Adaptive Frequency Dependent Gradiometry Applied to SQUID Magnetocardiography

Marcel Bick, Grigory Panaitov, Michael Schiek, Yi Zhang, and Hans-Joachim Krause

***Abstract*—In the case of magnetocardiography (MCG), gradiometry is a commonly used method to reduce environmental noise. Here, the balance of the gradiometer is one of the main parameters determining the achievable noise reduction. In earlier work, we reported the use of frequency dependent gradiometer coefficients to effectively balance a gradiometer consisting of signal and reference sensors. In this work, the advantages of adaptive determination of these coefficients during a measurement without perturbing the MCG signal are investigated. MCG measurements were recorded with first and second order high temperature SQUID gradiometers inside and outside magnetic shielding. It will be shown that the heart signal is not distorted by applying our software noise reduction technique. Furthermore, by recalculation of gradiometer coefficients during the MCG measurement, an improved signal-to-noise ratio is achieved. The optimum repetition time for coefficient recalculation is determined.**

***Index Terms*—Adaptive noise cancellation, gradiometry, magnetocardiography.**

I. Introduction

THE measurement of MCG signals in the presence of large magnetic disturbances requires high quality measuring systems and sophisticated noise cancellation techniques. To avoid the use of high cost magnetically shielded rooms, several HTS SQUID gradiometers have been developed to suppress environmental noise outside magnetic shielding, e.g., [1]–[4]. However, to record high quality MCG signals, these systems require the use of notch filters at power line frequencies or a limited bandwidth of less than 130 Hz. Notch filters may destroy signal information and MCG measurements require a bandwidth of 250 Hz [5]. Therefore, improved noise reduction techniques are desirable.

HTS SQUID gradiometers often consist of signal and reference sensors. These can be combinations of magnetometers [3], [4] or intrinsic 1st order gradiometers [2]. The reference sensors with amplitude b_i are used to subtract environmental noise from signal sensors with amplitude a situated close to the signal source. The subtraction is performed either electronically or by software. Balancing coefficients k_i are determined, so that a noise reduced output $s = a - \Sigma\, k_i \cdot b_i$ is generated [6].

It has been shown that adaptation of these coefficients to the local noise environment is advantageous compared to fixed coefficients predetermined in homogeneous and gradient calibration fields [7], [8]. Furthermore, it was demonstrated that the determination of frequency dependent factors $k_i(f)$ leads to improved noise reduction especially at power line frequencies [4], [9], [10]. This is due to the fact that noise sources generating high order gradient fields at different frequencies require different balancing coefficients.

When noise changes quickly in amplitude and phase, it is advantageous to recalculate balancing factors during the measurement. Kuriki *et al.* [11] have adaptively determined 50 Hz filter coefficients to track temporal changes of power line disturbances. They used an oscillator to generate a sinusoidal signal with a fixed frequency of 50 Hz which was fed into a compensation coil. As amplitude and phase of this signal were extracted from the bandpass filtered signal of the sensing magnetometer, information about the source signal at this frequency is lost. Furthermore, this method seems not to be suitable for noise reduction at multiple frequencies as it would require multiple oscillators.

In this work, we will show that recalculating frequency dependent gradiometer coefficients *during* MCG measurements leads to an improved signal-to-noise ratio (SNR). In this way, tracking of temporal noise changes at multiple frequencies is possible. Only a minor noise reduction is achieved when coefficients are adapted to the local noise environment *before* the measurement. Furthermore, we will demonstrate that there is no distortion of the source signal when applying our noise reduction technique.

II. Method: Frequency Dependent Gradiometry

In earlier work, we reported on Frequency Dependent Gradiometry (FDG) to improve noise reduction of HTS SQUID gradiometers [10]. The principles of FDG are described in [12]. In summary, the time series of signal and reference sensors are Fourier transformed using overlapping Hanning windows. By data averaging over several time windows, frequency dependent gradiometer coefficients, $k_i(f)$, are calculated. Subsequently, the reference data are subtracted from the signal data in the frequency domain to generate a noise reduced output.

