CASUAL FILTER APPLICATIONS IN THE SUBTRACTING METHOD FOR POWER-LINE INTERFERENCE REMOVING FROM ECG

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The article develops the subtraction method for removing PL interference from ECG in case of multiple sampling and casual filters application. Generalized formulae are composed to express the symmetrical FIR filters both for odd and even multiplicity. On the base of them a uniform formula is generated for its casual equivalent. A new modification of the linear criterion is introduced which is casual and retains all needed features for multiple sampling. The usage of casual filters in the subtraction method allows the algorithm of the subtraction method to be easily performed in a real-time mode. Experiments with odd and even multiplicity show that the method successfully compensates the PL interference, retaining a low level of the absolute error.

Keywords: Digital filtering, ECG filtering, Interference rejection.

1. INTRODUCTION

The subtraction method for removing the power-line (PL) interference from ECG signals [1] shows high efficiency and is object of a series of investigations [2]. Its structure includes three main stages:

1. Each ongoing sample X_i of the ECG signal is checked whether it belongs to a linear segment (with existing interference). The linearity of the segment is verified by introduced criterion of linearity Cr, whose value must be less than a practically defined threshold M (linearity threshold)

$$Cr < M\ . \tag{1}$$

2. If the ongoing sample belongs to a linear segment, with a non-recursive digital filter (so called K-filter) of kind

$$Y_i = \sum_{j=-m}^{m} a_{i+j} X_{i+j}, . \tag{2}$$

the interference is removed and only the free signal sample Y_i remains. Simultaneously, by simple subtraction between the non-filtered X_i and the filtered Y_i sample, the ongoing sample of the interference B_i is calculated.

$$B_i = X_i - Y_i\,, \tag{3}$$

which is stored in a temporal buffer that keeps n preceding values of the power-line interference $B_{i-1}, B_{i-2}, \ldots, B_{i-n}$.

3. When the treated sample X_i does not belong to a linear segment, a preceding sample B_{i-n} of the interference is taken from the temporal buffer

$$B_i = B_{i-n}\,, \tag{4}$$

that is phase locked with the ongoing interference sample. It is compensated (is subtracted) in the treated sample X_i

$$Y_i = X_i - B_i. \tag{5}$$

and is refreshed in the temporal buffer.

The linearity criterion used most often is $Cr = |D_i|$, where D_i is a so called D-filter [3], mathematically corresponding to the second derivative of the signal

$$D_i = (X_{i+n} - X_i) - (X_i - X_{i-n}) = X_{i+n} - 2X_i + X_{i-n}. \tag{6}$$

This is a second difference of incoming signal samples, where first differences are taken by samples located at a distance of one period of the PL frequency, thus eliminating the interference influence on the linearity evaluation.

The filtering in linear segments is usually performed by the non-recursive symmetrical digital filters according Eq. (2) in [4] that could be expressed by the generalized formula

$$Y_i = \frac{1}{n}\left[\sum_{j=-m}^{m} X_{i+j} - \frac{\overbrace{2m+1-n}^{a_m}}{2}\left(X_{i-m} + X_{i+m}\right)\right] \tag{7}$$

where $n = \Phi / F$ is the number of samples in one period of the PL interference. (Φ is the sampling rate and F is the power-line frequency). At an 'odd multiplicity' $n = 2m+1$ while at an 'even multiplicity' $n = 2m$. The parameter $a_m = 2m+1-n$ represents the kind of the multiplicity and has a value 0 or 1 at an odd or even multiplicity respectively. The generalized formula for the transfer coefficient of the filter by Eq. (7) is

$$K(f) = \frac{1}{n} \cdot \frac{\sin\frac{n\pi f}{\Phi}}{\sin\frac{\pi f}{\Phi}} \cos\frac{a_m \pi f}{\Phi}. \tag{8}$$

Summarizing and subtracting two distanced of n ending terms with weight coefficients k/n (k is an integer in a range $0 \div m$) in the impulse response of the K-filter by Eq. (7), causes an asymmetry in the response and shifts the central term toward the summarized ending term. The 'shifted' K-filter is described by the equation

$$Y_i = \frac{1}{n}\left(\sum_{j=-m-k}^{m-k} X_{i+j} - \frac{a_m - 2k}{2} X_{i+m-k} - \frac{a_m}{2} X_{i-m-k} - kX_{i+m-n-k}\right) \tag{9}$$

In Fig. 1 is shown the alteration of the K-filter by Eq. (9) when applying $k = 0$ (symmetric averaged filter) and $k = 1$ (asymmetric shifted filter) in case of Φ =250 *Hz*, F = 50 *Hz* (n = 5).

