Excitation with alternating dc bias: the excitation waveform (a) and the fluxgate output (b). Compared to Fig. 2, the dc bias reverses its polarity every $T = 20t$ excitation cycles. The signal parts shaded by gray ($4t$ segments in this example) were omitted from the fluxgate output and the remaining parts were concatenated (c).

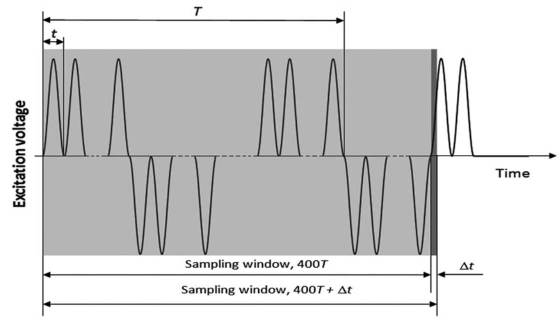

FIG. 4. Duration of the fluxgate output sampling window as compared to the excitation waveform: t is the period of the ac excitation cycle, T is the period of the alternating dc bias, and Δt is the deviation of the sampling window duration causing spectral leakage.

A. Measurements synchronization

No spectral leakage is present in the alternating dc bias mode if the sampling window duration is an integer multiplication of the ac excitation period, t, and the period, T, of the alternating bias reversals (see Fig. 4). To evaluate the effect of the spectral leakage, we introduced deviations, Δt, of the sampling window duration from its spectral-leakage-free value of $400T$ (see Fig. 4). As one can see from the dashed curves in Fig. 5, even very small Δt causes a substantial rise of the floor level of the fluxgate output spectrum near the excitation fundamental.

B. Excess noise suppression

The equivalent magnetic noise at the fluxgate input was found by dividing the output voltage noise by the fluxgate sensitivity. For $\Delta t = 0$ (see Fig. 4) and a sampling window duration of $400T$, the fluxgate noise is at its minimum: 29 pT/$\sqrt{\text{Hz}}$ at a 1 Hz from the excitation fundamental. However, this noise value is still greater than that in the constant dc bias mode: 22 pT/$\sqrt{\text{Hz}}$. We attribute the difference in the above-mentioned noise values to the excess noise caused by the domain dynamics of the fluxgate magnetic core. As mentioned in Sec. I, reversing the dc bias polarity in the alternating dc bias mode changes the direction of the fluxgate core magnetization and generates a strong excess magnetic noise.[8–11] It takes some time[12,13] for the excess magnetic noise to relax, depending on the dynamics of the magnetic domains nucleated in the fluxgate core. As a result, the corresponding portions of the

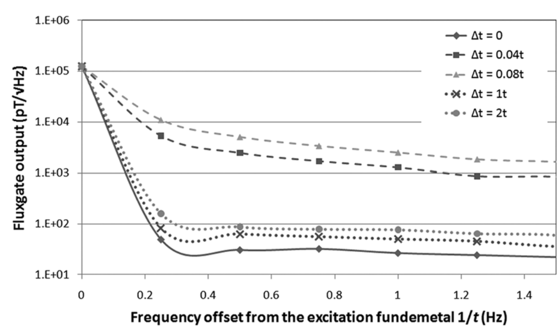

FIG. 5. Amplitude spectral density of the fluxgate output as a function of the sampling window duration: even very small deviations Δt of the sampling window duration from its spectral-leakage-free value of $400T$ (see Fig. 4) cause significant increase in the floor of the fluxgate output spectrum (dashed curves). Deviations from T in the multiplications of t appear as dotted curves.

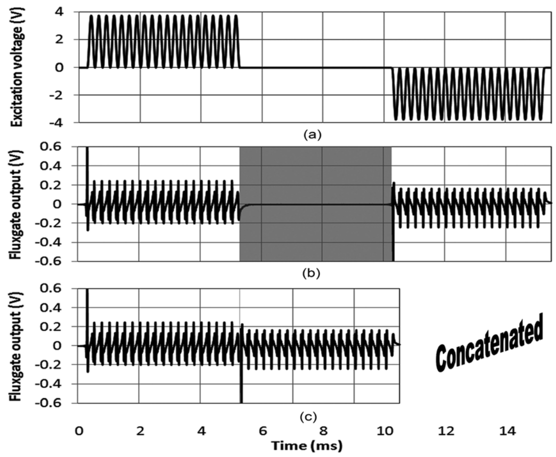

FIG. 6. Excitation with idle intervals between the dc bias reversals: the excitation waveform (a) and the fluxgate output (b). The signal parts shaded by gray ($10t$ segments in this example) were eliminated from the fluxgate output and the remaining signal parts were concatenated (c).

fluxgate output appearing right after the dc bias reversals becomes "contaminated" with excess noise.

