Simple High-Q Comb Filter for Mains Interference and Baseline Drift Suppression

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Abstract **- This paper presents a simple digital high-Q comb filter for baseline wander and power-line (PL) interference suppression. The filter concept relies on a first difference – a discrete version of the signal first derivative, resulting in a high-pass roll-off in combination of the so called a comb frequency response. The presented filter is evaluated by Matlab simulations with real ECG signal contaminated with high amplitude PL interference. The made simulations show that this filter has minimal influence on processed ECG signal. Due to its high-pass characteristic and high-Q notches only at PL harmonics the presented filter is appropriate for almost all biosignal acquisition applications where PL interference and baseline drift suppression is needed. The filter is suitable for real-time operation with popular low-cost microcontrollers.**

Keyword s - **power-line interference, comb filter, baseline drift, FIR filter, IIR filter**

I. INTRODUCTION

One of the common problems in almost all biosignal acquisition applications is a baseline wander due to imperfect electrode-skin interface. The difference in electrode polarization potentials, and its time variation, produces a baseline drift which is usually suppressed by a high-pass analog filter after the first amplification stage. For a standard ECG processing the implemented high-pass filter should have a time constant of 3s, corresponding to a high-pass cut-off frequency of 0.05Hz. In some cases a cut-off frequency of 0.05Hz is too low, and the baseline drift suppression should be enhanced by additional high-pass filtering in a digital domain.

Power-line (PL) interference (hum) is another common problem in almost all biosignal acquisition applications. Because the body serves as a capacitively coupled antenna, a part of the picked up PL interference currents traverses the electrodes and produces a common mode voltage over an amplifier common mode input impedance. At the amplifier output some AC noise remains as a consequence of electrode impedance imbalance and/or due to the finite value of the amplifier CMRR [1], even when special signal recording techniques are applied (shielding, driven right leg, body potential driving, etc.). A further reduction of the interference should be implemented by either post-digital or post-analog filters.

The most common option for mains interference suppression is to use a low-pass averaging digital filters with firs zero at the PL frequency. The name of such a filter is known also as an averager, smoother, moving-average, rolling-average or running-mean filter. Because of introduced additional signal bandwidth limitation these filters significantly attenuate important frequency components. A special FAS (Filtration-Addition-Subtraction) algorithm can partially improve their high-frequency response [2].

Smart approaches such as adaptive noise cancellation [3], subtraction procedure [4] and various lock-in techniques [5] require sophisticated software organization.

Recently an interesting linear phase high-pass, and at the same time high-Q comb frequency response was presented [6]. By an averaging of several first differences, each one using the current and the delayed in multiple PL periods sample, a high-Q response is achieved, with a price of ripples in the pass-band, and a large amount of data (PL periods) that have to be processed.

Although in presence of many different approaches, the problem of interference removal still exists and the researchers continue to find a simple solution to result in a 'high fidelity' and 'clean' recordings.

This paper presents a simple digital high-pass high-Q comb filter for PL interference suppression. Based on a recursive (IIR) feedback extension [7] of a simple first difference comb filter, a very narrow band (high-Q) frequency response can be achieved.

The main advantage of the presented filter is that it rejects the baseline drift and all harmonics of the rated PL interference.

II. FILTER CONCEPT

The comb filters are widely used in digital signal processing. They are widely spread in either audio signal processing to achieve special sound effects (echo, flanging, etc.), or in TV signal processing for separating the luminance (black & white) and chrominance (color) signals from composite video signal [8].

In a nutshell, a simple first difference comb filter is achieved when incoming signal samples are subtracted from their delayed copy. Thus a high-pass roll-off and alternating constructive and destructive spectrum interference are produced as a function of the time delay between original and delayed signals.

A simple first difference feed forward (FIR) comb filter is shown in Fig. 1.

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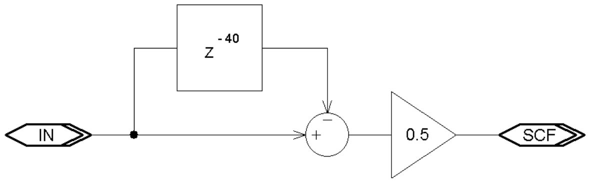

Fig. 1 Simple first difference comb filter for PL interference rejection. Sampling frequency is 2 kHz, i. e. z^{-40} corresponds to frequency independent delay of 20 ms

For certain frequency components, where the delayed samples are appeared in-phase towards its original, the amplitude of these components is increased two times. For other frequencies and DC, where the delayed samples are in opposite phase, they are canceled out. Thus all harmonics of the rated PL frequency are effectively canceled out. To make unity gain transmission in the pass-band, the output should be divided by 2. The frequency response of this filter is shown in Fig. 2.

