BIOCYBERNETICS AND BIOMEDICAL ENGINEERING 33 (2013) 171–178

Available online at www.sciencedirect.com

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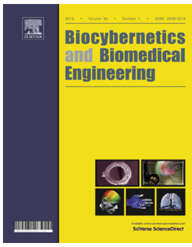
journal homepage: www.elsevier.com/locate/bbe



Original research article

Time-efficient removal of power-line noise from EMG signals using IIR notch filters with non-zero initial conditions

Jacek Piskorowski *

Department of Systems, Signals and Electronic Engineering, West Pomeranian University of Technology, Szczecin, Poland

ARTICLE INFO

Article history:
Received 16 November 2012
Accepted 26 February 2013
Available online 9 July 2013

Keywords:
Signal processing
Power-line noise
EMG signal
Notch filters
Transient response
Initial conditions

ABSTRACT

Power-line interference is always a problem when biopotential signals are recorded. This paper presents a technique for time-efficient power-line interference suppression from EMG signals using digital IIR (Infinite Impulse Response) notch filters with reduced transient response. The reduction of the transient response is obtained by finding optimal non-zero initial conditions for the considered notch filters. Simulations verifying the effectiveness of the proposed technique are presented and compared with the performance of the traditional notch filters with zero initial conditions using EMG signal with unwanted sinusoidal interferences as a study case.

1. Introduction

The field of electromyography research has enjoyed a rapid increase in popularity in the past number of years. The progressive understanding of the human body, the advancement of sensor technology, and the exponential increase in computational abilities of computers are all factors contributing to the expansion of electromyography research. With so much information and so many different research goals, it is necessary to take care of the quality of recording and processing of EMG signals. For this aim many various structures of filters can be used.

One of the important problems in the recording of electromyographic and other physiological signals is that the measurement signal is often distorted by additive power-line noise. A well-known method capable of reducing this kind of noise is to use a single-notch or multiple-notch filter characterized by a unit gain at all frequencies except at notch frequencies where the gain is zero. When the frequency of the power-line interference is known in advance, fixed notch filters can be used (for example, see [1–4]). However, when this frequency is unknown or time-varying, adaptive notch filters are applicable (for example, see [2,5–8]). In this paper, we will focus on the case when the frequency of the power-line interference is known in advance.

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* *Corresponding author at*: Department of Systems, Signals and Electronic Engineering, West Pomeranian University of Technology, ul. Gen. Sikorskiego 37, 70-313 Szczecin, Poland.
E-mail address: jacek.piskorowski@zut.edu.pl.

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http://dx.doi.org/10.1016/j.bbe.2013.07.006

Signal processing by traditional filtering algorithms brings many problems, such as transient response at the beginning of the processed signal [9]. When a noised signal passes through a notch filter for the removing of sinusoidal interference, the transient response distorts the filter output on the start-up. This phenomenon is particularly noticeable at low frequencies, where the transient process duration can take as long as several seconds. In the literature one can find only a few works which discuss the problem of the reduction of the transient duration in notch filters. In their work, Pei and Tseng present a technique for suppressing the transient response of IIR notch filters, which uses the vector projection to find better initial values for the considered notch filters [10]. When a notch filter is used to remove the power-line interference in the recording of ECG signals, the performance of the notch filter with transient suppression is better than that of the conventional notch filter with arbitrary initial conditions. The improvements with this technique are at the cost of additional computation load at the beginning of filtering process. Another technique for reducing the transient response of notch filters was proposed in [11,12]. In these papers the notch filter with zero initial conditions and time-varying quality factor was considered.

In this paper, a modified version of the technique proposed by Pei and Tseng, used to the removal of power-line noise from EMG signal is presented. This modification will have a very large impact on the filtering quality. The outline of the paper is as follows. In Section 2, digital IIR notch filters are discussed with more detail. The idea of non-zero initial conditions in notch filters is discussed in Section 3. In Section 4, examples of using the proposed method for filtering the EMG signal distorted by additive power-line noise are given. Finally, some concluding remarks are given in Section 5.

