MODERN FLUX-GATE MAGNETOMETERS DESIGN

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ABSTRACT

The most important metrological parameters of the flux-gate magnetometers - noise level, thermal drift, long-term stability - are considered. The ways of their improvement are analysed and some results of experimental investigation of the upgraded magnetometers are presented.

Keywords: flux-gate, magnetometer, sensor, noise, excitation, temperature

1 INTRODUCTION

The last years the tendency to miniaturize the flux-gate sensors (FGS) and to improve their parameters repeatability by the shift of the manufacturing technology to the microchip or printed circuit board (PCB) level is clearly observed [1, 2, 3]. Simultaneously, it is commonly accepted that their parameters dramatically degrade when reducing the core size. Hence such way automatically puts the fluxgate sensors into the zone, where other types of the magnetic sensors, such as magnetoimpedance, anisotropic and giant magnetoresitive and even Hall effects based ones have similar metrological characteristics and cover the same range of consumer applications. Another aspect is the power consumption. As it has been shown [4] the consumed power necessary for the sensor excitation mainly originates from the losses in the excitation coil. So, the use of the PCB or microchip coil instead of the wire one gives us *a priori* worse ratio between the metrological parameters and the power consumption at the same magnetic core. In spite of some progress in the technology and theory of the PCB or microchip based flux-gate sensors it may hardly be expected that in the nearest future their metrological parameters reach the level of the FGS based on the traditional technology.

That is why we continue to apply our efforts in modernization of the high sensitive fluxgate magnetometers with traditional structure. If to range the metrological parameters of such magnetometers for measuring weak magnetic field according to their importance at practical use, the sequence will be the following:

- noise level;
- thermal drift;
- long-term stability;
- all other parameters.

We are going to consider in this paper some possibilities of improvement of first three parameters.

A practice of flux-gate magnetometers (FGM) development and manufacturing shows that the level of their principal characteristics directly depends on the properties of the material from which both flux-gate sensor core housing and its components are produced. Also modern requirements to the reduction of sensors dimensions, their energy losses and noise level are mutually excluding ones and all of them first of all depend on the FGS core material quality and its excitation conditions. The thermal stability in the relatively large magnetic field includes such aspects as stability of the compensation field and orientation of the sensor axes. The both problems require using in the compensation windings frame the highest possible quality materials with low linear expansion coefficient and perfect long-term stability of their physical dimensions. Some results of using such materials as glass-ceramic (Zerodur® and Macor®) and quartz ceramic are discussed in the paper. These postulates trustworthiness is demonstrated in the report.

2 FGM PARAMETERS IMPROVEMENT

2.1 Noise level

If to consider the sources of the mentioned errors in detail one can find that noise level and zero offset stability are limited mainly by the quality of the sensor magnetic core and its excitation mode parameters. Due to the variety of the magnetic core geometry of the flux-gate sensors (ring-core, racetrack, bar-core etc), their excitation modes and the methods of measured signal extraction, the comparison of the different sensor by the noise level is not an easy task. For the modern magnetometers the main part of their noise is caused by the fluctuations of the Barkhausen jumps parameters during cyclic magnetization reversals of the sensor core. There are following directions for decreasing noise level of the flux-gate sensors:

- Developing of the new magnetic materials with increased uniformity of the Barkhausen jumps, mainly amorphous alloys [5, 6] or single domain materials as an yttrium iron garnet [7] or specially prepared magnetic alloys [8, 9].
- Increasing of the magnetic core volume [10], optimization of both its geometry [11, 12] and excitation mode [10, 13].
- Using the effect of the magnetic noise decreasing at the magnetic core operation close to the Curie point [5, 14, 15].

Investigations conducted in LC ISR reveal that racetrack, ring-core and bar-core geometry of the flux-gate sensors could provide approximately equal noise level at the same volume of the magnetic core, in contradistinction with commonly accepted opinion that ring-cores have the advantage over other core structures. Practically, taking into account secondary, but important factors (e.g., inter-layers friction and vibration, tape inhomogeneity, possibility of the magnetic tape pre-selection etc.) the bar-core geometry allowed us to get lower noise level as ring-cores or race-track ones.

