Performance of Fourier versus Wavelet Analysis for Magnetocardiograms using a SQUID-Acquisition System

B. Arvinti *, A. Isar**, R. Stolz***, M. Costache*

* "Politehnica" University of Timisoara/Physical Foundations of Engineering, Timisoara, Romania
** "Politehnica" University of Timisoara/ Faculty of Electronics and Telecommunications, Timisoara, Romania
*** Institute of Photonic Technology (IPHT)/ Department of Quantum Detection, Jena, Germany

Abstract—A lately developed clinical investigation method for the diagnosis of heart disease, the magnetocardiogram (MCG) is described in this paper. Sensitive sensors based on Superconducting Quantum Interference Devices (SQUID), developed at IPHT-Jena, Germany are used for the acquisition of reliable data. MCGs are sensitive to magnetic interferences and procedures in order to enhance the signal-to-noise ratio have to be developed. The paper aims at the comparison of the performance of Fourier versus Wavelet analysis applied to the input signal in order to enable the choice of the optimal processing technique for MCGs, advantages and drawbacks of each procedure being shown. A wavelet based baseline drift correction method and a denoising technique for the reduction of the biological noise of MCGs have been developed and compared to the Fourier based filtering procedure from IPHT-Jena.

I. INTRODUCTION

The connection between electricity and magnetism has been proven through the experiments of Ørsted in the 19th century, but the biomagnetic fields generated by the electrical activity of the human body could be measured only lately, through the improvement of the technical devices [1]. Magnetocardiograms (MCG) are a non-invasive clinical method in biomedicine used for the diagnosis of heart disease. Through the electrical activity of the heart, a biomagnetic field will be generated, the MCG revealing thus similar data to an electrocardiogram (ECG). The main difference between the two diagnostic techniques consists in the acquirement of data: for ECGs we use multiple electrodes in contact with the skin of the patient, while the MCGs are acquired with contactless transducers using sensitive Superconducting Quantum Interference Devices (SQUID). The electrodes used for the acquisition of ECGs might be a noise source for the system if the contact is not realized properly, a drawback that is not encountered in the case of MCGs.

Another advantage for the use of MCGs refers to the acquisition of fetal records. Fetal MCGs can be recorded in conditions when the acquisition of fetal ECGs is made difficult by the development of the vernix caseosa, a white, waxy substance that covers and protects the skin of the fetus [2]. Studies reveal the fact, that during the 25th and the 36th week of gestation, the probability of an increased failure rate for fetal ECGs is high [3] while, on the contrary, MCGs show higher signal-to-noise ratios in the advanced period of gestation.

The importance of the development of a reliable data acquisition system for MCGs is given by the weak intensity of the biomagnetic field: as an example, for adults we measure between 3-30 pT/m, while the biomagnetic field gradient of fetuses can reach even lower values, depending on the gestational age. As a comparison, the magnetic field of the Earth is approximately $10^6$ or $10^7$ times stronger than the biomagnetic field produced by the human heart. The surrounding magnetic fields will interfere with the recorded MCGs making the inspection of the MCGs difficult. These considerations highlight the importance of the diagnostic technique through the immense increase of the costs for the whole system. A sensitive sensor has to be coupled with the correct signal processing method in order to improve the performance of the acquisition system.

The aim of this paper is to compare two different processing techniques, the Fourier and the wavelet analysis, using an MCG acquisition system based on SQUIDs, highlighting advantages and drawbacks of each technique and enabling the choice of the optimal processing technique and the development of an optimal algorithm for the MCG data acquisition system.

