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New type of fluxgate magnetometer for the heart's magnetic fields detection

Abstract: The application area of fluxgate sensors is limited by their sensitivity. Medical researches create high demand on the magnetometers with the characteristics of high accuracy and sensibility for measuring weak magnetic fields produced by the human body, such as the heart‘s magnetic field. Due to the insufficient sensitivity of fluxgate sensors, superconducting magnetometers (SQUID) take the dominant position for the cardiomagnetic measurements. They have to be cooled by liquefied gases and it leads to high service costs. Therefore an idea of creating a high sensitive sensor based on fluxgate principles and known methods of measurement is attractive and up to date. This paper is dedicated to the modified fluxgate sensors based on Racetrack technology with a new approach of signal demodulation. The improved fluxgate sensor system provides detection of the heart‘s magnetic field without additional expenditures for use.

Keywords: Fluxgate sensors; Magnetometers; Heart's magnetic field; Magnetocardiography (MCG)

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1 Introduction

Since the magnetic field of the heart is very weak in comparison with natural and artificial magnetic fields of the environment, there are very high requirements for the instruments used to measure it, they are also called magnetometers. They must have a high sensitivity and at the same time must be suitable for measuring weak magnetic fields with a very strong magnetic noise. In addition, they should allow to measure both constant and alternating magnetic fields in the frequency range from 0.1 up to 10^3 Hz. Measuring of the heart‘s magnetic field requires precision and sensitivity of the magnetometers with accuracy up to 10pT.

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Therefore, currently SQUIDs take the dominant position for the heart's magnetic fields registration – they are based on superconducting quantum interferometers [1]. According to their extremely high sensitivity, they are almost without a rival. However, it has following disadvantages - too complicated construction, the high cost of manufacture and service and, the most important issue, the difficulties and inconveniences associated with the need to maintain the superconducting elements of the device operating at liquid nitrogen or helium temperatures (77K or 4K) [2]. That is why scientists often try to apply other methods to measure weak magnetic fields, which could replace the SQUIDs.

2 Methods

As an alternative to SQUIDs, we have developed a new type of fluxgate magnetometer [3]. By analogy with classical fluxgates [4] a new type of sensor uses single excitation coil to measure magnetic fields. It works based on the principle of the superposition of fields, produced by the current flowing in the core's winding. The structure of the sensor (see Figure 1) can be represented as follows:

- the core made up of ferromagnetic material can be circular or rod shaped, as in the classical differential fluxgate.
- excitation coil, which performs two functions simultaneously: saturates the core till it reaches the state of saturation and takes part in the measurement because its readings include the information about the measured magnetic field.

The main feature of this sensor is that the excitation winding consists of two semi-circular opened circuits having common A and B points, at which the current, generated to saturate the core, is measured. On condition of an external magnetic field *Hext* appearing, at the moment of the core saturation by the auxiliary field *Hm* an inductance imbalance occurs in the coils *L1* and *L2* that is detected by a differential amplifier *2*. The modulated signal is generated at the output of the amplifier. Its amplitude is changing proportionally to the change of the external magnetic field.

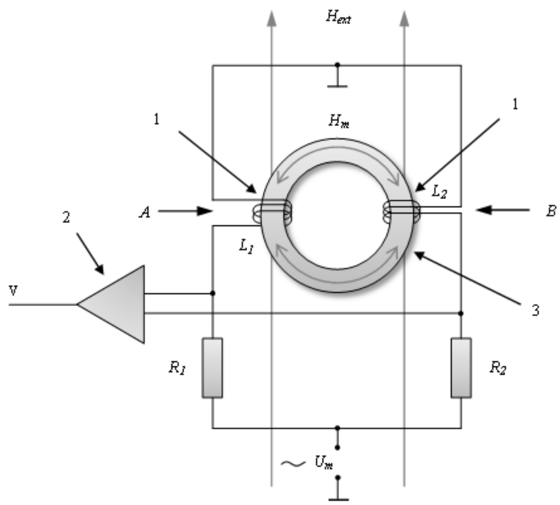

Figure 1: Circuit diagram of the differential fluxgate sensor. 1- saturation winding 2 - differential amplifier 3 - permalloy core.

