# A Tube-Core Orthogonal Fluxgate Operated in Fundamental Mode

Eugene Paperno, Eyal Weiss, and Anton Plotkin

Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel

**In this paper, we suggest applying fundamental-mode operation to orthogonal fluxgates with tube cores. Excitation current in these fluxgates flows through a toroidal coil wound around the tube core, whereas in the orthogonal fluxgates with amorphous wires, it flows directly through the core. Having no excitation current inside the core reduces its heating and, hence, decreases the fluxgate thermal drift. Employing the toroidal coil also allows decreasing the excitation current by simply increasing the number of coil turns, while keeping the same intensity of the excitation field. Our experiments have shown a much higher efficiency of the new operating mode as compared with the second-harmonic mode. Adding a great enough dc bias to the ac excitation has caused a dramatic noise reduction. This effect is especially pronounced at relatively low frequencies, below 10 kHz. The fluxgate resolution in the fundamental mode, 10 pT/$\sqrt{}$Hz at 1 Hz, is by a factor of 30 better than in the second-harmonic mode. The sensitivity in the fundamental mode exceeds by a factor of 12.5 the sensitivity in the second-harmonic mode. We have also observed an about two times lower thermal drift of the fluxgate output. We have also found in this work that the phase noise of the excitation current is the main contributor to the fluxgate noise at low frequencies. It contributes about 67% to the fluxgate noise power density near the fundamental.**

***Index Terms*—AC bias, dc bias, fundamental mode, magnetic noise suppression, orthogonal fluxgate, second-harmonic mode, tube core.**

## I. Introduction

THE recently suggested fundamental mode of operation has opened up new possibilities for the improvement of orthogonal fluxgates with amorphous wire cores [2]–[5]. In the fundamental mode [1], the wire core of an orthogonal fluxgate [see Fig. 1(a)] is excited with a unipolar electrical current, rather than being traditionally excited with a bipolar current. The unipolar excitation is obtained by adding a dc bias to the fluxgate ac excitation. The fluxgate output can then be detected at the excitation fundamental rather than at the second harmonic.

The fundamental-mode operation increases the sensitivity of orthogonal fluxgates with amorphous wire cores [1], [2], reduces their offset [3], noise [4], and thermal drift [5], thus, making them competitive with the state-of-the-art parallel fluxgates [6].

In this paper, we suggest applying the fundamental-mode operation to a different type of orthogonal fluxgates, namely, to orthogonal fluxgates with tube cores [see Fig. 1(b)]. Excitation current in these fluxgates flows through a toroidal coil wound around the tube core, whereas in the orthogonal fluxgates with amorphous wires, it flows directly through the core. Having no excitation current inside the core reduces its heating and, hence, decreases the fluxgate thermal drift. Employing the toroidal coil also allows decreasing the excitation current by simply increasing the number of coil turns, while keeping the same intensity of the excitation field.

Our main goals in this work are as follows: 1) to compare the performances of tube-core orthogonal fluxgates operated in the fundamental and in the second-harmonic modes, 2) to compare the performances of fluxgates with tube and wire cores, both operated in the fundamental mode, and 3) to reveal the dominant noise origin that limits the fluxgate resolution at low frequencies.

## II. Experiments

### A. Experimental Setup

We have chosen a 22-$\mu$m-thick, 5-cm-wide Metglas 2705M amorphous ribbon as a material for the fluxgate core. The direction of the magnetic anisotropy within the ribbon was determined by measuring its longitudinal and transverse hysteresis loops (see Fig. 2). The hysteresis loop shapes have demonstrated well-defined uniaxial anisotropy pointing along the ribbon length.

To assemble the fluxgate core, we cut a 5 cm $\times$ 5 cm square from the amorphous ribbon and coiled it inside a nonconductive pipe, aligning the ribbon anisotropy circumferentially. The outer diameter of the core was imposed by the inner diameter (8 mm) of the nonconductive pipe [see Fig. 1(b)].