2. Digital IIR notch filters

Generally, the input of a notch filter can be described in the following form

$$x(n) = s(n) + \sum_{k=1}^{M} A_k \sin(n\Omega_{Nk} + \phi_k) = s(n) + d(n) \tag{1}$$

where $s(n)$ is a desired signal and $d(n)$ is a sum of sinusoidal interference signals with frequencies $\Omega_{Nk} \in (0, \pi)$, phase shifts ϕ_k, and amplitudes A_k ($k = 1, \ldots, M$, where M is the number of sinusoidal interference signals). In order to extract $s(n)$ from the corrupted signal $x(n)$ without distortion, the specification of an ideal notch filter is given by

$$\left|H(e^{j\Omega})\right| = \begin{cases} 0 & \text{for} \quad \Omega = \Omega_{Nk}, \quad k = 1, \ldots, M \\ 1 & \text{for} \quad \Omega \neq \Omega_{Nk} \end{cases} \tag{2}$$

In the literature one can find many methods that can be used to design IIR notch filters. One of the simplest and most useful techniques for designing notch filters is the pole/zero placement method. The location of the poles and zeros of the filter determine the behavior of the filter. The pole/zero placement design procedure is based on a radial representation of the filter transfer function. For notch filters the zeros are placed on the unit circle at the prescribed notch frequencies Ω_{Nk}, i.e. $z_k = e^{\pm j\Omega Nk}$ and the poles, at the same frequencies, very close to the unit circle, i.e. $p_k = re^{\pm j\Omega Nk}$, where r is the pole radius. For stability, it is required that $r < 1$. Of course, the closer r is to unity, the sharper are the notches and the more constant is the response at the other frequencies. The 3 dB rejection bandwidth of the notch filter is related to the pole radius by the following relation $\Delta\Omega = (1 - r)\pi$ [13].

The transfer function of a multiple-notch filter with M notches can be written in the following form

$$H(z) = \prod_{k=1}^{M} \frac{1 - 2\cos\Omega_{Nk} z^{-1} + z^{-2}}{1 - 2r\cos\Omega_{Nk} z^{-1} + r^2 z^{-2}} = \frac{B(z)}{B(r^{-1}z)} \tag{3}$$

where $B(z) = \sum_{k=0}^{2M} b_k z^{-k}$ is a symmetrical polynomial, that is $b_0 = b_{2M} = 1$ and $b_{2M-k} = b_k$ ($k = 0, \ldots, M - 1$). Given the notch frequencies $\Omega_{Nk}(k = 1, \ldots, M)$ the coefficients b_k can be computed by using a recursive relationship (for example, see [13]).

3. Non-zero initial conditions in notch filters

3.1. Filtering algorithm

As it was mentioned in the introduction, in the literature one can find only a few works devoted to the problem of transient reduction in notch filters. In their work, Pei and Tseng proposed a method which uses the vector projection to find better initial conditions for the IIR notch filter in order to reduce its transient response.

The suppression technique can be divided into two steps. In the first step, the vector projection is used to decompose the first L samples of an input signal into sinusoidal interference component and the desired signal component. Then the desired signal component is used as initial values of the notch filter to perform the filtering operation. As a result, the transient response of the filter can be considerably reduced.

The algorithm for the suppression technique is as follows. Given the measurement signal $x(n)$, the number of its samples N, the number of samples L to be decomposed, and the traditional notch filter designed for specified notch frequencies Ω_{0k}, $k = 1, \ldots, M$ and pole radius r, it is necessary to:

(1) construct input data vector **X**

$$\mathbf{X} = [x(0)x(1)\ldots x(L-1)]^T = \mathbf{S} + \mathbf{D} \tag{4}$$

where

$$\mathbf{S} = [s(0)s(1)\ldots s(L-1)]^T \tag{5}$$

$$\mathbf{D} = [d(0)d(1)\ldots d(L-1)]^T \tag{6}$$

(2) construct matrix **A**

$$\mathbf{A} = \begin{bmatrix} 1 & \cos(\Omega_{01}) & \cos(2\Omega_{01}) & \ldots & \cos[(L-1)\Omega_{01}] \\ 0 & \sin(\Omega_{01}) & \sin(2\Omega_{01}) & \ldots & \sin[(L-1)\Omega_{01}] \\ 1 & \cos(\Omega_{02}) & \cos(2\Omega_{02}) & \ldots & \cos[(L-1)\Omega_{02}] \\ 0 & \sin(\Omega_{02}) & \sin(2\Omega_{02}) & \ldots & \sin[(L-1)\Omega_{02}] \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 1 & \cos(\Omega_{0M}) & \cos(2\Omega_{0M}) & \ldots & \cos[(L-1)\Omega_{0M}] \\ 0 & \sin(\Omega_{0M}) & \sin(2\Omega_{0M}) & \ldots & \sin[(L-1)\Omega_{0M}] \end{bmatrix} \tag{7}$$