The high-pass cut-off frequency f_{3dB} and the corresponding quality factor Q are:

$$f_{3dB}=f_o/4,$$

$$Q = \frac{f_o}{\Delta f} = \frac{f_o}{2 f_{3dB}} = 2 \qquad (1)$$

here f_o is the filter first notch frequency, Δf is the rejected bandwidth at 3dB at f_o, and f_{3dB} is a high-pass cut-off frequency. Although, this filter has very simple structure and linear phase response, its Q factor is too low, or its f_{3dB} frequency too high (12.5Hz), and so the filter application for biosignal processing is limited.

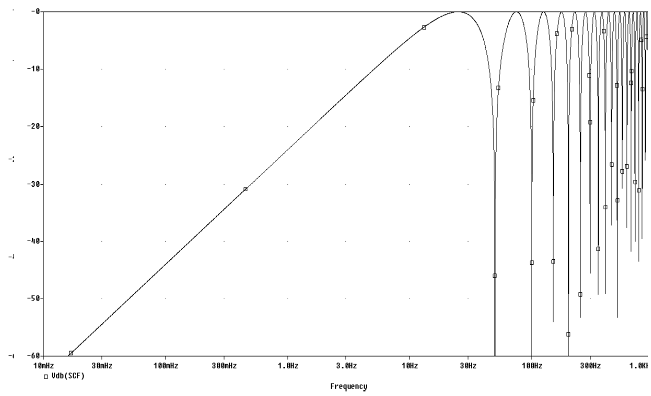

Fig. 2 Frequency response of a simple first difference comb filter from Fig. 1

Adding a simple feedback loop with coefficient *k*, the high-pass cut-off frequency f_{3dB} can be decreased, i.e. the filter Q factor can be increased, and set to this value, which is needed. The improved Q factor filter structure is shown in Fig. 3.

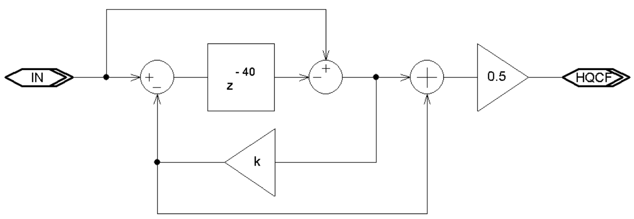

Fig. 3 High-Q first difference comb filter for PL interference and baseline drift rejection. Sampling frequency is 2 kHz

The filter is stable for $0 \le k < 1$. We note that when $k = 0$ the structure is converted to a simple comb filter shown in Fig. 1. The filter has the following transfer function:

$$T(z) = \frac{1 - z^{-40}}{1 - k \cdot z^{-40}} \cdot \frac{1 + k}{2} \qquad (2)$$

The high-pass cut-off frequency f_{3dB} depends on *k* and can be approximated as:

$$f_{3dB} = (1-k)(1-0.36k)f_o/4 \qquad (3)$$

Thus the Q-factor is:

$$Q = f_o/(2f_{3dB}) = 2/((1-k)(1-0.36k)) \qquad (4)$$

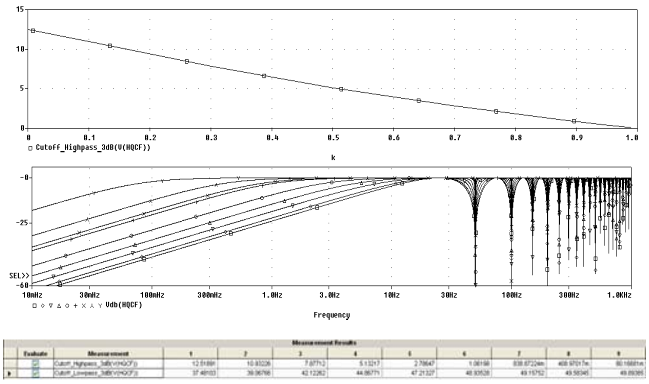

Fig. 4 Frequency response of high-Q first difference comb filter from Fig. 3. Coefficient *k* takes values: 0, 0.1, 0.3, 0.5, 0.7, 0.875, 0.9, 0.95 and 0.99

As can be seen from Fig. 4, the filter rejects all harmonics of PL interference.

III. SIMULATION RESULTS

The presented filter was tested by MATLAB simulations. A real, interference free ECG signal, sampled at 2kHz is used as an input. At the beginning of simulation, the amplitude of the PL interference is 0 LSBs. At 1.5s simulation time the PL amplitude is changed to 1000 LSBs.

Simulation results are shown in Fig. 5. The first and second traces are the original ECG signal, and the ECG signal with added PL interference. The fourth trace shows the original signal (from trace 1) after a high-Q first difference comb filter from Fig. 3. The value of *k* is 0.875, and corresponds to $Q \approx 23$.