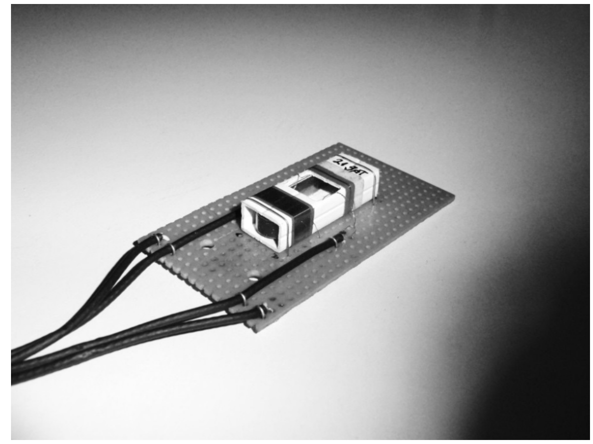

Figure 2: Fluxgate sensor prototype.

The peculiarity of this structure has a significant impact on the functionality of the sensor. The use of the single measuring coil enables to reduce requirements for the input signals, to minimize the thermal noise of the sensor and also to reduce the geometrical dimensions of the sensor.

On the basis of this model a prototype of the new sensor with the parameters shown in the table 1 was developed.

Table 1: Parameters of the designed magnetometer.

Parameter	Value
Sensor outline parameters [mm^3]	**35x10x5**
Core alloy:	**VITROVAC 6025 Z**
Number of tape layers [N_core]	**4**
Optimal frequency of the magnetization [Hz]	**10^4**
Number of turns in the windings *L1* and *L2* [N]	**100**
Voltage amplitude for the core's saturation [V]	**5**

Experimental design (general view) of the developed fluxgate sensor is shown in Figure 2. The magnetometer's core is made of a VITROVAC 6025 Z alloy with a thickness of 25 um in an elongated racetrack shape. Compared with the annular core this shape has a higher magnetic permeability [5].

To saturate the core a generator of the triangular signal coupled between terminals *Um* is used. At the first stage the flowing in both windings current induces a circular magnetic field *Hm* in a core. This field magnetizes the core along the hysteresis loop. Since the shape of the core is symmetrical about its longitudinal axis, the excited in the core field *Hm* uniformly influences to both halves A and B. Respectively, in a half cycle of the auxiliary magnetic field change *Hm* the magnetic field intensity is algebraically added with an external magnetic field $Hm + Hext = A$, on one side of the core, and on the other it is subtracted $Hm - Hext = B$. As a result, the difference of magnetic flux, passing through the excitation winding, changes by the external magnetic field. This affects the inductance of the windings $A - B \neq 0$ that causes their imbalance. The difference of the complex impedances between two circuits (R_1, L_1) and (R_2, L_2) is registered by the differential amplifier. The output signal of the magnetometer is presented in the following graph.

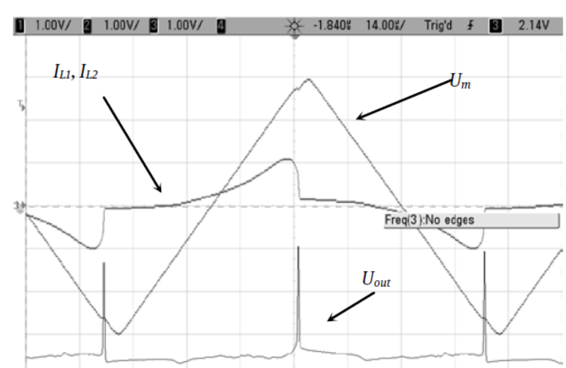

Figure 3: Measured output signals waveforms.

The amplitude of the output signal *Uout* carries information about the strength of the applied external magnetic field. The peaks polarity *Uout* varies depending on the polarity of the applied external field. The spectrum of the output signal is dependent on the frequency and amplitude of the signal, as well as on the exciting core, and can reach several hundred kHz. The sensitivity of the presented sensor was measured in magnetically shielded room. The performed experiments showed that the sensitivity of the magnetometer achieves 100 $pT/\sqrt{Hz}$.

