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A digital filtering scheme for SQUID based magnetocardiography*

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Considering the properties of slow change and quasi-periodicity of magnetocardiography (MCG) signal, we use an integrated technique of adaptive and low-pass filtering in dealing with two-channel MCG data measured by high T_c SQUIDs. The adaptive filter in the time domain is based on a noise feedback normalized least-mean-square (NLMS) algorithm, and the low-pass filter with a cutoff at 100Hz in the frequency domain characterized by Gaussian functions is combined with a notch at the power line frequency. In this way, both relevant and irrelevant noises in original MCG data are largely eliminated. The method may also be useful for other slowly varying quasi-periodical signals.

Keywords: SQUIDs, adaptive filter, magnetocardiography
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1. Introduction

Magnetocardiography and other biomagnetic signals are in general very weak. Their detection should be made with SQUIDs in a magnetically shielded room, the construction of which is usually costly. Therefore, it is practically desirable to realize the biomagnetic measurements with both a simplified shielded room of reduced cost and a high quality output signal. Recently, the efforts along this diagram have been made by many researchers.[1−4] In most MCG measurements with cheap and simple magnetic shielding, the signals are usually weak in comparison with environmental noises. In this case, the signal retrieval from a status buried in the environmental noises is essential. With the great progress of modern digital technique, the application of digital data processing for noise rejection is getting wider and wider today. Adaptive filtering, one of the modern data processing methods, is very powerful especially for the data sequences heavily buried in environmental noises, of which the statistic characteristics are not well known.

Least-mean-square (LMS) and recursive-least-square (RLS) algorithms are two of the most popular algorithms for adaptive filtering. Many authors have developed new forms of these two algorithms, such as normalized LMS,[5] data-reusing LMS,[6] and fast-speed RLS algorithms.[7] In this paper, we use a noise feedback NLMS algorithm to reduce the rebounds of weight vector of the algorithm to a very small degree and eliminate the noise produced by the rebounds. In this way the noise in MCG signal can be suppressed down to a level comparable to the intrinsic noise of the SQUID electronics.[8] After that the resulting MCG data are processed further through a three-step filter in frequency domain. Firstly, according to the quasi-periodic property of the MCG data, we multiply the Fourier transformation of the data by a frequency dependent periodic function consisting of sectional Gaussian functions. Secondly, we cut off the data component with frequency higher than 100Hz. And finally, we filter the data with a notch at the power line frequency.

In the next section, we introduce briefly the adap-

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tive filtering for MCG data processing based on our noise feedback NLMS algorithm. In the third section, we present the three-step filtering characterized by the periodical function combined with the low pass and the notch for the further treatment of the resulting MCG data. Finally, discussions and conclusions are made in the last section.

2. A noise feedback NLMS algorithm for adaptive filtering

The MCG data acquisition is carried out by using two high T_c dc-SQUID sensors immersed in liquid nitrogen of a fibreglass dewar inside a one-layer magnetically shielded room.[9] One of the SQUID sensors for signal channel is vertically placed at the bottom of dewar inner tail as close as possible to the subject's chest and the other one for reference channel is positioned in parallel to the former one 10cm apart above the chest. The vertical magnetic field data sequences of the two channels are simultaneously acquisitioned with a sampling frequency of 2kHz.

An adaptive filter that we proposed with noise feedback NLMS algorithm[8] is used for the data processing. A block diagram of the filter is schematically depicted in Fig.1.

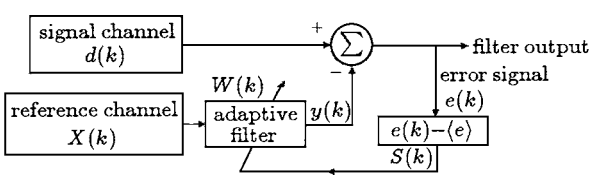


Fig.1. Block diagram of a noise feedback adaptive filter for noise elimination.

The algorithm can be expressed by the following equations:

$$y(k) = W^{\mathrm{T}}(k)X(k), \tag{1}$$

$$e(k) = d(k) - y(k), \tag{2}$$

$$W(k+1) = W(k) + \mu(k)X(k)S(k), \tag{3}$$

$$S(k) = e(k) - \langle e \rangle, \tag{4}$$

$$\mu(k) = \frac{\alpha}{X^{\mathrm{T}}(k)X(k) + \gamma}, \tag{5}$$

where functions $d(k)$, $X(k)$, $W(k)$ and $\mu(k)$ are time-dependent data sequences of the signal channel, the reference channel, the filter weight, and the step-size of the adaptive filtering respectively, and have their ordinary meanings as those in NLMS algorithm. The superscript T denotes the transposition of the relevant vectors and M is the filter length. Parameters α and γ are two adaptive constants.

