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# High-Q Comb Filter for Mains Interference Suppression

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*Abstract* - **This paper presents a digital high-Q comb filter for power-line (PL) interference suppression. The filter structure is based on a high-Q first difference filter, paralleled with a lossy integrator stage to restore the low-frequency filtered components. 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-Q notches only at PL harmonics the presented filter is appropriate for almost all biosignal acquisition applications. The filter is suitable for real-time operation with popular low-cost microcontrollers.**

*Keywords* – **power-line interference, comb filter, moving-average filter, FIR filter, IIR filter**

## I. Introduction

Power-line (PL) interference (hum) is a 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].

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

Recently a simple high-pass, and at the same time high-Q comb filter for rejection of both the baseline drift and PL interference, was presented [6]. The filter additionally high-passes, or in other words, additionally differentiates the applied signal. Thus it is inapplicable in cases when only PL suppression is needed.

Although in presence of many different approaches, the problem of PL 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 high-Q comb filter for PL (or other periodical) interference suppression. The filter is based on a high-Q first difference comb filter [6], wherein the filtered low frequency components are restored by a parallel low-pass lossy integrator stage.

The main advantage of the presented filter is that it rejects all harmonics of the rated PL interference with minimal influence on processed signal.

## II. Filter Concept

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. If a simple recursive feedback loop is added, the high-pass cut-off frequency can be decreased, i.e. the filter Q factor increased, and set to this value, which is needed [6].

The idea for usage of a first difference high-Q comb filter only for PL interference rejection is quite simple - the high-pass roll-off at DC can be compensated with a corresponding low-pass roll-off with the same cut-off frequency as shown in Fig. 1.

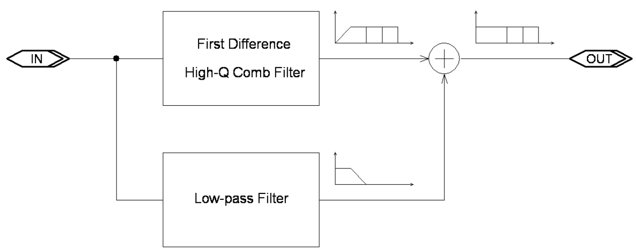


Fig. 1 High-Q first difference comb filter with compensated high-pass roll-off

The high-Q first difference comb filter structure is redrawn from [6] in Fig. 2. The filter is stable for $0 \le k < 1$ and has the transfer function for sampling frequency $f_s$=2kHz:

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

The high-pass cut-off frequency $f_{3dB}$ depends on $k$ and can be approximated as [6]:

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

thus Q is:

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

If $k = 0.875$, then $f_{3dB} = 1.07$Hz and Q = 23.

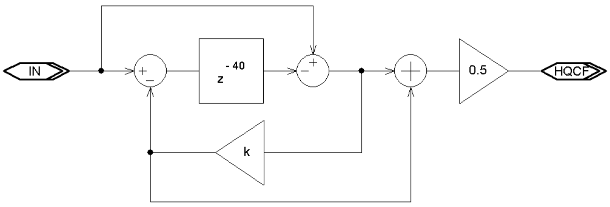


Fig. 2 High-Q first difference comb filter for PL interference and baseline drift rejection

For the low-pass filter block, shown in Fig. 1, a simple lossy integrator stage described in [7] can be used. Its structure is redrawn in Fig. 3.

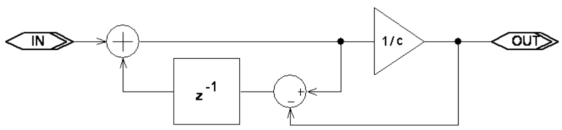


Fig. 3 Simple lossy integrator

The filter has the following transfer function and 3dB frequency:

$$T(z) = \frac{1}{c - (1-c)z^{-1}} \qquad (4)$$

$$f_{3dB} = \frac{1}{2\pi\tau} \qquad (5)$$

Here $\tau = \frac{c}{f_s}$, and $f_s$ is the sampling frequency.

Combining (2) and (5) leads to:

$$c \approx \frac{2}{\pi} \cdot \frac{f_s}{f_o} \cdot \frac{1}{(1-k)(1-0.36k)} \qquad (6)$$

From (6) taking into account that $f_s = 2\text{kHz} = 40f_o$, it can be calculated that for $k = 0.875$, $c \approx 298$.