A toroidal excitation coil was wound around the core with 115 turns of a 0.2-mm diameter copper wire. A two-layer solenoidal sensing coil was wound above the toroidal coil with 280 turns of a 0.1-mm diameter copper wire. The excitation coil was connected to the signal source of an SR785 dynamic signal analyzer (made by Stanford Research Systems, Inc., Sunnyvale, CA), and the sensing coil was connected to its signal input.

We have also used an SR850 lock-in amplifier for the synchronous detection of the fluxgate output. A PXI modular system (made by National Instruments, Inc.), with a 24-bit data acquisition module, was used to investigate the correlation between the noise of the fluxgate and the noise of the excitation.

### B. Optimal Excitation Parameters

The optimal excitation parameters in the fundamental mode were found by varying the magnitudes of the ac and dc currents in the toroidal coil, while monitoring the fluxgate signal-to-noise ratio (SNR). In the second-harmonic mode, no dc bias was applied. In both modes, the SNR was measured for two excitation frequencies: 1 and 32 kHz.

We have found that the excitation with a 6-mA root mean square (rms) ac and 40-mA dc currents provides the maximum SNR in the fundamental mode. The maximum SNR in the

Digital Object Identifier 10.1109/TMAG.2008.2001587

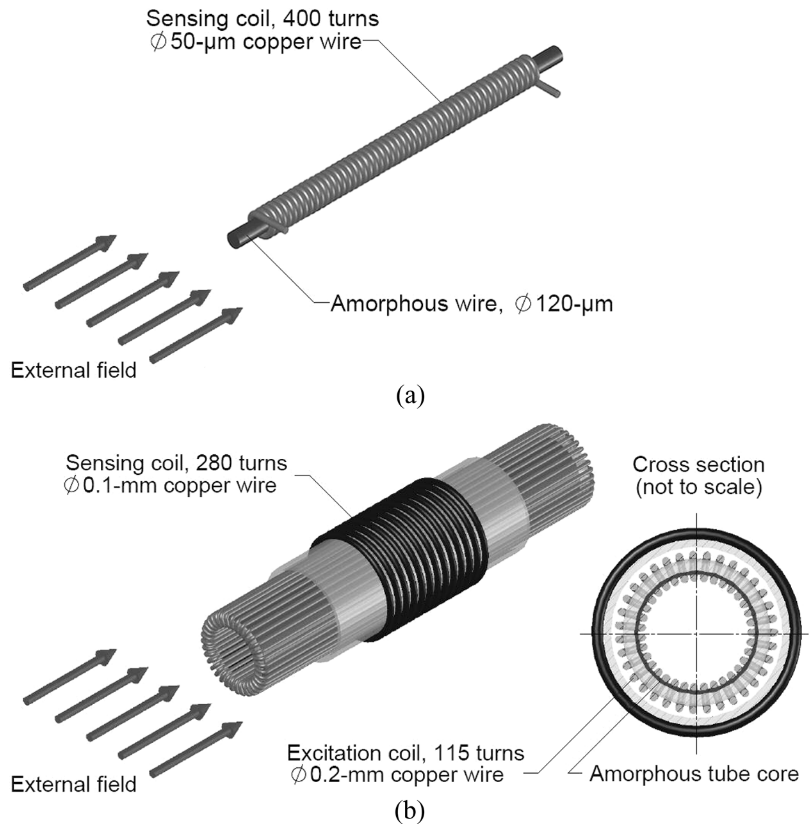


Fig. 1. Orthogonal fluxgates: (a) with amorphous wire core and (b) with tube core.

