Orthogonal Fluxgate Employing Digital Selective Bandpass Sampling

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Orthogonal fluxgate employing digital selective band pass sampling is developed and tested. The fluxgate output is sampled only once, at a single time instance during a number N of excitation cycles. This provides reconstruction of a measured magnetic field with a finite bandwidth from dc to $1/2N$ Hz. The sampling time instances correspond to the minimum magnitude of the fluxgate equivalent magnetic noise within the excitation cycles. As a result, the fluxgate resolution is improved by 40% compared to that obtained by conventional methods, where the fluxgate output is sampled a number of times and then averaged over each excitation cycle. The proposed approach not only improves the fluxgate equivalent magnetic noise, but also simplifies the fluxgate output processing by eliminating the need for analog synchronous detection.

***Index Terms*—Band limited signals, magnetic noise, magnetometers, sampling methods.**

I. Introduction

ORTHOGONAL fluxgates are very competitive, miniature, precise, and low power magnetometers. In contrast to parallel fluxgates, they do not employ excitation coil; their excitation current is applied directly to the fluxgate core. Orthogonal fluxgate can be operated in the fundamental mode, where a dc bias is added to the ac excitation [1]. The fundamental mode doubles the fluxgate sensitivity [2], suppresses magnetic noise [2]–[4], and allows the elimination of offset [1], [4], [5]. The power consumption of orthogonal fluxgates can be significantly reduced by employing discontinuous excitation [6].

In a conventional orthogonal fluxgate, the output signal is gathered throughout the excitation cycle [7]–[9] and therefore the entire excitation cycle is being averaged. The fluxgate equivalent magnetic noise, however, varies significantly within the excitation cycle [10]–[13]. Therefore, the conventional method does not provide the lowest equivalent magnetic noise of the fluxgate. Selective sampling of the output signal at time instances when the equivalent magnetic noise is minimal, could improve the fluxgate resolution.

In many applications, the measured magnetic field have a narrow bandwidth [14], [15]. The bandwidth of the fluxgate output is much wider, because the measured signal is modulated by the high frequency excitation. However, according to the bandpass sampling theory [16], the sampling frequency can be much lower than double the Nyquist frequency. Sampling at frequencies related to the signal bandwidth rather than to the maximum frequency is known as bandpass sampling or under sampling [16]. Bandpass sampling is performed at a rate that intentionally aliases the modulated carrier, $f_{excitation}$, into the base band [16].

Therefore, the measured signal can be sampled only once during a number of excitation cycles. For example, if a measured field has the bandwidth of 5 Hz and the excitation frequency is 4 kHz, the signal can be sampled at 10 Hz, which corresponds to a single sample for every 400 excitation cycles.

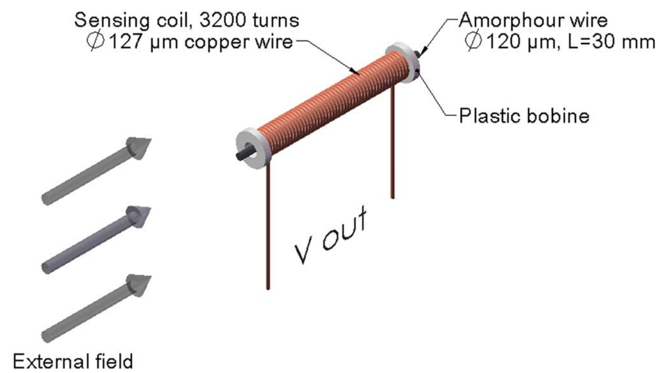

Fig. 1. Orthogonal fluxgate employing an amorphous wire.

In this paper, we show that applying the above concept to an orthogonal fluxgate enables us to improve its equivalent magnetic noise.

The paper is organized as follows: the experimental setup is described in Section II, the method is introduced in Section III, the discussion is performed in Section IV, and the conclusion is given in Section V.

II. Experimental Setup

The fluxgate experimental setup comprises (see Fig. 1) a Co-based amorphous wire (AC-20 type made by Unitica) of a 120-μm diameter, 30-mm length, and a sensing coil with 3200 turns of a 127-μm copper wire.

The excitation current is applied directly to the fluxgate core, and the output voltage is generated by the sensing coil. The excitation signal is produced by a NI PXI-5421 function generator. The external magnetic field is produced by a calibrated solenoid. The fluxgate is placed inside a three-shell magnetic shield to reduce the ambient magnetic noise. The fluxgate output is amplified by a low-noise AD8605 operational 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.

The fluxgate is operated at a 4-kHz excitation frequency, 36-mA zero-to-peak current and 36-mA zero-to-peak dc bias.

Manuscript received March 01, 2012; revised May 21, 2012; accepted June 16, 2012. Date of current version October 19, 2012. Corresponding author: E. Weiss (e-mail: eyal_we@yahoo.com).