In this algorithm, we have designed a new error function $S(k)$ in Eqs.(3) and (4) instead of $e(k)$ in conventional NLMS algorithm. The weighted average $\langle e \rangle$ of near past error data can be regarded approximately as instantaneous signal component to be discarded. It may be expressed by the following equation:

$$\langle e \rangle = \sum_{i=1}^{n} p(i)e(k-i) \Big/ \sum_{i=1}^{n} p(i) \quad (i = 1, 2, \cdots, n), \tag{6}$$

in which the weights in average are

$$p(i) = \frac{\exp(-i/l)}{|S(k-i)| + \beta}, \tag{7}$$

where l is the correlation length of the MCG signal, and β is a small positive number used to avoid the divergence of Eq.(7). With this modified algorithm the rebounds of weight vector $W(k)$ from its optimal value due to the signal component in $e(k)$ of conventional NLMS can be largely avoided.

Typical MCG experimental results of noise feedback NLMS algorithm with parameters M=6, α=0.0009, $\gamma = 1 \times 10^{-8}$, l=1, n=5 and $\beta = 1 \times 10^{-6}$ are depicted in Fig.2.

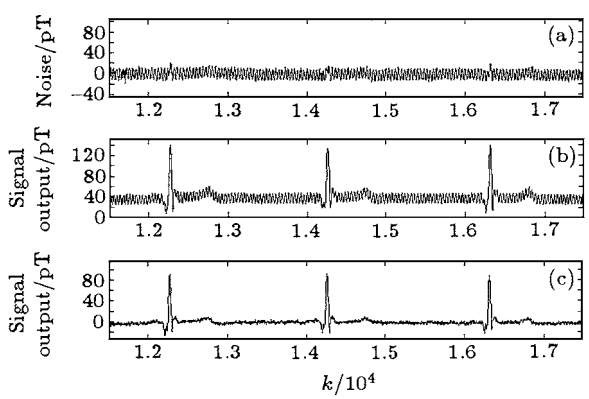


Fig.2. MCG experimental results (a) environmental noise in the reference channel, (b) MCG information plus noise in the signal channel and (c) the signal at the filter output.

With the peak-to-peak values about 28pT and 100pT of input noise and signal fields respectively as shown in Figs.2(a) and 2(b), the original signal to noise ratio is less than 4. From the output sequence in Fig.2(c) we can see that the ratio is improved more than three times.

3. Data filtering in the frequency domain

Although our modified NLMS algorithm has suppressed most of the relevant noises in MCG data, it

still does not satisfy the needs of its application to medical diagnosis. More treatments of the experimental data after having been adaptively filtered are necessary. One of the popular methods is averaging the data in n periods of cardiac activity. In this way the noise amplitude can be reduced by a factor of $\sqrt{n}$,[10] and the method is equally effective both for relevant and irrelevant noises. Nevertheless, the average will wash out all the non-periodic signals, which may have special meaning in diagnosis.

As we know, the frequency spectrum for an ideal periodic function is a sequence of discrete peaks centred at the fundamental frequency and its harmonics with zero width of each peak. However, any practical magnetocardiographic field is not exactly periodic and the heart beating is not strictly rhythmic due to both normal physiological function and possible heart diseases. In addition, the length of the collected data sequence is finite. This makes the width of the peaks in its frequency spectrum not infinitesimal.

From the statistical point of view the useful information in a quasi-periodic MCG is contained most likely in the frequency domain near its average frequency ω_0 and the harmonics. For this reason we construct a filter function, which consists of a sequence of normalized Gaussian functions centred at the averaged fundamental frequency ω_0 and its harmonics in MCG spectrum with a properly chosen mean-square error σ as shown in Fig.3(a).

The filter functions can be expressed as

$$G(\omega) = \max\{\mathrm{e}^{-(\omega - n\omega_0)^2/2\sigma^2}, \quad n = 0, 1, 2, ..., (N-1)\}, \quad \omega \geq 0 \qquad (8)$$

where N is the number of Gaussian functions, which depends on the sampling frequency. In addition, we take $\sigma = 0.67$ here. After the adaptive filtering, we multiply the frequency spectrum of resulting MCG data by $G(\omega)$.