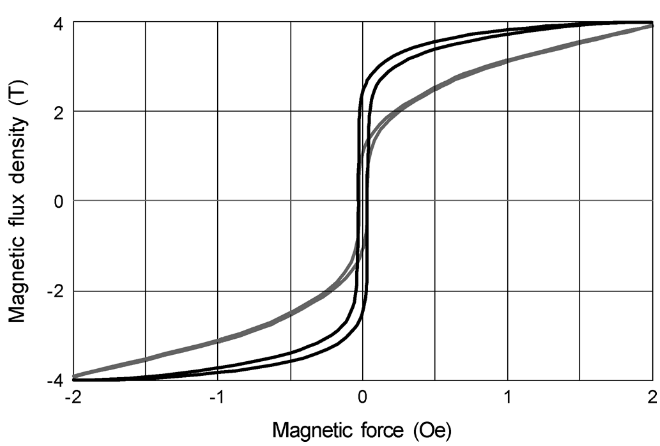


Fig. 2. DC hysteresis loops of the Metglas 2705M amorphous ribbon measured along (the black lines) and across (the gray lines) the ribbon length. The loop shapes reveal well-defined uniaxial anisotropy pointing along the ribbon length.

second-harmonic mode was obtained using the same, 6-mA rms, ac excitation.

### *C. Magnetic Noise Suppression*

We have also found in the above experiment that a great enough dc bias has caused a dramatic noise reduction (see Fig. 3). A 40-mA dc bias suppresses [see Figs. 3 and 4(a)] the fluxgate noise down to the spectrum analyzer noise floor (6 nV/$\sqrt{\text{Hz}}$).

A similar effect was observed in [4] for an orthogonal fluxgate with amorphous wire core. However, in our present case, noise suppression is especially pronounced only at relatively low frequencies of the excitation, below 10 kHz. The noise in this case is reduced by a factor of 70 compared to that in the second-harmonic mode.

Fig. 3(b) demonstrates a much higher SNR obtained in the fundamental mode compared to the second-harmonic mode. A sinusoidal external magnetic field was applied to the fluxgate at a 100-Hz frequency. The field magnitude was 7-nT rms in the fundamental mode and 100-nT rms in the second-harmonic mode. Note that in the fundamental mode, the SNR is relatively high (about 33 dB), whereas in the second-harmonic mode, the spectral components of the signal are completely covered with the noise.

At higher frequencies, the noise in the second-harmonic mode decreases [see Fig. 4(b)]. As a result, the noise difference between the two modes of operation is less pronounced, yet still significant: the noise level in the fundamental mode is 3 to 5 times lower than that in the second-harmonic mode.

### *D. Fluxgate Sensitivity*

The fluxgate sensitivity increases with frequency in both modes. For a 1-kHz excitation, it is 40 nV/nT in the fundamental mode and 3.2 nV/nT in the second-harmonic mode. For a 32-kHz excitation, it is 1800 nV/nT in the fundamental mode and 144 nV/nT in the second-harmonic mode. Thus, the sensitivity in the fundamental mode exceeds by a factor of 12.5 the sensitivity in the second-harmonic mode.