The choice of two free FDG parameters mainly determines the effectiveness of the method: the threshold parameter, σ_k, and the repetition time for coefficient recalculation, τ_A. The number of averages in the Fourier domain determines the standard deviation, σ, of the calculated coefficients. By definition, environmental noise is detected at a certain frequency if a coefficient can be determined with a standard deviation smaller than a threshold parameter σ_k: $\sigma < \sigma_k$. At all other frequencies, the coefficients are set to zero and the reference data are not subtracted from the signal data. This enhances the signal-to-noise

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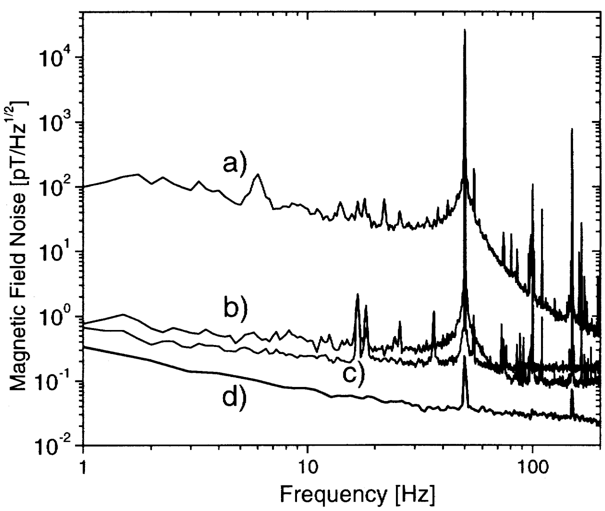

Fig. 1. Magnetic field noise in unshielded environment of a) magnetometer, b) bottom FOG of the SOG and c) SOG. (d) shows the field noise of the highly sensitive FOG described in [13] recorded inside the MSR.

ratio because the noise of the reference sensor is not added to the overall system noise [12]. To track noise changes, the coefficients can be recalculated during the measurement within a time interval τ_A. Ideally, they are known at every point in time ($\tau_A \rightarrow 0$). This is not possible due to the need to average over several time windows. Therefore, a short repetition time, τ_A, for recalculation will reduce the achievable accuracy of the coefficients, as this depends on the number of averages used for calculation. On the other hand, a small τ_A will improve the rate of adaptation to changing noise sources. Thus, an optimum parameter τ_A has to be determined for the given noise environment to achieve maximum noise reduction. This will be analyzed in detail in Section IV.

III. Experimental

To investigate the possibility of adaptive determination of frequency dependent gradiometer coefficients, we performed MCG measurements with a 2nd order gradiometer (SOG) in an unshielded environment. The SOG consisted of 3 axially arranged HTS rf SQUID's with baseline distances of 7.5 cm [3]. The system noise was 150 fT/$\sqrt{\text{Hz}}$ (Fig. 1(c)). The bottom and center and the center and top magnetometer, respectively, formed two 1st order gradiometers (FOG), which were electronically balanced achieving a common mode rejection of 10^4. The background noise in our laboratory and the magnetic field noise of FOG and SOG are displayed in Fig. 1.

To apply FDG, the upper gradiometer of the SOG was used as a reference. MCG time series of signal and reference sensor (bottom and top FOG) were simultaneously recorded with a PC. A bandwidth of 250 Hz, including a high-pass filter at 0.05 Hz, and a sample rate of 1 kHz were used. No notch filters were employed. The total recording time, T, was 110 s. Noise reduction of the time series of the signal sensor was achieved by calculating frequency dependent coefficients and subtracting the reference from the signal data in the frequency domain as described in Section II. The threshold parameter, σ_k, and the time interval for coefficient recalculation, τ_A, were varied within the following ranges: $0.1\% \leq \sigma_k \leq 50\%$, and $4\text{ s} \leq \tau_A \leq T$. Coefficients with standard deviations larger than σ_k were set to zero. For $\tau_A = T$, the coefficients are calculated only once; for $\tau_A = 4$ s, they are recalculated every 4 s to improve the adaptation to noise changes.

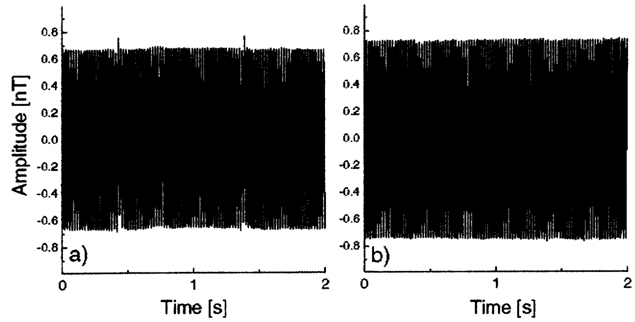

Fig. 2. MCG time series simultaneously recorded with the bottom FOG (a) and the top FOG (b) of the SOG in unshielded environment.