To eliminate the excess noise, we employed two different methods. In the first method, the "contaminated" parts were simply trimmed away from the fluxgate output. The trimmed span, T_r, varied from 0 to $10t$. The remaining parts of fluxgate output were concatenated. An example for $T_r = 4t$ is shown in Fig. 3(b), and the concatenated output is shown in Fig. 3(c). The fluxgate sensitivity was measured at the effective excitation frequency f_{ex1} that differs from the frequency of the ac bias, f_{ex}, because of the compression of the fluxgate output by concatenation:

$$f_{ex1} = f_{ex} \pm \frac{T}{T_r} f_a, \tag{1}$$

where f_a is the frequency of the applied magnetic field.

The diamond symbols in Fig. 7 illustrate the noise reduction as a function of T_r. It shows that the excess noise is suppressed (approaches the noise in the constant dc bias mode) for $T_r > 4t = 1$ ms. Additional extending of T_r does not further reduce the fluxgate output noise.

The second method for suppressing the excess noise is based on adding idle intervals T_i between the dc bias reversals (see Fig. 6), allowing the domains to relax.[13] Subsequently, the corresponding idle samples are eliminated in the fluxgate output.[13] The idle intervals were increased gradually from $T_i = 0$ to $T_i = 20t$. An example of adding an idle interval for the case of $T_i = 10t$ can be seen in Fig. 6(b), where the added intervals are marked in gray. The fluxgate output voltage after removing the idle intervals and concatenation can be seen in Fig. 6(c). The sensitivity in this case was measured at the effective excitation frequency f_{ex2}:

$$f_{ex2} = f_{ex} \pm \frac{T + T_i}{T} f_a \tag{2}$$

Figure 7 shows that the second method reduces the excess noise almost down to its level in the constant dc bias mode if the suppression time T_i is greater than $9t = 2.25$ ms. Hence, one can conclude that it takes 2.25 ms for the magnetic noise to relax.

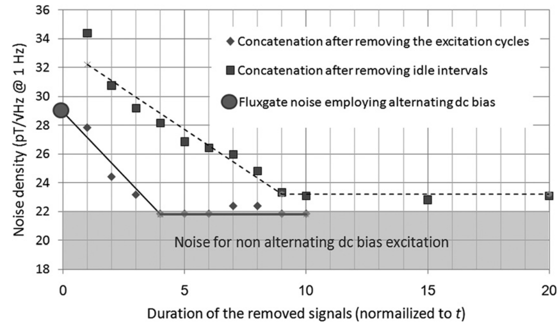

FIG. 7. Flux gate noise spectrum as a function of the fluxgate output suppressing. The noise level in the alternating dc bias mode with no suppressing of the fluxgate output (●). The noise as a function of the suppressed parts in the fluxgate output appearing right after each dc bias reversal (■). The noise as a function of the idle intervals between the dc bias reversals and subsequent suppressing the corresponding idle samples in the fluxgate output (◆).

The approximately twofold difference in the noise suppressing times implies that the ac bias reduces the magnetic domain relaxation time. The slight difference in the noise levels between the methods may be attributed to the "jump" in the fluxgate output following the idle interval that is not trimmed out [see Fig. 6(c)] in the second method. Whereas in the first method, the dc bias reversal occurrence is removed [see Fig. 3(c)]. Additionally, as the wire core is excited in a noncontinuous mode, less power is consumed by the core.[13]

III. CONCLUSION

It has been shown that the fluxgate excess noise related to the magnetic domain dynamics can be avoided either by excluding the parts of the fluxgate output appearing right after the dc bias reversals or by delaying the ac excitation parts with the opposite dc bias. In the processing of the fluxgate output, we concatenate the output parts that do not contain the excess noise. As a result, the excess noise is practically eliminated, and the fluxgate total noise approaches that in the constant dc bias mode.

Suppressing the excess noise in the alternating dc bias mode is important because in this mode the fluxgate offset can be eliminated.[8–11] Thus, it becomes possible to construct an orthogonal fluxgate with both a very small offset and noise.

ACKNOWLEDGMENTS

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