II. DATA ACQUISITION SYSTEM

SQUIDs are most sensitive sensors for magnetic flux which provide information about the biomagnetic field generated by the cardiac activity. The technology of the presented data acquisition system was developed at the Institute of Photonic Technology (IPHT) Jena, Germany. The measurements are realised through a multi-channel acquisition system, six channels being used for the recording of adult and fetal MCGs. The system incorporates three first order gradiometers which measure the local vertical magnetic field components Bz along the x-direction and three orthogonal magnetometers used to suppress the effect of a homogenous magnetic field on the gradiometers.
In this paper we describe a method using gradiometric sensors based on SQUIDs manufactured in standard all-refractory Nb/AIOx/Nb technology developed at IPHT Jena [4]. Each gradiometer has two pick-up loops of 2.5 cm x 2 cm connected in series and inductively coupled to a second-order gradiometer SQUID having eight parallel connected loops with flux transformers. Three low-sensitive orthogonal SQUID washers-type magnetometers with an outer diameter of 140 μm are used to suppress in a post-processing step the remaining sensitivity of the gradiometers for homogenous magnetic field. To operate the SQUIDs, flux loop (FLL)-electronics controlled by a computer via a RS232 port, has been used. The FLL-electronics is directly coupled, without flux modulation. The main parameters of the FLL-electronics which operates the SQUID system are given in Table I. The electronics can be controlled by a PC through a standard serial RS232 interface. The SQUID signals were digitized using a self developed recording system with 24 bit ADC which amplifies and digitizes the signals of the SQUID sensors at a sampling rate of 1 kHz. The SQUID system is mounted in a cryostat, developed by Cryotom Ltd. Moscow [5], which ensures the temperature of 4.2 K needed for the superconducting state. The external diameter of the cryostat is approx. 180 mm with a length of approx. 700 mm. The hot-to-cold distance is approx. 12 mm. It can contain up to 5,2 l of liquid helium, the complete evaporation time being more than 3 days. The initial noise of the cryostat is inferior to 5 fT/√Hz.

The MCG signals are picked up using the described system. The signal gradiometers G1 and G2 are placed parallel aligned to each other at the bottom of the cryostat. The biomagnetic signal will be picked up above the chest or the abdomen of the patient (in the case of fetal MCGs) by G1 and G2. Both gradiometers (G1 and G2) will measure a mixture of the magnetic signal of mother, fetus and interfering noise. The third gradiometer G3 is placed 9 cm above the signal gradiometers G1 and G2 in the cryostat. It records a strongly reduced fetal signal. If the surrounding environment does not cause strong magnetic gradients, G3 measures almost the same amplitude of the mother’s heart signal and the interfering noise. Therefore, if the second order gradients (d²Bz/dxdz) are built, e.g. G1-G3 and G2-G3, in a post-processing the remaining signal should stem from the fetal heart. The system provides another advantage: by rotating the cryostat, often a position could be found where the mother’s heart signal is strongly reduced. In this case the mother heart beat could almost be removed out of the processed second order gradiometer signal.

III. DESCRIPTION OF FOURIER AND WAVELET ANALYSIS

The SQUID acquisition system has been employed for recording in unshielded environments, in a hospital environment in Jena. The value of the biomagnetic field to be recorded being weaker than the surrounding magnetic fields, there will appear interferences and thus procedures in order to suppress the external noise have to be developed. As hardware procedure was envisaged the development of highly balanced planar SQUID gradiometers which reduce the effect of the three orthogonal magnetic field components on the measured gradients. The weak signal-to-noise ratio is further enhanced through software methods, like digital filtering. Two procedures of digital filtering based on Fourier and Wavelet analysis are studied and developed in this paper.

The method based on Fourier analysis has been developed at IPHT-Jena [6] and applied on recorded data in hospital and laboratory environment. The measurements were performed both on adult men and on pregnant women, in the 25th – 36th week of gestation.

The procedure based on the Fast Fourier Transform (FFT) requires the following steps (Fig. 1): first, a least square algorithm was used to build electronically the second order gradiometer, through the substraction of the reference gradiometer G3 from G1 or G2. The same procedure is applied to G1-G3 and G2-G3 using the signals of the reference magnetometers. To the resulting signals is applied a FFT. We can thus examine the spectral components of the MCG. Now high-pass and low-pass filters are built in Fourier space, setting all frequency components below 0.5 Hz and above 80 Hz to zero. The residual peaks in the spectra are reduced with a linear interpolation in the frequency space. The interpolation is done using the mean value of 20 frequency taps before and after the peak. The width of the 50 Hz peak is assumed to be 4 Hz and the widths of the other peaks are assumed to be 0.4 Hz. After this filtering procedure, the complex valued Fourier spectrum is transformed back into the time space.

The wavelet based filtering procedure uses the Stationary Wavelet Transform (SWT), because it represents a more flexible analysis tool for the processing of quasi-periodical biological signals, such as the ECGs [7] than the Discrete Wavelet Transform (DWT). There are two steps to be taken: first, we must apply a baseline drift correction method and afterwards the processed signal has to be filtered. The working algorithm for the SWT uses several high-pass (HP) and low-pass (LP) filters in order to calculate the approximation and the detail coefficients of the wavelet transform.