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Digital Object Identifier 10.1109/TMAG.2012.2205906

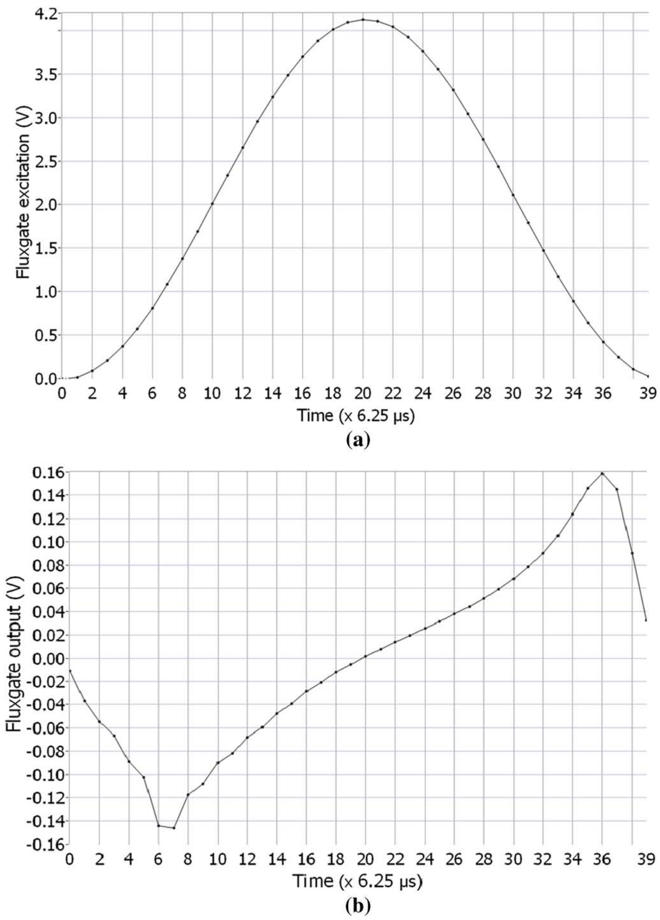

Fig. 2. Fluxgate excitation voltage (a) and the output signal (b).

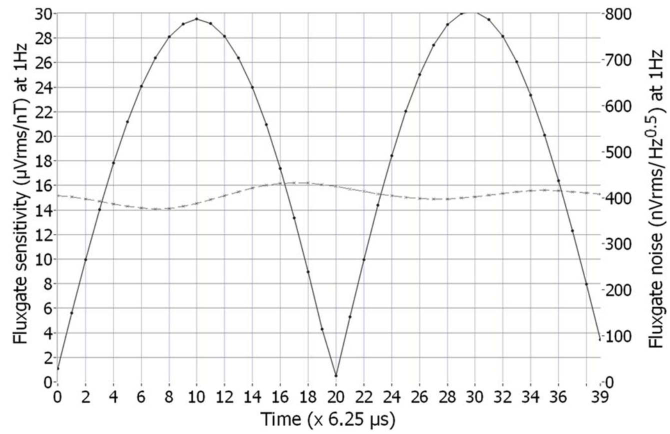

Fig. 3. Fluxgate output noise (the dashed curve) and sensitivity (the solid curve) as a function of the sampling instances within the excitation cycle.

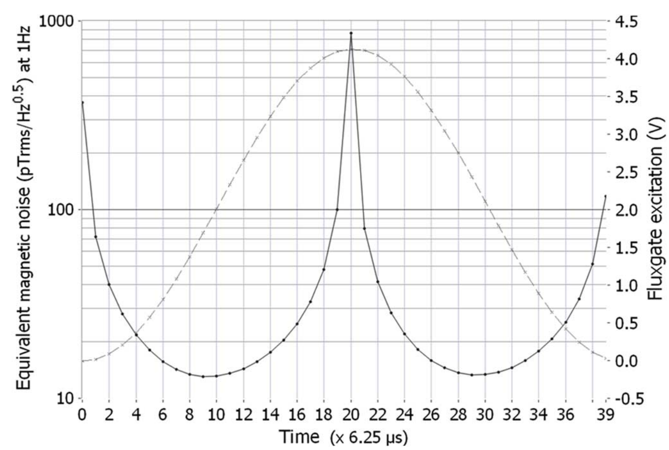

Fig. 4. Fluxgate equivalent magnetic noise (the solid curve) as a function of the sampling instances within the excitation cycle (the dashed curve).

The fluxgate excitation waveform is presented in Fig. 2(a), and the output is presented in Fig. 2(b). The chosen excitation waveform and dc bias minimizes our fluxgate equivalent magnetic noise. The fluxgate output is not a sine wave because the core is not on the verge of deep saturation during the entire excitation cycle. This is because the excitation current drops to zero in each excitation cycle. The core, however, remains magnetized in the excitation field polarity due to the residual magnetization of the amorphous wire.

All the measurements are post-processed by the LabView software.

III. Method

To find the time instances when the fluxgate equivalent magnetic noise is minimal, we have calculated the equivalent magnetic noise as a function of the sampling instances within the excitation cycle. To this end, we measured the fluxgate output voltage noise and sensitivity (see Fig. 3), and obtained the equivalent magnetic noise (see Fig. 4) by dividing the output noise by the sensitivity.

