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Drive signal waveform for a fluxgate

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Abstract. One of the obvious applications of magnetometers is a system of magnetic vacuum which is able to minimize the influence of external magnetic fields on the operation of electronic instrumentation. In magnetic field systems, fluxgate magnetometers are commonly used in the capacity of absolute magnetic field sensors. However, the quality improvement of magnetic vacuum requires the improvement of the fluxgate performance, in particular, its sensitivity.

1. Introduction
Magnetic field measurement is the most important for and widely used in space and geophysical explorations [1-2], navigation, attitude and stabilizing control systems [3], quantum computer shielding systems [4-5], magnetic resonance imaging, brain imaging, flaw detection, non-destructive testing, etc. One of the obvious applications of magnetometers are systems of magnetic vacuum which are able to minimize the influence of external magnetic fields on the operation of electronic instrumentation. Such systems utilize passive and active techniques of magnetic shielding. Passive techniques include the application of shields made of materials highly permeable to magnetic fields. Magnetic field in active techniques is compensated by a coil system. Coils are included in a closed-loop system, where the magnetic field is measured by sensors adjacent to a shielded object. In magnetic field systems, fluxgate magnetometers are commonly used in the capacity of absolute magnetic field sensors. However, the quality improvement of magnetic vacuum requires the improvement of fluxgate performance, in particular, its sensitivity. The improvement of fluxgate performance is provided in three directions, namely: optimization of sensor and core configurations and winding arrangement; careful selection of core material; optimum amplitude, frequency, drive signal waveforms and algorithms of processing measurement data.

The purpose of this paper is to improve the fluxgate sensitivity through the analysis of the fluxgate operation with different waveforms of drive signals.

2. Mathematical analysis
In work [6] we suggested (1) for the output signal (electromotive force) and (2) for the fluxgate sensitivity. Both equations are for any harmonics irrespectively of the drive signal waveform and approximation method of the average magnetization curve.

$$E_{\text{meas}}(t) = -sw_2 H_{\text{q}}(t)\sum_{i=1}^{j} a_{2i-1}(2i-1)\left[\left(H_{\text{dc}} + H_{\text{exc}}(t)\right)^{2i-2} - \left(H_{\text{dc}} - H_{\text{exc}}(t)\right)^{2i-2}\right];$$
$$H_{\text{q}}(t) = \frac{dH_{\text{exc}}(t)}{dt} = \omega H_{\text{exc.m}}\sum_{g=1}^{m}\left(b_g \cos(g\omega t + \pi/2) + c_g \sin(g\omega t + \pi/2)\right)g, \tag{1}$$

$$S_g = \lim_{T\to\infty}\frac{1}{ET}\int_0^T \frac{dE_{\text{meas}}(t)}{dH_{\text{dc}}}\sin(g\omega t)dt. \tag{2}$$

Sinusoidal, square, and triangle waveforms are typical for drive signals of the fluxgate magnetometer. With a view to evaluate the fluxgate sensitivity and select the optimum drive signal, let us study the operation of the differential fluxgate depending on the drive signal waveform and the approximation method used for the average magnetization curve. First, compare the sensitivity of the differential fluxgate on the second, fourth, and sixth harmonics during the excitation of magnetic field intensity induced by signals of sinusoidal, square, and triangle waveforms.

Let us write the equation for the magnetic field intensity driven by the square-wave signal as a Fourier series:

$$H_{\text{exc.s}}(t) = k_{\text{s}} H_{\text{exc.m}}\sum_{g=0}^{m}\frac{(-1)^g}{(2g+1)^2}\sin\left(\omega t(2g+1)\right), \tag{3}$$

where k_{s} is the coefficient equaling $4/\pi$.

Similarly, the equation for the magnetic field intensity driven by the triangular-wave signal takes the form

$$H_{\text{exc.t}}(t) = k_{\text{t}} H_{\text{exc.m}}\sum_{g=0}^{m}\frac{1}{(2g+1)^3}\sin\left(\omega t(2g+1)\right), \tag{4}$$

where k_{t} is the coefficient equaling $8/\pi^2$.

The magnetic field intensity driven by the sinusoidal-wave signal can be obtained from

$$H_{\text{exc}}(t) = H_{\text{exc.m}}\sin(\omega t). \tag{5}$$

A third-degree polynomial approximation is used to carry out a qualitative analysis of the fluxgate sensitivity:

$$B = \sum_{i=1}^{j} a_{2i-1} H^{2i-1}, \tag{6}$$

where a_i is the i-th approximation coefficient.