<table>
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<th>TABLE I. MAIN PARAMETERS OF THE FLL-ELECTRONICS</th>
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<td>PARAMETER</td>
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<td>White noise</td>
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<td>1/ corner frequency</td>
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<td>Bandwidth</td>
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Figure 1. The algorithm of the filtering procedure based on FFT.
There will be several decomposition levels $i$, the iteration number depending on the MCG sampling frequency $f_s$ and selected to satisfy the condition $2^i/f_s \geq 1$ [7]. The wavelet based approach on MCG processing needs the pre-selection of two features: the mother wavelet used for the computation of the SWT and the number of decomposition levels. The proposed baseline drift correction method is based on the removal of the estimation of the baseline wander and comprises several steps (Fig. 2):

- application of the SWT to the input signal;
- setting of the detail coefficients to zero;
- application of the inverse SWT (ISWT), the new sequence representing the estimation of the baseline drift;
- removal of the baseline drift through the subtraction of the computed estimation.

This method allows us to obtain very selective filters. As mother wavelet, similar good results have been obtained with Daubechies5 and with Coiflet4, the use of mother wavelets with good temporal localization being recommended [8].

For a sampling frequency of the MCGs of 1 kHz, the proposed number of iterations is 10.

The second step of the proposed wavelet based analysis of the MCG consists in the application of a denoising technique for the reduction of the noise contained in the biomagnetic signal $s$.

For the proposed wavelet based denoising method, we are taking into consideration the additive nature of noise (1), the noise $N_{\text{sig}}$ being additively added to the useful signal $U_{\text{sig}}$:

$$s = U_{\text{sig}} + N_{\text{sig}}.$$  \hspace{1cm} (1)

There are three steps for applying this filtering method:

- application of the SWT to the input MCG;
- filtering of the wavelet coefficients;
- application of the ISWT, the signal being thus back-converted in the time domain.

The wavelet coefficients $w$ resulted through the computation of the SWT will also reflect the additivity of the noise (see (1)):

$$w = \text{SWT}(U_{\text{sig}}) + \text{SWT}(N_{\text{sig}}) = y + n_0.$$  \hspace{1cm} (2)

so we will have useful ($y$) and noisy ($n_0$) wavelet coefficients and we will take an inter-scale dependency between the coefficients into consideration. There will be a distinction between parents and children coefficients.

The input-output relation of the filter proposed in this paper is:

$$z_i = \|w| - t\|w|,$$  \hspace{1cm} (4)

where $t$ represents a threshold and:

$$X_s = \begin{cases} X, & \text{for } X > 0 \\ 0, & \text{otherwise.} \end{cases}$$

We have used the threshold value proposed by D. Donoho [9, 10], depending on the length of the processed samples $k$:

$$t = \sigma_{N_{\text{sig}}} \cdot \sqrt{2 \cdot \log(k)}.$$  \hspace{1cm} (5)

For the first decomposition level, the noise standard deviation $\sigma_{N_{\text{sig}}}$ can be estimated from the median of the detail wavelet coefficients $w(1,i)$ for that level:

$$\sigma_{N_{\text{sig}}} = \text{median}(|w(1,i)|)/0.6745.$$  \hspace{1cm} (6)

IV. PERFORMANCE OF FOURIER VERSUS WAVELET ANALYSIS

In order to test the limits of the two different procedures, the signals were recorded in unfavorable conditions. The performances of the Fourier and the wavelet based denoising algorithm will be examined on the same database, namely on adult and fetal MCGs recorded at IPHT-Jena. One of the advantages of the FFT method is the possibility of examining the frequency distribution of the processed signal.

The paper will refer to mother and fetal MCG records because they present a low signal-to-noise ratio being thus better suited to illustrate the performance of the applied filtering procedures and because it is often difficult to determine the exact position of the fetus’ heart so as to obtain noiseless measurements.

In Fig. 3 is examined the frequency spectrum of a MCG obtained from the second-order gradiometer G1-G3 of a patient, provided by IPHT-Jena and representing both mother and fetal signal. The fundamental frequency $f_{\text{MCG}}$ of the MCG can be estimated measuring the QRS pulse rate of the patient. Healthy adults show a rate between 60 and 80 beats/minute, fetuses have a little higher rate, depending on the gestational age. Dealing both with adults and fetuses at the acquisition of MCGs we will consider the $f_{\text{MCG}}$ around 1 Hz. From Fig. 3, we can observe high peaks at the frequency of 16.67 Hz and 50 Hz, suggesting serious magnetic interferences from the electric train power and power line. Fig. 4 shows the recorded signal before the application of any filtering procedure.

In Fig. 5, the described Fourier based filtering procedure has been applied. The resulting fetal MCG

![Figure 2. Scheme of the baseline correction method.](image-url)
reduces the initial baseline drift, but still presents a high baseline wander. A zoom has been made on five beats of the processed signal, to illustrate better the necessity of further denoising the MCG (Fig. 6). The noise components are still present for fetal MCGs recorded in unfavorable conditions.