As it was shown [16], the spectral density of the magnetic noise power is inversely proportional to the magnetic core volume, if the additional noise sources such as winding defects, mechanical stresses and so on are suppressed. In order to achieve this conclusion the topologically similar in geometry cores with different volume of ferromagnetic material and made in each set from the same batch of material with a common heat treatment and identical shape and amplitude of excitation field were studied. The derived dependency allowed us to propose to use the introduced parameter C_B – noise spectral density referred to core volume – for the convenient comparison of the magnetic materials. The values of this parameter (Table 1) for the best magnetic materials were calculated using data from the papers [10, 17, 18] and investigations results carried out in LS ISR.

Also the sensor units with cores of different materials from different producers have been tested. Unfortunately, it was not always possible to achieve the repetition of product performances; in most cases, it was necessary to adjust the circuits in accordance with given sensor parameters.

Table 1: Comparison of the magnetic material by the noise level

Magnetic material	$C_B \cdot 10^{15}$, $T \cdot m^{3/2} \cdot Hz^{-1/2}$
Permalloy ($Ni_{83}Fe_{11}$) [10]	0.8
Mo-Permalloy ($Ni_{81}Mo_6$) [17]	0.23
Vitrovac6025 (stress annealed) [18]	0.36
$Co_{68}Fe_3Cr_3Si_{15}B_{12}$(annealed in the longitudinal magnetic field, LC ISR)	0.2…0.36

The continuous study of the materials properties for FGM sensors have allowed developing a new version of processing technology of such materials and to reach the stable repetition of the processing results. As far as the process of the production of metal tape of an alloy of necessary composition as basic material is very complicated and requires corresponding specialized high-cost equipment, a decision was made to concentrate efforts at the final processing of amorphous materials as the most promising direction. As such a processing the annealing at the certain temperature conditions with usage of several additional factors influencing the annealing mode (magnetic field, medium of inert gas, mechanical stresses, etc) was selected. At that such FGS parameter as its own noise level at the core operation inside the sensor was determined as the selection criterion. Measurements of the noise level have been carried out using second harmonic of excitation frequency as an information parameter. In the results the reducing of the noise level from 3 to more than 10 times was achieved for different types of amorphous magnetic material.

The details of the study are exposed in the report and experimental results confirming the theoretical calculations are given.

2.2 Excitation mode selection

It is well known for the skilful in the art that the properly selected excitation mode of the FGS core may considerably improve the main FGM parameters. The peculiarities of different types of the excitation modes were thoroughly studied at the early stages of FGM development [19, 20] and a bit later a so called “ferroresonance excitation mode” (FEM) was proposed as optimal one [21]. The peculiarity of FEM was the use of the non-linearity of the ferromagnetic resonance circuit when the impedance of the coil L_e with high permeability ferromagnetic core differs in many times during the periods of the saturated and non-saturated states of this core (the simplest circuit realizing FEM and the plots of currents and voltages in this mode are given in Figure 1). By this the excitation i_g current has sinusoidal shape what made it much easier to damp the second harmonic of the excitation current source frequency, and the excitation voltage u_e has the shape very close to the rectangular one, which was generally accepted as the best possible [20] to reduce the FGS noise. The ability to provide the strong excitation field makes FEM suitable for sensors which should withstand an overload by great magnetic field. The perming error – the zero offset after overload - is very small for sensors operated in FEM. The peculiarities of the possible FGS excitation modes are summarized in the Table 2. As it is clearly seen from the table, FEM provides the best combination of the excitation parameters.