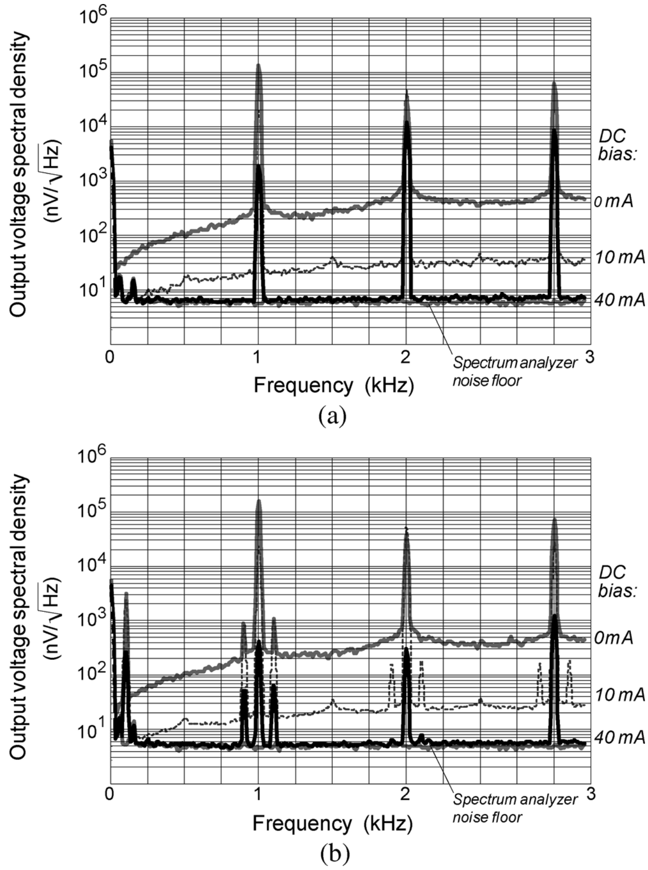


Fig. 3. Comparison between the output signal spectra obtained for different dc bias currents at the excitation frequency of 1 kHz. (a) A 40-mA dc bias corresponds to a purely unipolar excitation of the fluxgate core (fundamental mode), and a zero dc bias corresponds to a purely bipolar excitation (second-harmonic mode). (b) A sinusoidal external magnetic field is applied to the fluxgate at a 100-Hz frequency. The black line shows the first-harmonic response (obtained for a 7-nT rms external field) and the gray lines show the second-harmonic response (obtained for a 100-nT rms external field). Note that in the fundamental mode (at 1 kHz), the SNR is relatively high, whereas in the second-harmonic mode (at 2 kHz), the spectral components of the signal are completely covered with the noise (BMH window, 3200/400 linewidth).

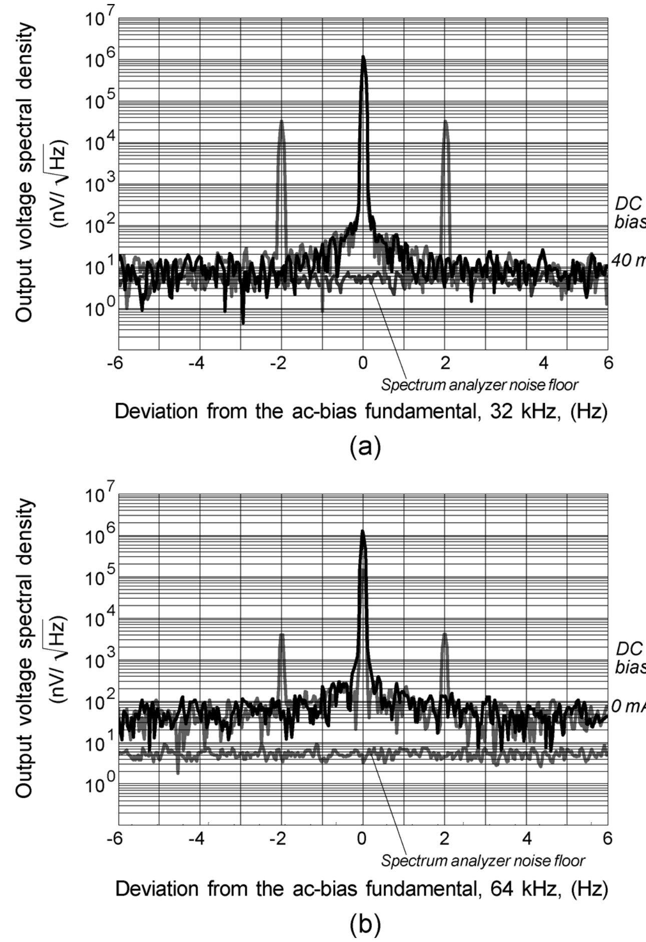


Fig. 4. Fluxgate resolution: the signal and noise (a) near the fundamental and (b) near the second harmonic. The gray line represent the case where a 7-nT rms sinusoidal external magnetic field is applied to the fluxgate at a 2-Hz frequency (BMH window, 12.5/400 linewidth).