To measure the fluxgate noise, we sampled its output signal $k = 40$ times within each excitation cycle, after which we removed out of band noise using a digital band pass filter. To find the noise magnitude for the i^{th} sample in Fig. 2, we collected the i^{th} samples during $M = 40,000$ excitation cycles. Then Fourier transform was performed, and the noise magnitude was calculated as the noise spectral density at 1 Hz. This band pass sampling procedure demodulated the output signal to base band. The noise was averaged over 20 sets of measurements.

To measure the fluxgate sensitivity, we repeated the same procedure with the fluxgate placed inside a solenoid producing a calibrated external field at 1 Hz. The frequency response of the fluxgate from DC to 100 Hz was measured and found to be uniform within $\pm 1.5\%$.

Fig. 4 shows that the equivalent magnetic noise significantly varies within the excitation cycle: from 13 to 850 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$ at 1 Hz. The equivalent magnetic noise curve has minimum at samples 9 and 30.

Fig. 5 presents the fluxgate equivalent magnetic noise versus frequency for two selected sampling time instances within the excitation cycle (9 and 20), compared to the conventional method where the entire cycle is being averaged.

IV. Discussion

To compare between the new sampling method and the conventional one, we have also calculated the fluxgate equivalent magnetic noise by applying a conventional method. To do this, we followed the procedure described in the Method section. However, to measure the fluxgate output noise and sensitivity in

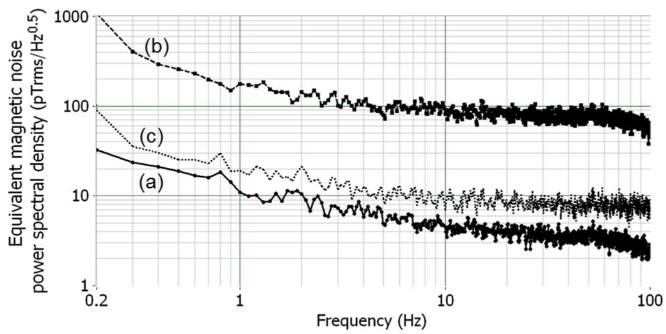

Fig. 5. Noise spectrum of the orthogonal fluxgate with (a) digital selective band pass sampling with the lowest equivalent magnetic noise (sample #9 in Fig. 4), (b) sampling point with the highest equivalent magnetic noise (sample #20 in Fig. 4), and (c) the conventional sampling method.

this case, we have performed Fourier transform to all the $k = 40$ samples in each excitation cycle for all the $M = 40,000$ excitation cycles.

The equivalent magnetic noise of the fluxgate without digital bandpass sampling is the average of the output noise divided by the average of the sensitivity within each cycle (see Fig. 3). The output noise and sensitivity were measured at a frequency of 1 Hz above the excitation frequency. The calculated equivalent magnetic noise has a magnitude of 18.5 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$, which is by 40% higher than the magnitude obtained with the new method.

Fig. 3 shows that the fluxgate output noise is nearly constant within the entire excitation cycle. On the other hand, the fluxgate sensitivity varies from 0.5 to 30 $\mu\mathrm{Vrms}/\mathrm{nT}$. As a result, the fluxgate equivalent magnetic noise in Fig. 4 varies from 13 to 850 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$ at 1 Hz. The minima of the equivalent magnetic noise nearly correspond to the maxima of the fluxgate sensitivity.

The equivalent magnetic noise presented in Fig. 5 demonstrates the improvement attained by selecting the best time instances within the excitation cycle.

The variations in the fluxgate sensitivity can be explained by variations in the slope of the excitation current [see Fig. 2(a)], according to the orthogonal fluxgate model [1].

The proposed method can be applied to both demodulate and sample the output of a fluxgate. The excitation cycle and the sampling clocks must be synchronized, and the sampling time instances set to one of the two optimal points. The exact sampling point can be experimentally found for each fluxgate configuration.

V. Conclusion

We show in this work that it is possible to decrease the equivalent magnetic noise of an orthogonal fluxgate by employing digital selective bandpass sampling of its output signal. This is because the sensitivity varies within the excitation cycle, while the output noise is almost constant. As a result, the equivalent magnetic noise reaches minima twice within the excitation cycle. Selective digital band pass sampling at time instances corresponding to the equivalent magnetic noise minima provides 40% improvement compared to that obtained by the conventional method. Employing digital selective bandpass sampling also simplifies the fluxgate output processing. Further simplification can be attained by exploiting the possibility to employ low sampling rates. In this case, the digital band pass filter should be replaced with an analog one which is required to eliminate unwanted aliasing.

Acknowledgment

The authors would like to acknowledge B. Ginzburg and M. Butta for their support. This work was supported in part by Analog Devices, Inc., National Instruments, Inc., and the Paul Ivanier Center for Robotics Research and Production Management.

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