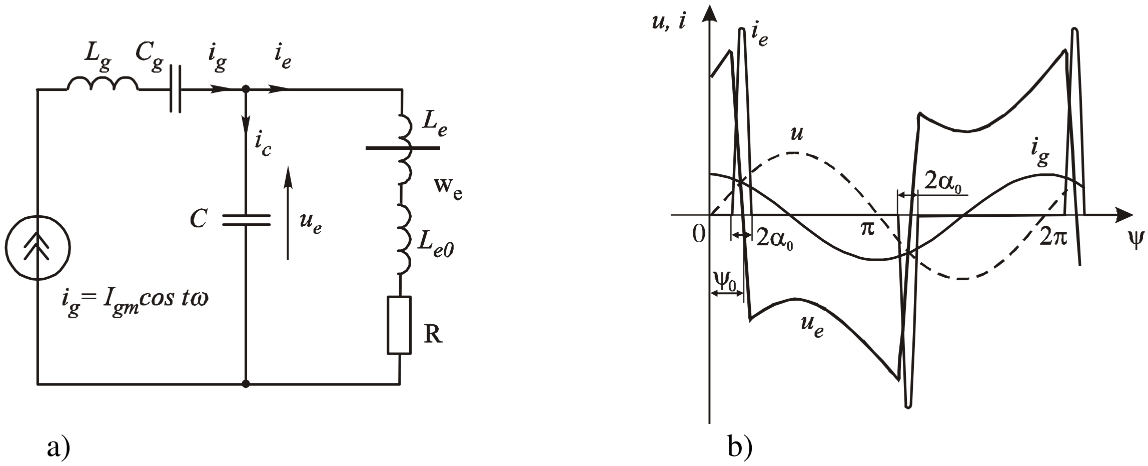

Figure 1: a – the circuit for realizing of FEM;
b – the plots of the currents and voltages during FEM.

Table 2. Comparison of the FGS excitation modes

Parameter	Excitation mode						
	Current (shape)				Voltage (shape)		
	sinusoidal	triangular	trapezoidal	step-wise rectangular	sinusoidal	triangular	FEM
Sensitivity threshold	+	0	0	0	++	+	++
Even harmonic error	+	0	0	0	++	+	++
Generator voltage changes error	+	+	+	++	0	0	++
Perming error	0	0	0	+	+	+	++
Sensitivity stability	0	0	0	++	+	+	++
Rapidity	+	+	0	0	++	++	++
Self-heating of FGS	0	0	0	0	+	+	++
Realization simplicity	++	+	0	0	++	++	+
Analysis and calculation simplicity	++	++	++	++	0	+	0

Notes 0 – unsatisfactory value of the parameter;
\+ – satisfactory value of the parameter;
++ – good value of the parameter.

2.3 FGM thermal stability

As it was already mentioned upper, the FGM zero line stability with changing temperature may be provided, first, by the appropriate material selection for the construction of FGS housing and its components. As it may be shown, the very small tilts of FGS axes may produce considerable shifts of its output signals. So, first requirement to the sensor housing material is as low as possible factor of thermal expansion. One of the best known results gives the combination of the sensor housing manufacturing from marble and the compensation winding frame for each component – from quartz. Such FGS construction was proposed by O. Rasmussen [22] and many years successfully used in the observatory magnetometers. But the raise of the requirements to the thermal stability of modern FGMs, especially for field use, stimulated new research in this direction. First improvement was obtained with the help of using of a specific glass-ceramic having thermal expansion factor below 10^{-6} in the FGS operation temperature range (-40 ÷ +40 ºC). But still one factor – non-uniformity of the compensation field – did not allow further decreasing of the FGM thermal drift as it is required today – below 0.1 nT per ºC. For space magnetometers this problem was competed by using a spherical construction of the compensation winding frame [23], which produces the highly uniform compensation field in the sensor volume. But rather high price of such a construction and technological difficulties of FGS manufacturing do not allow using it in the serially produced FGMs. The executed research showed more efficient way to decrease this component of the thermal drift. The main idea of the proposed approach is to optimize the shape of compensation field non-uniformity in such a way that the small deviations of the length or/and position of the FGS core have practically no influence on the value of the compensation field averaged by core length. The experimental investigations [24] reveal significant improvement of the scale factor stability of the magnetometer with optimized the shape of the compensation field (comparable with other shapes of non-uniformity) at the changes of the excitation field. Using this approach the new sensor with volume compensation, combining three dual rod cores in a Macor® cube with the side dimension of 20 mm was created for the small magnetometer in low-mass experiment (SMILE) [25]. Despite the short length of the fluxgate cores, the noise level was typically 20 pT/sqrt(Hz) at 1 Hz and the non-orthogonality did not exceed 20 arc minute, and the values were stable in the whole range of the excitation currents. The temperature coefficient of the scale factor was below 10 ppm per °C, the angle stability was better than 3″ per °C. Using such an approach we hope to create an advanced fluxgate sensor for geophysical applications.

3 CONCLUSIONS

Basing on such detailed study of the ways to improve the FGS parameters, already during many years LC ISR managed to develop and manufacture of flux-gate magnetometers and equipment including them traceable to highest international standards. The requirement to decrease simultaneously “weight-consumption-noise” set of parameters was continuously kept in mind. With the specially produced and processed amorphous tape the set of the sensors was created with noise level about 2-5 pT/sqrt(Hz) and as low consumed power as <10 mW. Using the modern materials and special design of the compensation coils the fluxgate magnetometers with low level of the temperature drift were created too.

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