In [5] is applied an asymmetric shifted filter in case of even multiplicity $n = 8$ with $k = 1$. Till now applied D- and K-filters are of non-casual type (physically unrealizable) thus making difficult the subtraction method applying in real-time mode. One needs a delay buffer incorporated that compensates the time shifting for non-casual D- and K-filters. The delay buffer length has to be at last equal to the number of non-casual terms in D- and K-filters.

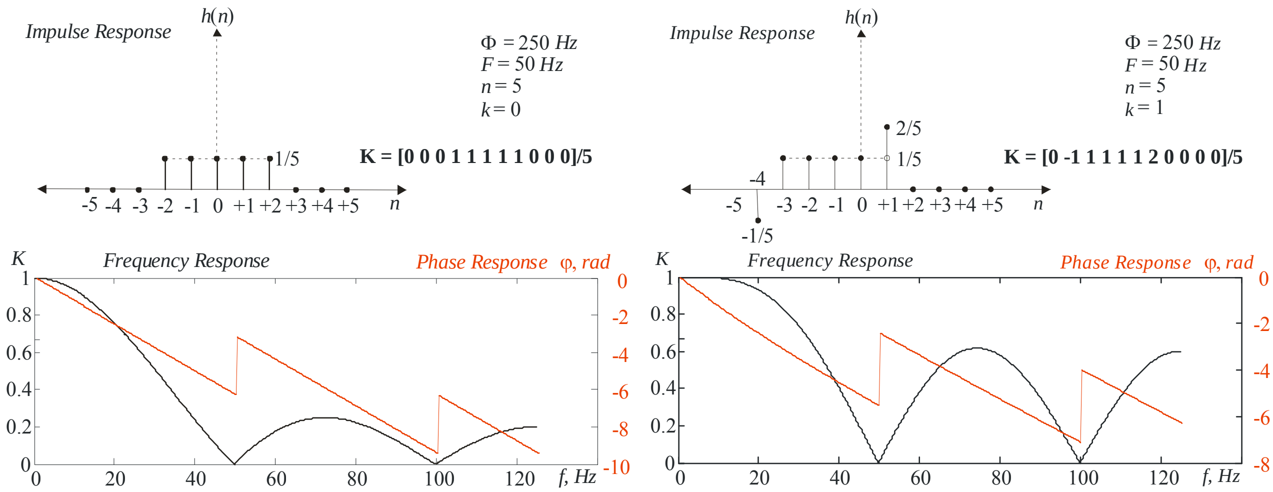

Fig. 1. Asymmety involving in an averaged FIR filter.

2. Theory and Method

The paper aims to investigate an adopting of casual (physically realizable) filters in the subtraction method for PL removing. Thus drops off the necessity of the delay buffer, the algorithm of the subtraction method is easily performed in real-time mode as well. The generalized structure of the casual subtraction method is shown in Fig. 2.

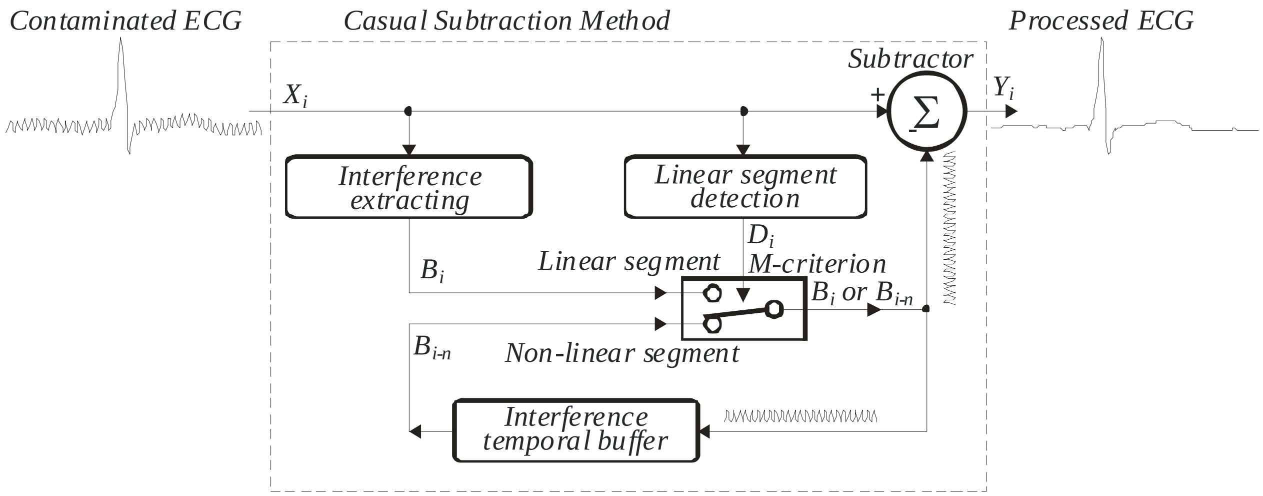

Fig. 2. Generalized structure of the casual subtraction method.