To investigate the preservation of the MCG signal while applying the FDG algorithm, we recorded the heart signal of the same subject inside a magnetically shielded room (MSR) with the highly sensitive 1st order gradiometer described in [13]. The magnetic field noise of this system inside the MSR (Fig. 1(d)) is much lower compared to the SOG in unshielded environment (Fig. 1(c)). Therefore, the recorded MCG signal is of high quality and can be taken as a reference for comparison with the FDG corrected signal measured outside magnetic shielding.

IV. Results

A. Adaptive Noise Reduction

An MCG sequence recorded with the bottom FOG of the 2nd order gradiometer is displayed in Fig. 2(a). The signal is dominated by external noise. Only the main component of the heart signal is visible. Fig. 2(b) shows the reference signal simultaneously recorded with the top FOG. The measurements were performed in unshielded environment.

Applying FDG, we first investigated the influence of the threshold parameter σ_k on the achievable SNR without coefficient recalculation during the measurement, i.e., $\tau_A = T$. T denotes the total length of the time series of 110 s. We found an optimum SNR for $\sigma_k = 6\%$ [Fig. 3(a)]. In this case, nine gradiometer coefficients could be determined with a standard deviation of $\sigma < 6\%$, mainly at power line frequencies [Fig. 3(b)]. At all other frequencies, no noise was detected, the coefficients were set to zero, and the signal data was not corrected for noise. For $\sigma_k = 0.5\%$, only two coefficients could be calculated – at the most dominant noise frequencies of 50 Hz and 150 Hz [Fig. 3(c)]. In this case, σ_k is chosen too small and existing noise sources at other frequencies are not detected by the algorithm. Thus, the SNR decreases dramatically [Fig. 3(a)]. If σ_k is too large, the number of coefficients with a large standard deviation is high [Fig. 3(d)]. This also leads to a reduction of the SNR [Fig. 3(a)]. Therefore, a suitable choice of σ_k is crucial to achieve optimum noise reduction.

Next, we investigated if adaptive determination of balancing coefficients during the MCG measurement lead to an enhanced

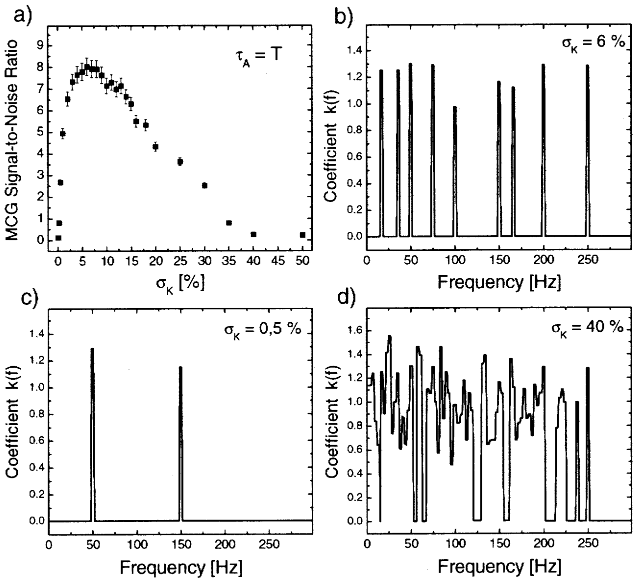

Fig. 3. Variation of the threshold parameter σ_k for $\tau_A = T$: The optimum SNR of the MCG time series is achieved for $\sigma_k = 6\%$ (a). (b)-(d) show calculated balancing coefficients $k(f)$ for different threshold parameters: (b) σ_k is optimum, (c) σ_k is too small, (d) σ_k is too large. Description see text.

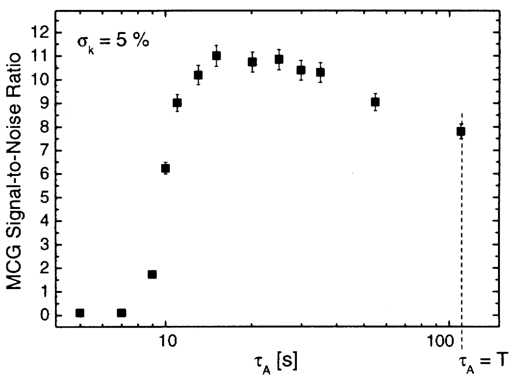

Fig. 4. Signal-to-noise ratio of an MCG depending on the time interval τ_A used for coefficient recalculation during the measurement. The optimum SNR is achieved if the coefficients are recalculated every 15 s.