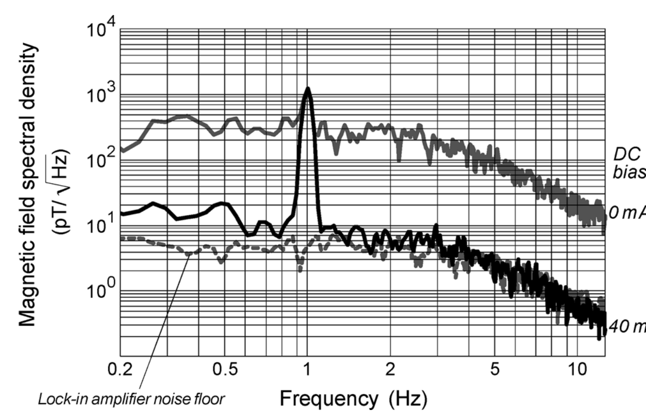


Fig. 5. Fluxgate noise spectra referred to the input. A 7-nT rms sinusoidal external magnetic field is applied to the fluxgate at a 1-Hz frequency. Note that the noise in the fundamental mode is by an order of magnitude lower than in the second-harmonic mode (BMH window, 12.5/400 linewidth).

### *E. Fluxgate Sensitivity Threshold*

We have measured the fluxgate sensitivity threshold at a 32-kHz excitation frequency. A 7-nT rms sinusoidal external magnetic field was applied to the fluxgate at a 1-Hz frequency. The fluxgate output was detected by an SR850 lock-in amplifier. The lock-in amplifier time constant was set at 30 ms, which corresponds to a 5-Hz signal bandwidth. The lock-in amplifier was synchronized either with the fundamental or with the second-harmonic, depending on the operating mode investigated.

We have found in this experiment (see Fig. 5) that the sensitivity threshold in the fundamental mode (10 pT/$\sqrt{\text{Hz}}$ at 1 Hz) is by a factor of 30 better than that in the second-harmonic mode (300 pT/$\sqrt{\text{Hz}}$ at 1 Hz).

### *F. Dominant Origin of the Noise*

The fluxgate excess noise near both the fundamental and the second-harmonic (see Fig. 4) resembles the phase noise of the excitation current [see Fig. 6(a)]. To find the contribution of the excitation phase noise to the fluxgate output, we have measured the sample coherence function of the fluxgate noise in the fundamental mode [see Fig. 4(a)] and the phase noise of the excitation [see Fig. 6(a)].

The result is shown in Fig. 6(b). One can see from this figure that the excitation noise contributes about 67% to the fluxgate noise power.