By raising the parameter k in Eq. (9) at its boundary value m, the filter becomes casual

$$Y_i = \frac{1}{n}\left(\sum_{j=-2m}^{0} X_{i+j} - \frac{1-n}{2} X_i - \frac{2m+1-n}{2} X_{i-2m} - mX_{i-n} \right). \tag{10}$$

Remaking Eq. (10) both for cases of odd and even multiplicity, an uniform formula is generated

$$Y_i = \frac{1}{n}\left(\sum_{j=-n+1}^{-1} X_{i+j} + \frac{n+1}{2} X_i - \frac{n-1}{2} X_{i-n} \right) \tag{11}$$

The formula for the transfer coefficient of this filter is

$$K(j\Omega)=\frac{1}{n}\cdot\frac{\sin\frac{n\Omega}{2}}{\sin\frac{\Omega}{2}}\left(\cos\frac{\Omega}{2}+j\cdot n\cdot\sin\frac{\Omega}{2}\right),\quad \Omega=\frac{2\pi f}{\Phi}. \tag{12}$$

The responses of two casual filters for the cases of Φ =250 *Hz*, F = 50 *Hz* (n = 5) and Φ =480 *Hz*, F = 60 *Hz* (n = 8) are shown in Fig. 3.

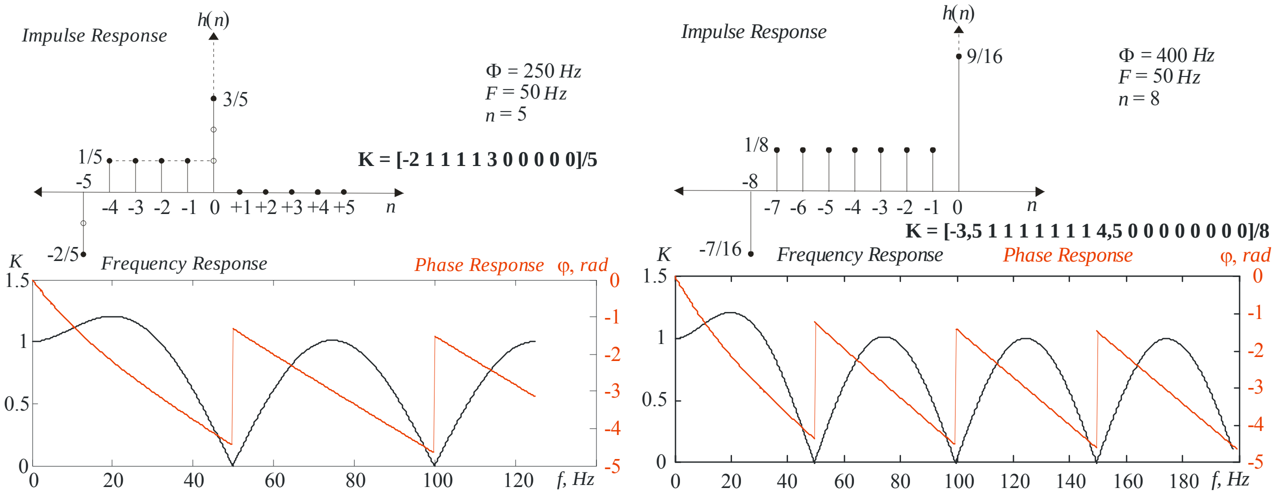

Fig. 3. Responses of casual K-filters.

In [6] are investigated some K-filters (including casual ones) for their applicability in the subtraction method, but the investigation is performed using linearity criteria of non-casual type.

The casual D-filter is built on the base of Eq. (6) by shifting it on n samples

$$D_i=\left(X_i-X_{i-n}\right)-\left(X_{i-n}-X_{i-2n}\right)=X_i-2X_{i-n}+X_{i-2n}. \tag{13}$$

3. Experimental Results

The experimental investigation is performed in Matlab environment in the following sequence:

1. Two ECG recordings ('conditionally clean' of PL interference) are taken from the SIGNACOR Laboratory (`Data023.adc` и `Data029.adc`) database. The original recordings are with sampling rate Φ = 250 *Hz* and resolution 20 μ*V/bit*. The recording `Data029.adc` is resampled whit sampling rate Φ = 480 *Hz*. The duration of the episodes is 2,5 *s*.