Within this approach, the fluxgate sensitivity at the magnetic field intensity driven by the sinusoidal-wave signal on the second harmonics, can be written as

$$\left|S_2\right| \approx 6sw_2 a_3 \omega H_{\text{exc.m}}^2. \tag{7}$$

The fluxgate sensitivity on the fourth and the sixth harmonics is $S_4 = S_6 = 0$.

Substituting Eq. (3) into Eq. (2) in view of Eq. (6), we obtain the fluxgate sensitivity at the magnetic field intensity driven by the square-wave signal on the second, fourth, and sixth harmonics:

$$\left|S_{2\text{s}}\right| \approx 12\cdot sw_2 a_3 \omega H_{\text{exc.m}}^2; \left|S_{4\text{s}}\right| \approx 6\cdot sw_2 a_3 \omega H_{\text{exc.m}}^2; \left|S_{6\text{s}}\right| \approx 4\cdot sw_2 a_3 \omega H_{\text{exc.m}}^2. \tag{8}$$

The analysis of the fluxgate sensitivity driven by the square-wave signal shows that on the second harmonics it is twice higher than that driven by the sinusoidal-wave signal.

Substituting Eq. (4) into Eq. (2) in view of Eq. (6), we obtain the fluxgate sensitivity at the magnetic field intensity driven by the triangular-wave signal on the second, fourth, and sixth harmonics:

$$\left|S_{2\mathrm{t}}\right| \approx 3,64 \cdot s w_2 a_3 \omega H_{\mathrm{exc.m}}^2 ; \left|S_{4\mathrm{t}}\right| \approx 0,46 \cdot s w_2 a_3 \omega H_{\mathrm{exc.m}}^2 ; \left|S_{6\mathrm{t}}\right| \approx 0,14 \cdot s w_2 a_3 \omega H_{\mathrm{exc.m}}^2 . \qquad (9)$$

The analysis of the fluxgate sensitivity at the magnetic field intensity driven by the triangular-wave signal shows that on the second harmonics it is lower than when driven by the sinusoidal-wave signal. The detection of the fourth and the sixth harmonics with their subsequent results summarization does not allow increasing the sensitivity.

The synchronous detection of the second, fourth and sixth harmonics with their subsequent results summarization and the detection of the second harmonics only, increase the fluxgate sensitivity respectively by $\sim$3.6 and 1.8 times when driving the field intensity with the square-wave signal rather than with the sinusoidal-wave signal.

It should be noted that magnetic permeability of fluxgate cores depends on frequency and reduces after cutoff frequency which is particular for each material. In the traditional approach to the analysis of the fluxgate operation this dependence can be neglected when measuring the magnetic flux density merely on the second harmonics of the output electromotive force. However, the calculation of the fluxgate sensitivity on higher harmonics, it is expedient to multiply the resulting output signal in Eq. (1) by the permeability reduction factor $\dot{K}_{\mu}(\omega)$.

$$\dot{E}_{\mathrm{meas}}(\omega, t)=-s w_2 \dot{K}_{\mu}(\omega) H_{\mathrm{q}}(t) \sum_{i=1}^{j} a_{2i-1}(2i-1)\left[\left(H_{\mathrm{dc}}+H_{\mathrm{exc}}(t)\right)^{2i-2}-\left(H_{\mathrm{dc}}-H_{\mathrm{exc}}(t)\right)^{2i-2}\right] ; \dot{K}_{\mu}(\omega)=\frac{1+j \omega \tau_1}{1+j \omega \tau_2}, \qquad (10)$$

where τ_1, τ_2 are time constants for the permeability reduction, s.

Due to the spread of core characteristics during their manufacturing, it is advisable to experimentally compute the permeability reduction factor $\dot{K}_{\mu}(\omega)$ for each core.

3. Experimental

In order to test theoretical calculations, we used a standard differential fluxgate sensor. The experimental set-up was assembled to measure the fluxgate sensitivity depending on the signal waveform on the second, fourth and sixth harmonics.

The experimental set-up consists of a Fluke 5520A calibrator for the magnetic intensity excitation with the sinusoidal- and square-wave signals of the given amplitude and frequency; an Agilent 3458A multimeter for measuring the drive current of the fluxgate sensor; a PXI-1042Q instrumentation platform with installed NI PXI-5124 module for digitization and spectral analysis of the fluxgate drive signal and the output voltage which is proportional to the measured magnetic flux density.

Figure 1 contain the plots of dependences respectively between the second, fourth and sixth harmonics at the sensor output and the drive current during the excitation induced by sinusoidal- and square-wave drive signals.