As we know, when we probe a standard MCG signal, we may find that its major frequency component is below 40Hz and there is little left above 100Hz. Therefore, we use an additional low-pass filter with cut off frequency of 100Hz. The filter function can be written as

$$F(\omega) = 1 - \theta(\omega - \omega_c), \quad \omega \geq 0 \qquad (9)$$

where $\theta(\omega)$ is the step function, and here we take ω_c=100Hz. After the multiplication of the spectrum of MCG data by both $G(\omega)$ and $F(\omega)$, the spectrum is treated further. We note that in a simply shielded room the power line interference may still be severe even after an adaptive filtering, and so further treatment is still necessary sometimes. Considering that the waveform of power supply is also quasi-periodic, we use a notch filter at the power line frequency ω_p with a width $\Delta\omega_p$ of 0.4Hz. After taking these steps of the additional filtering, the data are converted back by the inverse Fourier transformation. Finally we obtain a real time MCG signal, in which most of the noises have been eliminated, as shown in Fig.3(b).

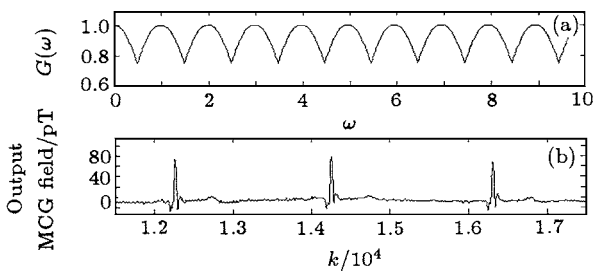


Fig.3. Filtering function (a) and the MCG signal in filter output (b).

From the comparison between Figs.2(c) and 3(b) we can see that the signal to noise ratio is further improved by the additional filtering, which is effective for both relevant and irrelevant noises. The combination of adaptive filtering in time domain and additional digital filtering in frequency domain makes the original signal to noise ratio improved largely. A real time trace of MCG with a signal to noise ratio of 25 is realized in our experiment.

4. Discussions and conclusions

In order to avoid any signal distortion we should pay attention to several issues in constructing the three-step filtering in frequency domain. One is that the peaks of the Gaussian functions must be kept in line with those of the MCG signal to be dealt with. At the same time the Gaussian mean-square error σ should be chosen properly. Another issue is that a larger cutoff ω_c will make the noise cancellation less effective, while a too small ω_c will make some useful information lost. Moreover, when we get rid of the power line interference, the notch should be performed successively by a cutoff centred at ω_p with a band width of $\Delta\omega_p$ and a smooth connection between the upper $(\omega_p + \Delta\omega_p/2)$ and the lower $(\omega_p - \Delta\omega_p/2)$ banks of the notch.

Using the noise feedback LMS algorithm, we may eliminate, the relevant noise part more effectively than

the ordinary NLMS algorithm in both convergence speed and tracking ability. By operating the additional low-pass filter both relevant and irrelevant noises can be further cancelled. Namely, by applying this combined technique MCG signals buried in the environmental and intrinsic noises can be well retrieved. We believe that with this technique a high attenuation shielded room becomes not essential for MCG measurement and that it will make the popularization of SQUID-based MCG in medical diagnosis more realistic. However, a simple-shielded room for keeping the SQUID sensors working stably during MCG measurement is still necessary.

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References

[1] Drung D 1995 *IEEE Trans. Appl. Supercond.* **5** 2112

[2] Vrba J 1997 *Proc. 19th Annual Int. Conf. IEEE-EMBS* Chicago, IL. USA, p1240

[3] Wakai R T, Wang M and Martin C B 1994 *Am. J. Obstet. Gynecol.* **170** 770

[4] Li Z, Chen G H, Zhang L H, Yang Q S and Feng J 2005 *Chin. Phys.* **14** 1095

[5] Treichler J R, Johnson C R and Larimore M G 1989 *Theory and Design of Adaptive Filter* (New York: Wiley)

[6] Jenkins W K, Hull A W, Strait J C, Schnaufer B A and Li X H 1996 *Advanced Concepts in Adaptive Signal Processing* (Norwell, MA: Kluwer)

[7] Carayannis G, Manolakis D G and Kalouptsidis N 1983 *IEEE Trans. Acoustic, Speech, and Signal Processing* ASSP-**31** p1394

[8] Zhu X M, Tian Y, Zhao S P, Chen G H and Yang Q S 2005 *Supercond. Sci. Technol.* **18** 1054

[9] Chen G H, Chen W C, Zhang L H *et al* 2002 *Proc. 13th Int. Conf. on Biomagnetism Jena* (Germany) p563

[10] Kong X Y, Wang H W, Tian Y, Huang X G, Zhang L H, Ren Y E, Chen G H and Yang Q S 2004 *Chin. Phys.* **13** 1820