Since peak-to-peak (p-p) measurement range of the human cardiogram magnetic field amounts 50 pT the sensitivity of the magnetometer is insufficient. To increase the magnetic field in the magnetometer's area magnetic concentrators were used. Flux concentrators, located near the core, concentrated field lines in the amount of flux gate, thereby increasing the conversion factor of the magnetometer [6].

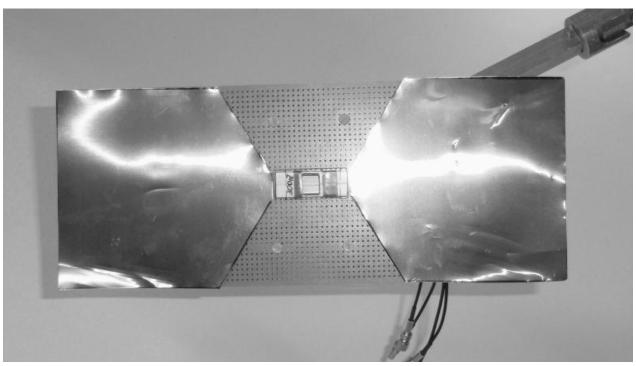

Figure 4: Fluxgate sensor with integrated magnetic flux concentrators.

Due to the concentrators from magnetic material Vitrovac 6025 that were placed around the edges the sensitivity of the magnetometer increased fivefold.

3 Measurement of heart magnetic activity

The tests were carried out in the magnetically shielded room (MSR) at the Biomagnetic Center, University Hospital Jena. Because of the strong magnetic noise produced by industrial devices, MCG measurements were performed in the MSR [7]. Noise spectral density in the room does not exceed 2 $fT\sqrt{Hz}$. Static magnetic fields, like the magnetic field of the earth, were compensated by an additional compensating coil.

The experiment was carried out with a volunteer positioned on a patient bed in the MSR. The signal from the fluxgate sensor was recorded at the distance of 10 mm from the chest of the test person. To carry out the analysis of the measured signal, the electrocardiogram of the test person was measured simultaneously. The two recorded signals were filtered. The bandpass filter limits of the frequency were from 1 Hz up to 1 kHz. It was difficult to determine the R-peaks of the magnetocardiogram in the received signal due to the strong noise. Therefore, the measured signal has been divided into several equal time intervals. Each R-peak of ECG was used as a trigger for the period's synchronization. Thus, each time interval contained one QRS complex of the cardiogram. To reduce noise, 200 intervals of MCG signal were collected and averaged subsequently. The resulting average signal is shown in Figure 5.

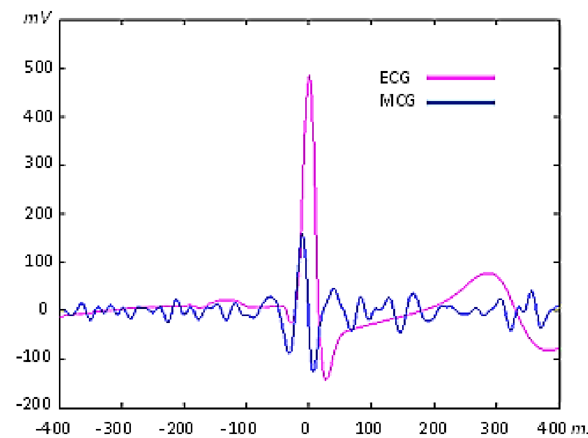

Figure 5: Average MCG and ECG signal.

The graph shows that two mutually independent measuring systems, MCG and ECG, recorded the R-peak in the same time interval. It means that the presented model of the fluxgate sensor is characterized by high magnetic sensitivity that allows for detecting the magnetic field of the heart.

4 Conclusion

The results of the research demonstrate that there is an opportunity to use fluxgate magnetometers for the measurement of biomagnetic fields without involvement of magnetometers, which are expensive in production and deployment. Perspectively such magnetometer could be used as a device for monitoring and controlling of the vital physiological parameters.

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Author's Statement
Conflict of interest: Authors state no conflict of interest. Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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