4. Conclusions

As follows from the figure 2, the fluxgate sensitivity on the second harmonics during the magnetic intensity excitation induced by signals of the square waveform was higher than that induced by signals of the square waveform. This was observed up to 2.0√2 mA drive current. At the same time, the maximum sensitivity was achieved at 1.5√2 mA drive current. Within the whole range of the drive current, the fluxgate sensitivity was considerably higher on the fourth and the sixth harmonics during the excitation induced by the square-wave signal.

Based on the results, it can be concluded that for excitation of the magnetic field intensity, it is advisable to apply a square-wave signal with the synchronous detection of the second, fourth and sixth

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harmonics followed by the results summarization. This allows increasing the fluxgate sensitivity and signal-to-noise ratio.

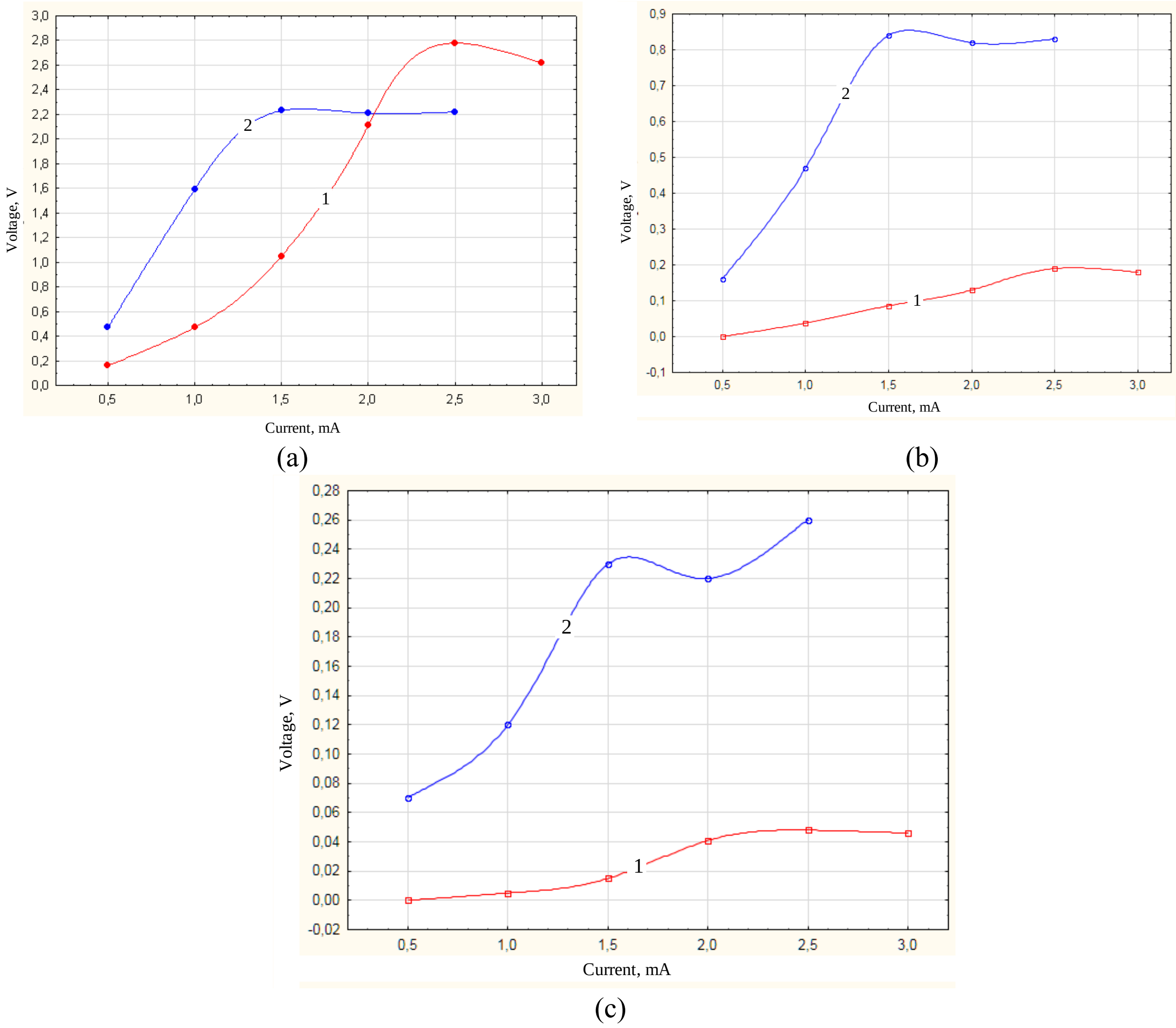

Figure 1. Dependences between the second harmonic (a), fourth harmonic (b) and sixth harmonic (c) at the sensor output and the drive current during excitation induced by sinusoidal (1) and square-wave drive signals (2).

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