Fluxgate Magnetometer with Rotational Magnetization Reversal Excitation of the Disc Magnetic Core

Lyubomyr Pavlyk[1], Sergii Ubizskii[1], Andriy Lozynskyy[2], Grygoriy Savytskyy[3]

Abstract – **A fluxgate magnetometer is described that is based on the magnetization reversal excitation of disc-shaped magnetic core by rotating magnetic field with magnitude enough to saturate it. The target field components are registered by means of the second harmonic of the current response signal. The model of response signal is developed and a sensor prototype was built and experimentally tested. The measured sensitivity dependences upon the excitation field amplitude at different frequencies coincide well with predictions of the model.**

Keywords – **Fluxgate, Magnetic field sensor, Modelling, Sensitivity, Response signal, Current read-out mode.**

I. INTRODUCTION

Fluxgate magnetometers are widely used for low frequency and weak magnetic field measurements in the range of 100 pT – 100 μT. Having low threshold of sensitivity and being relatively inexpensive they are beyond compare to the other magnetometers [1]. On the other hand, reduction of the threshold of sensitivity of fluxgates is limited by their sensing elements inherent noise. The inherent noise nature is the domain walls motion [2] in the fluxgate core. As it was shown earlier (see [3] for example) the fluxgate noise level can be reduced by holding the core in a single domain state during the whole cycle of magnetization reversal. This can be reached for example by magnetizing the disc-shaped core by the magnetic field rotating in the core plane and with amplitude large enough to saturate the core [4, 5]. Between the others advantages of such a magnetization reversal mode is a possibility to measure at least two in-plane magnetic field components by one sensing element and to perform so called resonance regime that increases the fluxgate sensitivity [6]. The prototype of the fluxgate with rotational magnetization reversal of a disc core was built and it let us to proof experimentally the results of theoretical simulations of such a method of magnetic field measurement.

II. FLUXGATE PROTOTYPE

The sensitive probe of the fluxgate with rotation magnetization reversal of a disc core consist of two flat solenoids placed one into the other with mutually perpendicular axes that lies in a plane of the core made of soft magnetic material (see Fig. 1). The currents in the coils with the phase shift of π/2 provides the excitation field $\mathbf{H}_e(t)$ rotating in the core plane with constant magnitude being enough to saturate the core. The coils are powered by a source of harmonic voltage with a phase shift appropriate to supply the uniform rotating field. In such configuration the target signal can be registered by the second harmonic of the current in the excitation coil.

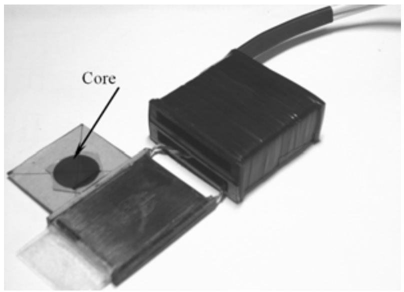

Fig. 1 Fluxgate sensing probe

Diameter of the wire used for coils winding is 0.2 mm and the turns' density for both coils is about 100 cm^{-1}. The (111) oriented epitaxial iron-garnet film was used as a core with diameter of 18 mm and a thickness of 10 μm. The film saturation magnetization is equal to 0.175 T and the saturation field is about 400 A/m.

The device block diagram one can see at Fig. 2. Here ADC 1 serves as a voltage source for both coils. The voltage amplitude as well as voltage phase shift between coils can be changed by the control block 2. As soon as the signal is amplified by the power amplifier 3 it fed into the coils 4. The response signal proportional to the coil current is added in antiphase by the summator 7 to the reference one which corresponds to the first harmonic of the excitation signal. Before being added the amplitudes of both signals are adjusted by control blocks 2 and 5. The measured signal feds into PC via ADC 8, buffer 11 and USB interface. All further processing are performed by means of software.

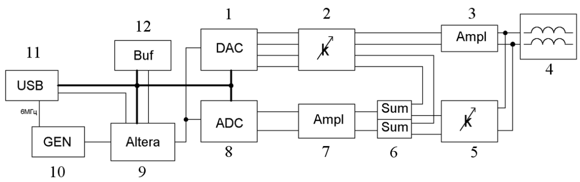

Fig. 2 The block diagram of the rotational fluxgate: 1 is a DAC; 2 is a unite to control an amplitude and phase of the excitation signal; 3 is power amplifier; 4 are excitation coils; 5 is an control unit of the amplifier 7 gain; 6 is a summator; 7 is a signal amplifier; 8 is an ADC; 9 is a PLIC Altera; 10 is a clocking generator; 11 is a USB interface; 12 is a buffer.

The entire device is controlled by programmable logic arrays (PLIC) 9, which are synchronized by the clock generator 10 together with DAC, ADC and the USB controller. It was provided also the possibility to change the voltage in each coil independently as well as their phase shift and to control the shape of the rotating excitation field by the third harmonic of the current.

[1] Lyubomyr Pavlyk, Sergii Ubizskii – Lviv Polytechnic National University, S. Bandery St., 12, Lviv, 79013, UKRAINE, E-mail: crystal@polynet.lviv.ua
[2] Andriy Lozynskyy – Karpenko Physico-Mechanical Institute of NAS of Ukraine, Naukova St., 5, Lviv, 79601, UKRAINE, E-mail: lozynsky@ah.ipm.lviv.ua
[3] Grygoriy Savytskyy – Pidstryhach Institute for Applied Problems of Mechanics and Mathematics of NAS of Ukraine, Naukova St., 3-b, Lviv, 79060, UKRAINE, E-mail: surface@iapmm.lviv.ua

Results of measurement of the sensitivity dependence on the excitation field amplitude at different frequencies by the current in one of the coil as well as the simulated ones are shown at Fig. 3.