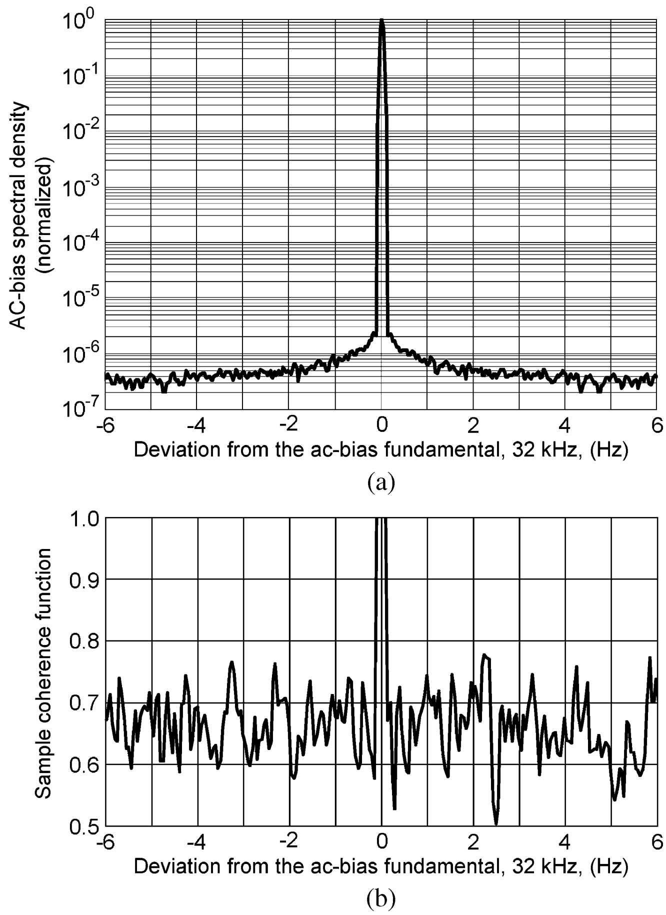


Fig. 6. Correlation between the noise of the fluxgate and the excitation. (a) Normalized amplitude spectrum of the excitation current (BMH window, 12.5/400 linewidth). (b) Sample coherence function of the fluxgate noise in the fundamental mode [see Fig. 4(a)] and the phase noise of the excitation in (a) (BMH window, 12.5/250 linewidth).

## III. Conclusion

Our experiments with a tube-core fluxgate have shown a much higher efficiency of the fundamental-mode operation as compared with the second-harmonic mode. A 40-mA dc bias has suppressed the fluxgate noise down to the spectrum analyzer noise floor. A 70-fold noise reduction was observed at a 1-kHz excitation, and a threefold to fivefold noise reduction was observed at a 32-kHz excitation. The fluxgate sensitivity has grown by a factor of 12.5. A 10-pT/$\sqrt{}$Hz resolution has been achieved at 1 Hz in the fundamental mode for a 32-kHz excitation frequency. This is better by a factor of 30 than the resolution in the second-harmonic mode (300 pT/$\sqrt{}$Hz).

The resolution obtained in the fundamental mode exceeds that of a fluxgate with amorphous wire core [3]. We have also observed an about twofold lower thermal drift of the fluxgate output compared to [4]. This allows us to conclude that the orthogonal fluxgate with tube core, operated in the fundamental mode, outperforms its counterpart with amorphous wire core.

We have also found in this work that the phase noise of the ac excitation is the dominant contributor to the fluxgate noise at low frequencies. It adds about 67% to the fluxgate noise power density near the fundamental.

In our future research, we intend to further reduce the fluxgate noise by taking into account its correlation with the phase noise of the excitation. Our hypothesis is based on the fact that the noise in the excitation current can be detected independently, hence, its corresponding part in the fluxgate noise may be compensated.

## Acknowledgment

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

## References

[1] I. Sasada, "Orthogonal fluxgate mechanism operated with dc biased excitation," *J. Appl. Phys.*, vol. 91, pp. 7789–7791, May 2002.
[2] K. Goleman and I. Sasada, "Symmetric response obtained with an orthogonal fluxgate operated in fundamental mode," *IEEE Trans. Magn.*, vol. 42, pp. 3276–3278, Oct. 2006.
[3] I. Sasada, "Symmetric response obtained with an orthogonal fluxgate operated in fundamental mode," *IEEE Trans. Magn.*, vol. 38, pp. 3377–3379, Sep. 2002.
[4] E. Paperno, "Suppression of magnetic noise in the fundamental-mode orthogonal fluxgate," *Sensors Actuators A: Phys.*, vol. 116, pp. 405–409, Oct. 2004.
[5] A. Plotkin, E. Paperno, A. Samohin, and I. Sasada, "Compensation of the thermal drift in the sensitivity of fundamental-mode orthogonal fluxgates," *J. Appl. Phys.*, vol. 99, no. 08B305, Apr. 2006, accepted for publication.
[6] P. Ripka, "Advances in fluxgate sensors," *Sensors Actuators A: Phys.*, vol. 106, pp. 8–14, Sep. 2003.

Manuscript received March 03, 2008. Current version published December 17, 2008. Corresponding author: E. Paperno (e-mail: paperno@ee.bgu.ac.il).