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SQUID MAGNETOMETER FOR BIOMAGNETIC SIGNAL DETECTION

BY

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Abstract. The paper presents theoretical and experimental results regarding the use of a SQUID magnetometer in detecting the biomagnetic fields, generated by bioelectric activity of the tissues. The work describes a SQUID magnetometer configured as a gradiometer, with first and second order and the electromagnetic environment in which such measurements can be made. Depending on the biological source, biomagnetic signal can have the induction value up to 50 pT. Considering a disturbing magnetic field source located at a given distance from the biological source, the work analyses the signal to noise ratio for the first and second order gradiometer configuration. Theoretical modelling shows an increasing signal noise ratio for the second order gradient of the magnetic field toward the simple measurement of the magnetic field or the first order gradient of the magnetic field. The signal noise ratio is even greater when the gradient is of higher order and the distance between the biomagnetic source and magnetic disturbance, increases. The experimental results show the SQUID gradiometer structure achieved and the recording of a biomagnetic signal generated by the heart's electrical activity – magnetocardiography.

Keywords: biomagnetometry; gradiometry; SQUID; magnetocardiography; magnetic shielded room.

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1. Introduction

Biomagnetic field measurements is a very special subdomain in magnetometry and is confronted with some difficult aspects such as the very small value of the measured parameters, which is from 10^{-15} T (the smallest) for the field generated by foetal heart to 10^{-12} T (the highest) generated by the adult heart and a poor signal/noise ratio (SNR) for these type of measurements. The omnipresence of environmental electromagnetic fields, with much higher values than the biomagnetic fields determines a poor signal/noise ratio and the necessity to carry out the measurements in spaces where the environmental electromagnetic fields are diminished to smaller values or comparable with the measured parameters, in order to improve the SNR. When it speaks about magnetic fields, the SNR refers to the level of the biomagnetic fields against the level of environmental electromagnetic fields and natural noises specific to the utilized magnetic sensor. The environmental magnetic and electromagnetic field spectrum is complex; therefore the methods to mitigate it are sophisticated from a conceptual and constructive standpoint. With these aspects in mind, the researches were focused on the diminution of ambient noise and/or on the development of certain measuring devices less sensitive to electromagnetic and magnetic environment. These developed systems with very high sensitivity threshold known up to now, for very weak magnetic field measurement, very versatile, are Superconducting Quantum Interference Device or SQUID, which are flux-voltage converters; they can measure any physical parameter that can be converted in magnetic flux (magnetic field, magnetic field gradient, magnetic susceptibility, voltage, current, mechanical displacement). One of the mostly known methods to improve the SNR is to configure, physically a classical magnetometric structure in a gradiometric structure. The gradiometers are preferable mainly because of their ability to detect magnetic field gradients and reject common vector of magnetic field.

2. Theoretical Aspects and Description of Gradiometer

The gradiometric structure is composed of two coaxial coils, with the same number of turns and identical sections, located in parallel planes, at a fixed distance, named baseline, connected in opposition in flux transformer circuit. This is the 1st order gradiometer but can obtain gradiometers with higher order by combining a desired numbers of first order gradiometers.

The biogradiometer was configured from a SQUID biomagnetometer and has three SQUID coaxial coils. The magnetometer sensors are connected through flux transformers to three independent electronic modules, such that to obtain three magnetometric channels.

The adopted solution is advantageous due to the fact that, from the three SQUID magnetometer channels, one can realize several SQUID gradiometers by using the electronic subtraction of the signal arrived from the three individual magnetometric channels (Baltag and Rău, 2015). By electronic subtraction produced at the output of the three channels, a four channel gradiometer was realized using the electronic subtraction operation at the output of the three channels, namely: two 1st order gradiometers with baseline Δz = 4 cm, a 1st order gradiometer with baseline Δz = 8 cm and 2^{nd} order gradiometer with baseline Δz = 4 cm. The configured gradiometer is shown in Fig. 1.