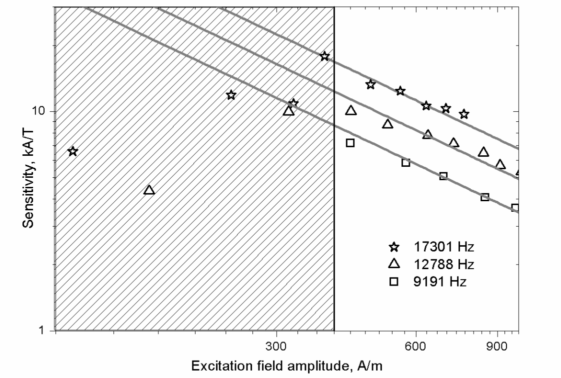

Fig. 3 Experimental (points) and theoretical (lines) dependencies of the fluxgate sensitivity on the excitation field amplitude measured for different frequencies of the excitation field. The core is out of saturation in shaded area.

The disagreement of experimental and theoretical data at the amplitudes of the excitation field below 400 A/m can be explained by the fact that the core is out of saturation in this region and thus cannot be described by the model taking into account only saturated core.

III. The Fluxgate Response Model

We have built the fluxgate response signal model making an assumption that the core is isotropic and made of soft magnetic material. We suppose also that the magnetization reversal takes place in equilibrium when the field frequency is not too high i.e. in every moment of time the condition of minimum of the energy of interaction of the core magnetization and the applied magnetic field $\mathbf{H}(t) = \mathbf{H_e}(t) + \mathbf{h}$ is satisfied. Here $\mathbf{h}$ is a target field that is small and constant. We considered the circuit of one of the excitation coils (see Fig. 4) that consists of inductance L, active resistance R, EMF source $\varepsilon_e(t)$ and some non-linear EMF $\varepsilon_n(t)$ that appears only at presence of the target field.

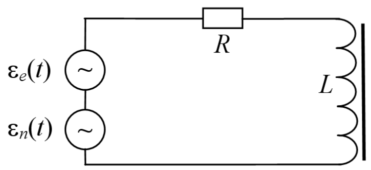

Fig. 4 Equivalent circuit of the fluxgate excitation coil powered by the EMF source

The second Kirchhoff's equation based analysis of such circuit gives us the following:

$$L\frac{d^2I}{dt^2} + R\frac{dI}{dt} = j\omega\varepsilon_e(t) + K_h\left(\left(\frac{dI}{dt}\right)^2 + I\frac{d^2I}{dt^2}\right), \quad (1)$$

where I is a current in the coil and a coefficient $K_h = 2n_x n_y V_c \frac{M_S}{H_0^3}\left(n_y h_x - n_x h_y\right)$, $n_x = n$, $n_y = n \cdot e^{j\pi/2}$, n is quantity of turns of the coil per unit of length, V_C is the core volume, M_S is a saturation magnetization of the core, H_0 is excitation field amplitude, h_x and h_y are orthogonal components of the target field in the core's plane. One can find the solution of the nonlinear equation (1) by asymptotic method [7] and the result gives us the sensitivity as the ratio of the second harmonic current amplitude of the response signal to the measured magnetic field h in a following expression:

$$S_{I_2} = \frac{2\omega\left(R^2 + \omega^2 L^2\right) n V_C \frac{M_S}{H_0}}{\sqrt{9\omega^4 L^4 R^2 + 6\omega^2 L^2 R^4 + 4\omega^6 L^6 + R^6}}. \quad (2)$$

Thus, the sensitivity has hyperbolic dependence upon the excitation field amplitude that can be calculated for given fluxgate coil parameters. The calculation results for built up prototype are shown by lines in Fig. 3. One can see that they coincide well with experimental points in the area where the core comes to saturation while there is no agreement at lower magnitudes of excitation field.

IV. Conclusion

A fluxgate with rotational magnetization reversal of a disc-shaped magnetic core was developed. The fluxgate operation was analyzed theoretically for the voltage driven mode when the target signal is read out from the second harmonic of the current response and the experiments shows a good agreement with developed model under assumption of saturated core.

References

[1] P. Ripka, M. Janosek, "Advances in magnetic field sensors", *IEEE Sensors Journal*, vol. 10, pp.1108-1116, June 2010.

[2] J. Deak, A.H. Miklich, J. Slonczewski, R.H. Koch, "A low-noise single-domain fluxgate sensor", *Appl. Phys. Lett.*, vol. 69, № 8, pp. 1157-1159, June 1996.

[3] R.H. Koch, J. Deak and G. Grinstein, "Fundamental limits to magnetic field sensitivity of fluxgate magnetic field sensors" *Appl. Phys. Lett.*, vol. 75, № 24, pp. 3862-3864, July 1999.

[4] A. Garcia, C. Moron, "Biaxial magnetometer sensor", *IEEE Trans. Magn.*, vol. 38, № 5, pp. 3312-3314, September 2002.

[5] P.M. Vetoshko, M.V. Valeiko, P.I. Nikitin, "Epitaxial yttrium iron garnet film as an active medium of an even-harmonic magnetic field transducer", *Sensors and Actuators*, vol. A106, pp. 270-273, 2003.

[6] L.P. Pavlyk, S.B. Ubizskii, A.B. Lozynskyy, G.V. Savytskyy, "The reactive excitation circuit analysis of the fluxgate with rotational magnetization reversal of the disc core", *Visnyk of Lviv Polytechnic National University*, № 646, pp. 202-211, 2009.

[7] A.H. Nayfeh, "Perturbation methods", *John Wiley & Sons, Inc.*, 1973.