The wavelet based filtering method comprises two steps: first we apply the baseline correction method and afterwards we will apply the denoising method.

The wavelet baseline correction has been applied to the same data as the Fourier based procedure, the results being shown in Fig. 7. We notice that the baseline corrected with the wavelet based procedure is closer to zero for the zones with high drift than the baseline presented in Fig. 5.

The need to further denoise the signal is clearly to be seen in Fig. 8. In Fig. 8a, it can be seen the baseline estimation in red, while the result of the drift correction is to be seen in Fig. 8b. The new baseline is close to zero everywhere.

The mother wavelets chosen for the computation of the SWT is Coiflet4, for a number of 10 decomposition levels. For a smaller value of the number of decomposition levels, disturbances of the useful components of the MCG could be induced, while for a larger value the baseline correction will show poorer results (see Fig. 9).
The computational time is increased with the increase of the iteration number and for a too large value of \(i\), the ability of the system to follow up the rapid variations of the MCG will be affected. The second step of the wavelet analysis, the wavelet based denoising procedure is applied to the corrected signals. To distinguish between the two steps, the denoised MCG has been marked with black. The flexibility of the method allows the separate selection of mother wavelets for the two procedural steps, baseline wander reduction and denoising. For the denoising method another mother wavelet has been chosen, namely Daubechies1, for the same number of decomposition levels \(i=10\). The result of the SWT based denoising algorithm is shown in Fig. 10 for the five beats already referred to. Comparing the result of the SWT based filtering procedure with the result of the FFT based filtering algorithm (shown in Fig. 6) we notice that there are less high frequency noise components in Fig. 10. The SWT based denoising method removes only the biological noise approximated by white Gaussian noise (such as myoelectric noise), but this noise is not the main noise that affects MCGs. Another wavelet based denoising procedure is still necessary to be developed for the complete elimination of noise.

V. CONCLUSION

The data acquisition system using SQUIDs is able to measure weak biomagnetic signals, such as the ones generated by the human heart. When recording in an unshielded environment, the SQUID system is sensitive to magnetic interferences and procedures in order to improve the performance of the acquisition system have to be developed. Besides the magnetic interferences produced by the consume of electrical energy of the neighborhood equipments, the MCGs are also affected by biological noise caused by muscle activity and by baseline drift due to the breathing mechanism.

In this paper the performances of two different procedures were compared for signals recorded in unfavorable conditions. A Fourier based filtering procedure, developed at IPHT-Jena for the reduction of the magnetic interferences was compared to the herein described Wavelet based filtering procedure, developed for the reduction of the biological noise and of the baseline drift. The wavelet method consists of two steps, a baseline drift correction method and a filtering procedure for biological noise reduction.

The Fourier based analysis technique enables the identification of the frequency content of the input signal. An insight into the spectral components of the MCGs and the identification of noise sources is made possible. The proposed Fourier based filtering procedure reduces the initial baseline drift, being effective especially for zones with moderate drift (see Fig. 5 compared to Fig. 4). For the zones with high baseline drift, the problem is not entirely solved, high baseline drift being still present.

The wavelet based baseline drift correction method, using the SWT and the Coiflet4 mother wavelets for 10 decomposition levels, solves the problem of the baseline drift reduction in a better way. The resulting baseline presented in Fig. 7 is closer to zero than the baseline shown in Fig. 5, the possibility of putting a correct diagnosis being thus enhanced.

The Fourier based filtering procedure does remove most but not all interferences during the acquisition of a fetal signal recorded in unfavorable conditions (a possible situation in the clinical environment), as can be seen in Fig. 5.

The wavelet based filtering procedure reduces only the biological noise which constitutes a main noise source in the case of ECGs but not being very effective in the case of strong magnetic interferences upon MCGs.

Comparing the results of the denoising procedures applied in Fig. 6 and Fig. 10, for the same five beats, we notice that the noise still presents a problem for the acquisition of the MCGs in unshielded environments for fetuses’ records, both procedures needing further improvements. The Fourier based filtering procedure must be developed further to reduce the biological noise and the baseline drift. The wavelet based methodology must be rethought to reduce the magnetic interferences.

Still, the QRS complex of the MCG is clearly to be seen for both cases and allows already the heart rate determination even in magnetically unshielded environments.

The development of a wavelet based denoising method to reduce interferences at discrete frequencies like power line 50Hz noise constitutes a research topic for further studies.
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REFERENCES