Note that for fast operation, with integer coefficient only, *k* should be selected to be proportional to some negative power of two. For example, in our case *k* is selected to be 0.875, and is realized only with a three bit shift and one subtraction as:

$$0.875 = 7/8 = 1 - 1/8.$$

For evaluation of the PL interference rejection, a comparison with a simple one PL period (20 ms) moving-average filter is shown in the fifth trace. The averager error, i.e. the difference between trace 1 and trace 5, is shown on trace 7. 1 LSB corresponds to 1μV.

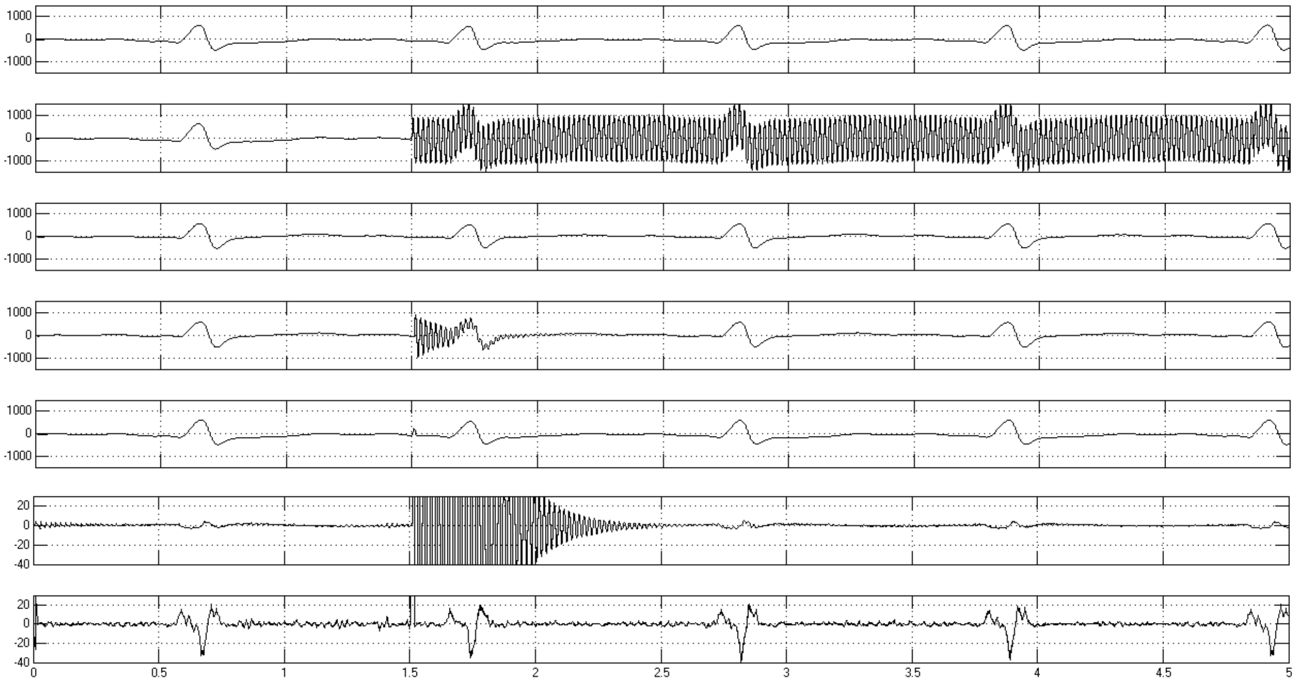

Fig. 5 Simulation results of high-Q first difference comb filter compared with one PL period (20 ms) averager

The high-pass slope of the presented filter resembles a first order analog high-pass filter with a cut-off frequency defined in Eq. (4). Any low-frequency drift with frequency below f_{3dB} will be rejected in accordance with this roll-off, for instance, because the filter cut-off frequency is f_{3dB}=1.07Hz, a drift with 0.1Hz will be rejected ten times or 20dB.

As was discussed, due to the fact that the filter additionally high-passes the applied signal, it is compared with a reference ECG signal derived by a high-pass filtering of the original ECG signal from trace 1, via a first order analog filter with a cut-off frequency f_{3dB}=1.07Hz. The reference ECG signal is shown on the third trace. The error, i.e. the difference between trace 3 and trace 4, is shown on trace 6. It can be seen that the error is below 5 LSBs, at the QRS complexes, and almost zero between them, which proves the statement that the filter high-passes the applied signal like a first order analog high-pass filter with a cut-off frequency defined in Eq. (4)

The implemented high Q factor ($Q \approx 23$) increases the filter adaptation time to about 0.5s.

IV. Conclusion

The presented High-Q comb filter provides a simple and powerful solution for rejecting the PL interference and baseline drift in almost all biosignal acquisition applications.

The main advantages of the presented filter could be summarized as:

- Simple solution for removal of fundamental frequency of the PL interference and its higher harmonics
- Simple solution for a baseline drift suppression
- Simple way for a change in the high-pass cut-off frequency and Q-factor by only one coefficient
- Suitable for real-time operation with popular low-cost microcontrollers.

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