2. Synthesized PL interference with frequency F = 50 *Hz* and F = 60 *Hz* and with amplitude of 0,2 *mV* is added to signals `Data023.adc` and `Data029.adc` respectively.

3. 'Contaminated' signals are processed by the subtraction method. The threshold of linearity is fixed M = 120 μ*V*.

4. The error committed by the subtraction method is calculated as absolute difference between the filtered and the non-filtered signals. The averaged error Err_avr and the maximal error Err_max are evaluated for the processed epochs.

The pilot experiments is performed using till now applied non-casual averaged filters by Eq. (7) and linearity criterion $Cr = \max\left(\left|D_i\right|, \left|D_{i-1}\right|\right)$, where D_i is calculated by Eq. (6). Results are shown in Fig. 4.

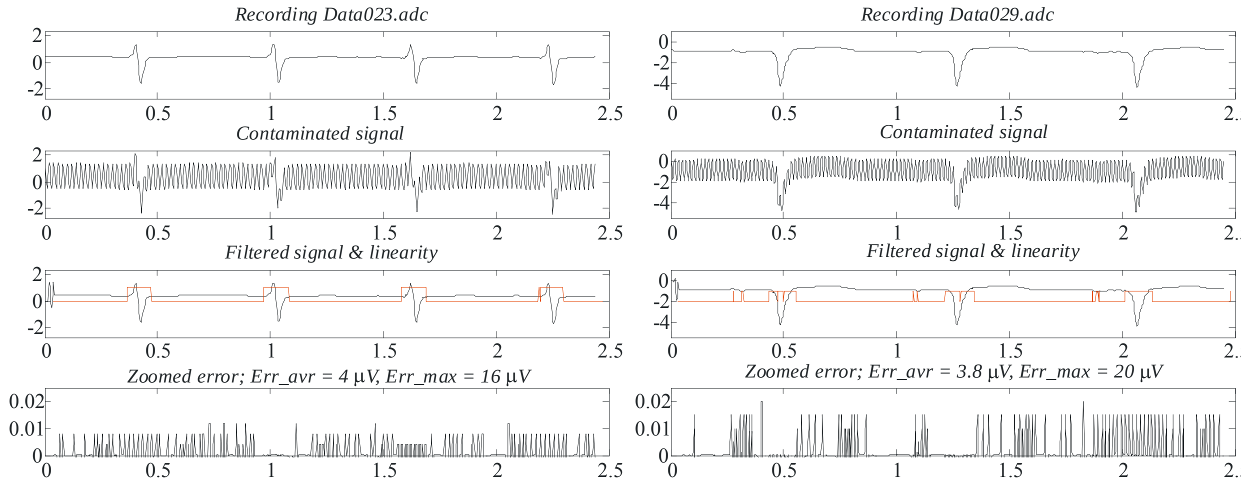

Fig. 4. Results from the pilot experiment.

The next experiment is performed with casual filters by Eq. (11) and the same linearity criterion, but D_i is calculated by Eq. (13). Results are shown in Fig. 5.