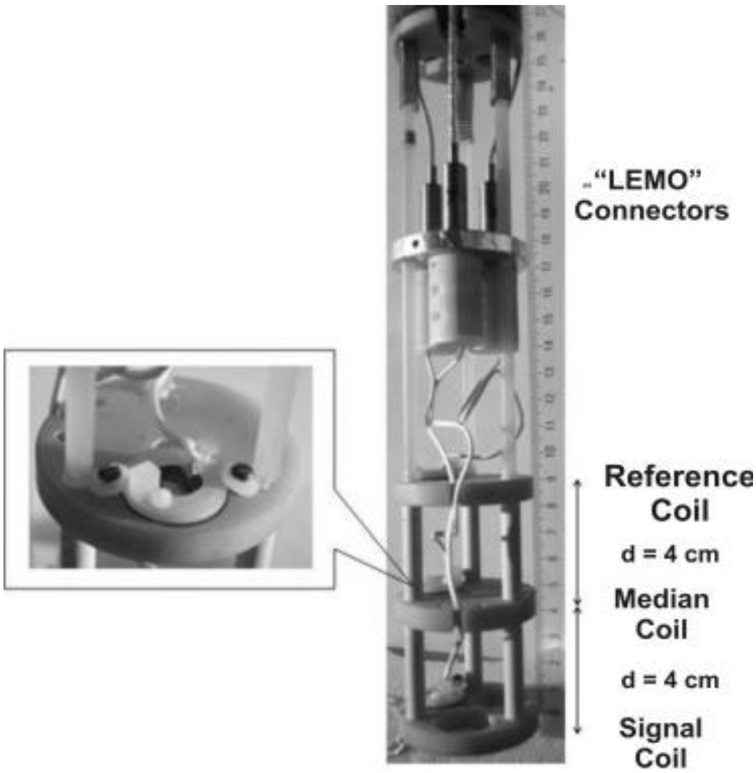

Fig. 1 – SQUID gradiometer.

For the operations of calibration and verification of the SQUID transducer, a Helmholtz coil was realized with a small field constant (comparable with biomagnetic fields); this permits to apply both fields and field gradients of known values.

Considering the magnetic moment of the biomagnetic source, *Ms* and the magnetic moment of the disturbance source *Mp*, one can compute, the SNR for the first order gradient, Eq. (1):

$$\left(\frac{S}{P}\right)_1 = \frac{G_s^1}{G_p^1} = \frac{M_s}{M_p}\frac{r_p^4}{r_s^4} \tag{1}$$

and for the second order gradient, one can compute the same ratio:

$$\left(\frac{S}{P}\right)_2 = \frac{G_s^2}{G_p^2} = \frac{M_s}{M_p}\frac{r_p^5}{r_s^5} \tag{2}$$

where S and P are signal respectively, perturbation (noise) source and r_p and r_s are the distance between the gradiometer SQUID and the perturbation source respectively biomagnetic source. Computing the ratio between the two relations it follows that the signal noise ratio is increased with a r_p/r_s factor, Eq. (3).

$$\frac{(S/P)_2}{(S/P)_1} = \frac{r_p}{r_s} \tag{3}$$

In practice, the factor $r_p/r_s < 100$.

We have analyzed the distribution with the distance of the magnetic field and of the 1st and 2nd order gradients produced by the two sources, one of disturbances and one of biosignal, and we found out that it is more advantageous to measure the 2nd order gradient than the 1st order gradient, as the SNR is improved, see Fig. 2 (Baltag and Rău, 2014).

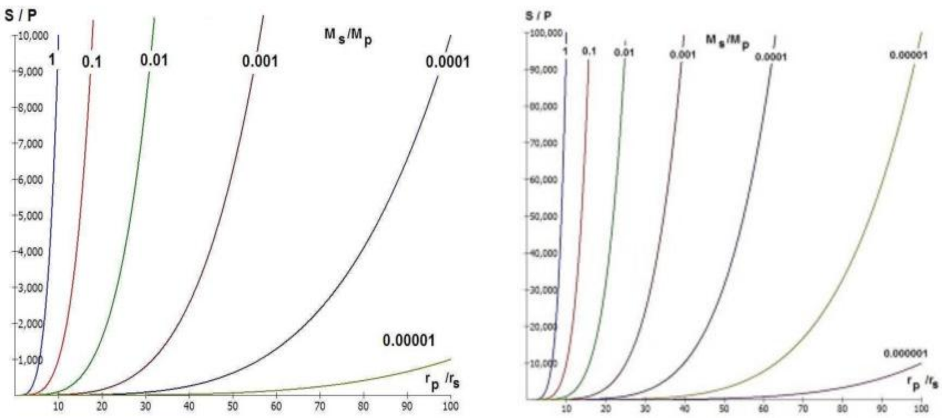

Fig. 2 – SNR for first and second order gradient.