noise reduction. The results are shown in Fig. 4. A short repetition time, τ_A, for coefficient recalculation should lead to a high rate of adaptation to a given noise environment. However, if τ_A is smaller than about 10 s, the SNR of the MCG signal decreases dramatically (Fig. 4). This is due to the fact that the number of averages in the frequency domain – i.e., the number of time windows – is not large enough to calculate the coefficients with sufficient accuracy. This leads to a minor noise reduction and consequently to a low SNR. If a very long repetition time, τ_A, is chosen (e.g., $\tau_A = T$), the adaptation to changing noise sources is reduced and thus the SNR decreases again (Fig. 4). Therefore, a compromise between optimum adaptation to noise changes and sufficient coefficient accuracy has to be found. As shown in Fig. 4, the optimum SNR is obtained with a repetition time of 15 s for our noise environment.

Fig. 5 demonstrates that the choice of optimum FDG parameters, $\sigma_k = 5\%$ and $\tau_A = 15$ s for our noise environment, results in a significantly improved quality of MCG signals compared

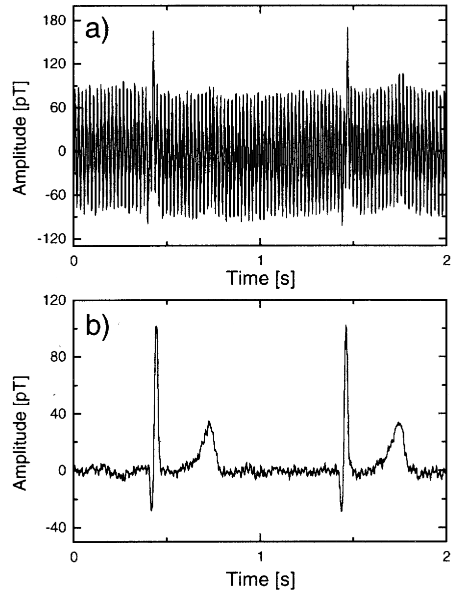

Fig. 5. MCG sequences recorded in unshielded environment with a bandwidth of 250 Hz without the use of notch filters: Frequency dependent balancing coefficients adaptively determined during the MCG measurement lead to a significantly improved noise reduction (b) compared to predetermined frequency independent coefficients (a).

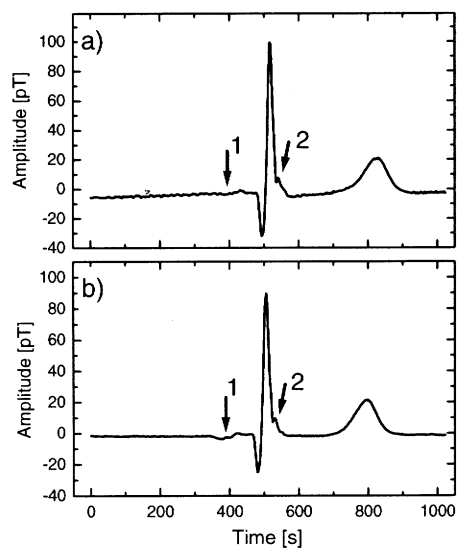

Fig. 6. Comparison of averaged MCG signals of the same subject: (a) noise reduced using FDG in unshielded environment, (b) recorded inside the MSR as a reference with a highly sensitive FOG.

to standard gradiometry with predetermined balancing coefficients.

B. Signal Preservation

The usability of a noise reduction technique significantly depends on the achievable preservation of the source signal. To investigate possible signal distortion due to the FDG algorithm, averaging of the still noisy FDG data is necessary. In this way, even small MCG details can be analyzed. In Fig. 6, two 100 times averaged MCG signals of the same subject are compared. Fig. 6(a) shows the data recorded in unshielded environment using FDG. Fig. 6(b) shows the data recorded inside magnetic shielding which can be taken as a reference. Both MCG signals exhibit the same small structures (1 and 2 in Fig. 6). This shows that the FDG algorithm does not distort the source signal even in the presence of large magnetic disturbances.

V. Conclusion

We have investigated the potential of adaptive determination of frequency dependent balancing coefficients to improve external noise rejection of gradiometers. MCG measurements in an unshielded environment with HTS SQUID gradiometers consisting of signal and reference sensors were performed. It was shown that recalculation of balancing coefficients during the MCG measurement leads to an improved adaptation to changing noise sources and thus to an improved signal-to-noise ratio of the MCG time series. A minor noise reduction was achieved using predetermined balancing factors. The optimum repetition time τ_A for coefficient recalculation depends on the achievable accuracy of the coefficients and on the local noise environment. It was found to be $\tau_A = 15$ s for our laboratory.

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