For simple integer coefficient only calculations, the coefficient $c$ is rounded to 292.57, thus the fraction $1/c$, see Fig. 3, is realized as:

$$1/292.57 = 1/256*7/8 = 1/256*(1 - 1/8).$$

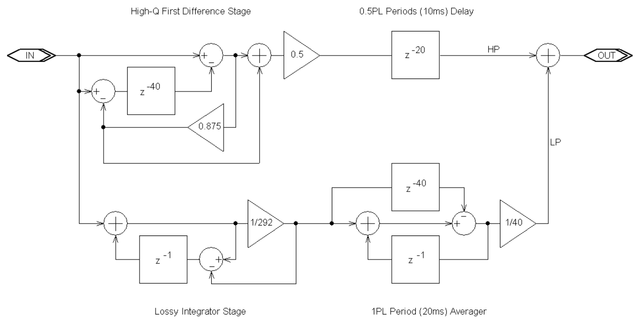


Fig. 4 High-Q comb filter for PL interference suppression. Sampling frequency is 2kHz, thus $z^{-1}$ denotes a 0.5ms delay

It should be noted that the lossy integrator stage does not reject PL harmonics like a comb filter, and if its cut-off frequency is increased the PL rejection will be decreased, for instance if $f_{3dB}$ of the lossy integrator is 5Hz than the PL rejection will be only 20dB. Therefore, for maximal PL interference suppression regardless $f_{3dB}$, the lossy integrator should have a comb response for PL harmonics. The simplest way for this is if it is cascaded with 1PL period averager, as shown in Fig. 4.

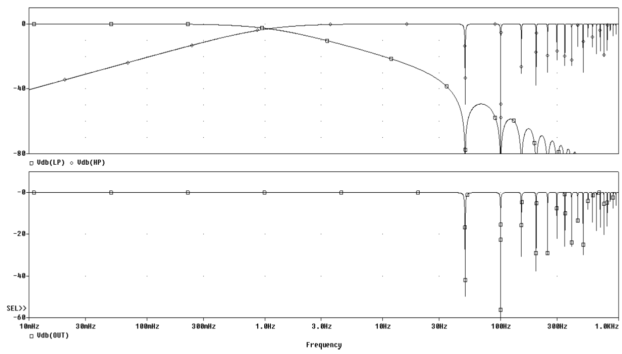


Fig. 5 Frequency response of high-Q comb filter from Fig. 4

The lossy integrator with averager frequency response $V_{db(LP)}$, see fig 4, the high-pass frequency response $V_{db(HP)}$, and the final output response $V_{db(OUT)}$ are shown in Fig. 5. It is visible that the final characteristic has a flat response and notches only at the PL harmonics.

## 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. 6. The first and second traces are the original ECG signal, and the ECG signal with added PL interference. The third trace shows the original signal (from trace 1) after the presented comb filter from Fig. 4. 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 one 3 bit shift and one subtraction as:

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


Fig. 6 Simulation results of high-Q comb filter compared with one PL period (20 ms) averager

A comparison with a simple one PL period (20 ms) moving-average filter is shown in the fourth trace. The error, i.e. the difference between trace 1 and trace 3, and trace 1 and trace 4 is shown on trace 5 and trace 6 respectively. 1 LSB corresponds to 1μV. It can be seen that the presented comb filter has minimal influence on processed signal. 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 in almost all biosignal acquisition applications.

In cases when a high-Q factor is implemented, i.e. $f_{3dB}$ is low enough, and results in sufficient rejection of the lossy integrator stage for PL frequency, the averager can be bypassed.

It should be noted that the value of the implemented Q-factor should be selected with reasonable tradeoff between the needed settling time, a desired sharpness notch at PL frequency and a still acceptable rejection when PL frequency differs from its nominal value. This means that higher Q-factors are effective only when the sampling rate is locked to the PL frequency.

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 way for a change in the implemented Q-factor. It can be done by only two coefficients change.
- Only one PL period data are needed for processing
- Suitable for real-time operation with popular low-cost microcontrollers.

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