3. Experimental Results

Given the fact that the SQUID magnetometer, an instrument with a very low sensitivity threshold, manifests some limitations connected with immunity from the external magnetic and electromagnetic environment, besides some precautions for providing an adequate screening, one must also take into account the electromagnetic conditions of the location. The configured SQUID biogradiometer is working properly only in a magnetic shielded rooms (RMS) sized (2x2x3)m with a dynamic system for annulment of the magnetic field, which is formed by a triaxial system of Helmholtz coils sized (4x4x4) m.

The squid gradiometer was used to record for the first time, in Romania, a biosignal generated by adult heart, a magnetocardiogram. The morphological aspects of the signal processed are very similar with the ECG signal, Fig. 3.

In the recorded magnetocardiogram signal one can establish the existence of some disturbing components produced by parasite external fields (50 Hz). The existence of the non-biological noise was also established in the absence of the examined patient. Therefore, an additional filtration of the obtained signal is necessary, being aware that it is mixed with this noise with the dominant frequency of 50 Hz in whose spectrum are also present the second and the third harmonics. In order to remove the residual signal of 50 Hz that appears at the gradiometer output, each electronic subtraction channel has in its composition circuits for phase correction of the residual signal of 50 Hz. The phase shifter permits the correction of 50 Hz residual phase such that to obtain a minimal residual signal at the output. Its peak to peak amplitude is of 21.6 pT_{pp}.

The obtained MCG signal is a primary signal. It was the first MCG signal recording in laboratory condition, from Romania (Rău, 2012).

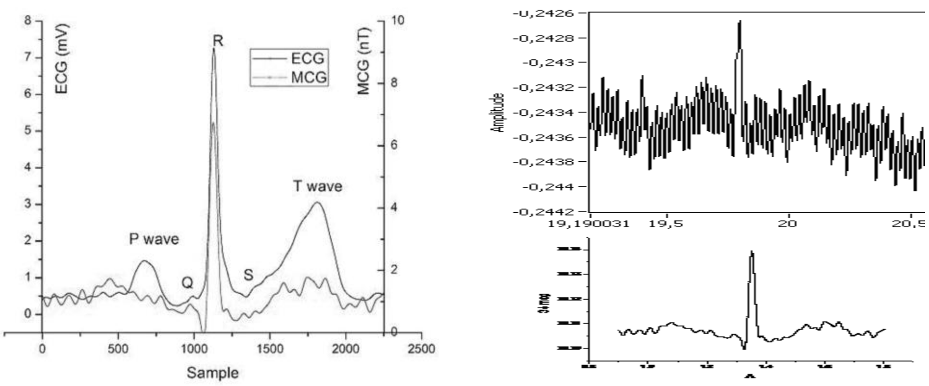

Fig. 3 – MCG/ECG signal.

4. Conclusions

The biogradiometer was configured from a SQUID biomagnetometer and has three SQUID coaxial coils. For theoretical aspects, we considering a disturbing magnetic field source located at a given distance from the biological source and analyses the SNR for the first and second order gradiometer configuration. Theoretical modelling shows an increasing SNR for the second order gradient of the magnetic field toward the simple measurement of the magnetic field or the first order gradient of the magnetic field. The SNR is even greater when the gradient is of higher order and the distance between the biomagnetic source and magnetic disturbance, increases. The morphological aspects of the obtained MCG biosignal are similar with the ECG biosignal.

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MAGNETOMETRU SQUID PENTRU DETECTAREA SEMNALELOR BIOMAGNETICE

(Rezumat)

Lucrarea prezintă rezultatele teoretice și experimentale referitoare la o instalație biomagnetometrică realizată de autori. Rezultatele teoretice demonstrează faptul că măsurătorile biomagnetometrice realizate în regim de gradiometrie au un raport semnal/zgomot mai mare decât cele realizate în regim clasic, iar între cele două tipuri de gradiometre acest raport este mai mare pentru măsurătorile făcute cu gradiometrul de ordin doi decât pentru cele făcute cu gradiometrul de ordin unu. Rezultatele experimentale au condus la performanța înregistrării primului semnal magnetocardiografic în România.