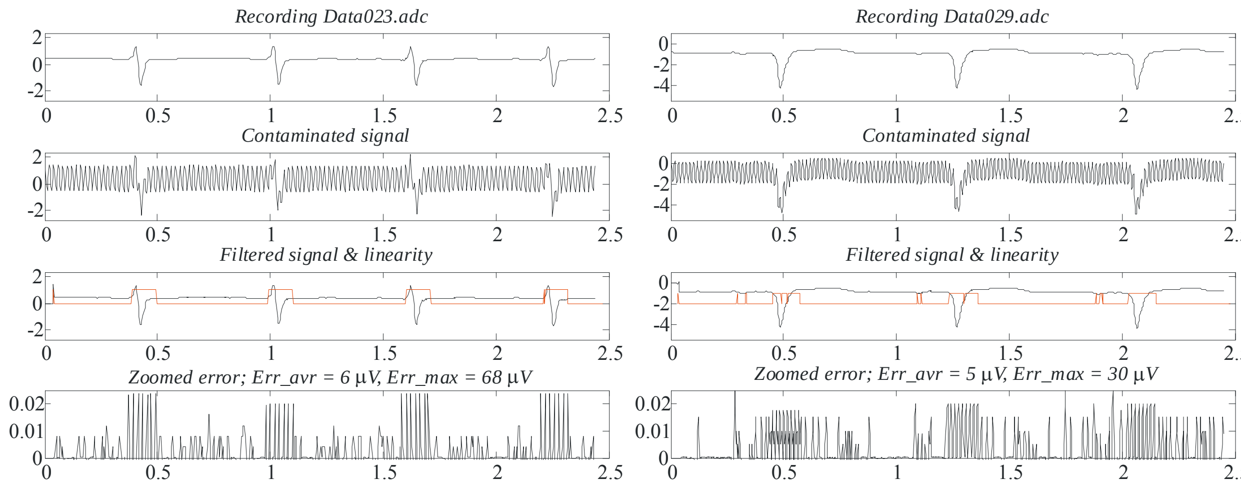

Fig. 5. Results from the experiment using casual K- and D-filters.

Obviously the error is higher. That is because in Eq. (11) participate the additional part $\frac{n+1}{2n}X_i - \frac{n-1}{2n}X_{i-n} \approx \frac{1}{2}FD_i$, where $FD_i = X_i - X_{i-n}$ is the ongoing first difference (such difference participates in the linearity criterion).

We applied an additional condition the ongoing first difference not to differentiate with more than $M/2$ from the other $n-1$ averaged differences. The additional auxiliary criterion Da_i is expressed by the equation

$$Da_i = 2\left(X_i - X_{i-n} - \frac{1}{n-1}\sum_{n+1}^{-1} X_{i+j} - X_{i-n+j} \right). \qquad (11)$$

The new complex linearity criterion is $Cr = \max\left(\left|D_i\right|, \left|Da_i\right|\right)$. Fig. 6 shows frequency responses of the basic and the additional criteria.

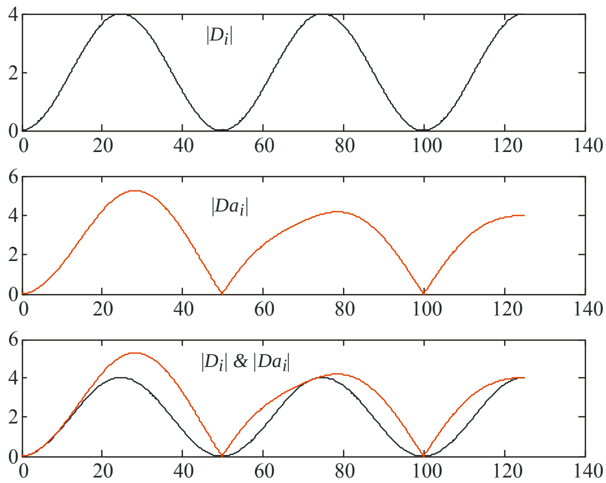

Fig. 6. Frequency responses of the basic and the additional criteria.

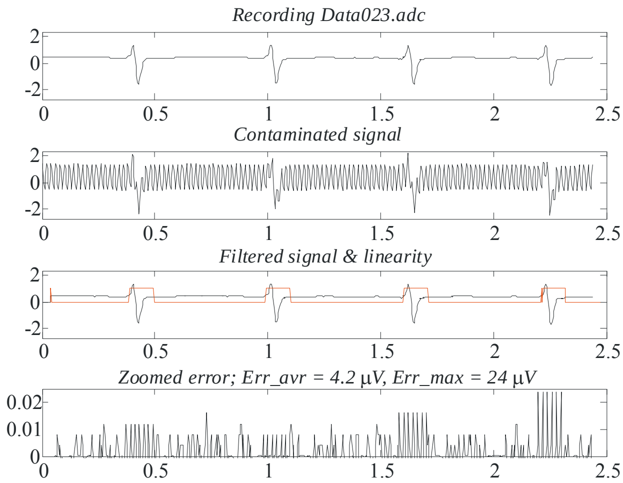

Fig. 7. Experiment whit the new linearity criterion.

Fig. 7 demonstrates an error reduction using the new complex criterion in the subtraction method whit the recording `Data023.adc`.

4. Conclusions

The article develops the subtraction method for removing PL interference from ECG in case of multiple sampling and casual filters application. Generalized formulae Eq. (7) and Eq. (8) are composed to express the symmetrical non-casual K-filters for both odd and even multiplicity. On the base of them, a uniform formula Eq. (11) is generated for its casual equivalent. A new modification of the linear criterion is introduced that uses casual D-filters and retains all needed features.

The usage of casual filters in the subtraction method allows the algorithm of the subtraction method to be easily performed in real-time mode.

Experiments with odd and even multiplicity show that the method successfully compensates the PL interference, retaining a low level of the absolute error.

5. References

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