COMBINED HIGH-PASS AND POWER-LINE INTERFERENCE REJECTER FILTER FOR ECG SIGNAL PROCESSING

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In this study we introduce one alternative approach for ECG high-pass filtering and interference rejection based on the simple principle for averaging of samples N with a predefined distance between them D. FilterDxN has a comb frequency characteristic with high-pass cut-off defined by the number of samples N and zeros at the integer ratio of the sampling frequency fs divided by the number of samples D. For a predefined fs, FilterDxN is easily adjusted to different cut-off and zero frequencies only by changing D and N. In this work, we present the mathematical background for deriving the frequency response of FilterDxN, as well as one particular application of the filter, i.e. Filter10x19 designed for fs=250 Hz, high-pass at 1 Hz, zero at 50 Hz. Tests with both standardized and real ECG signals proved that Filter10x19 is capable to remove very intensive baseline wanderings, and to fully suppress 50 Hz interferences with minimal affect on the ECG waveform. FilterDxN would be preferable in ECG systems operating in real time because of its linear filter equation with integer coefficients that hasten the speed of computations.

Keywords: Real-time ECG filtering, average filter, baseline drift, mains interference.

1. INTRODUCTION

Long-term electrocardiogram (ECG) monitoring devices work under considerable artifacts of intensive body and electrode movements or power-line interference. An adequate preprocessing filtering is required to provide high-quality ECG signals, supporting the accurate ECG interpretation. An extensive research is focused on the challenge for designing novel digital filters, which can correct baseline drift or reject power-line interference, while preserving the fidelity of ST and QRS. Various approaches for drift suppression have been proposed based on smart filtering techniques, such as the moving average filters [1], bi-directional high-pass filter [2,3], nonlinear filter banks [4], adaptive filtering [5], wavelet transforms [6], etc. For the effective rejection of the power-line interference, there are also a number of works, introducing notch filters [4,7], comb filters [8], adaptive filters [5], subtraction procedure [9], etc. Although the different filter solutions are attractive because of the reasonable frequency characteristics, most of them are not applicable in real time, since they rely on heavy computations or require certain ECG analysis prior to applying the filtering technique. The digital filters with integer coefficients are preferable for real-time applications but it is difficult to achieve desired frequency characteristics [10]. In this work we will present one alternative solution of integer-coefficients filter, which provides an adequate high-pass and power-line filtering.

2. METHODS

2.1. Digital filter design

A digital filter with integer coefficients was designed implementing the simple principle of moving averaging of N signal samples distanced each other by D samples as shown in Fig. 1. In order to avoid the phase shifting of the filtered signal versus the input signal, the number of the averaged samples N must be odd.

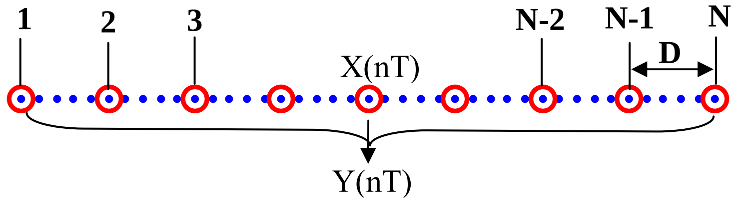

Fig.1.Principle of averaging of FilterDxN.

The filter is named *FilterDxN*, with difference equation given by (1):

$$Y(nT)=X(nT)-\frac{1}{N}[X(nT-D\frac{N-1}{2})+X(nT-D\frac{N-3}{2})+\ldots+X(nT)+\ldots+X(nT+D\frac{N-3}{2})+X(nT+D\frac{N-1}{2})]\,, \quad (1)$$

where $X(nT)$ is the input sample with index n, $Y(nT)$ is the respective output sample.

The equivalent z-transform domain equation of *FilterDxN* is presented in (2):

$$Y(z)=X(z)-\frac{1}{N}[X(z)z^{-D\frac{N-1}{2}}+X(z)z^{-D\frac{N-3}{2}}+\ldots+X(z)z^{0}+\ldots+X(z)z^{D\frac{N-3}{2}}+X(z)z^{D\frac{N-1}{2}}]. \quad (2)$$

The derived transfer function in the z-domain for *FilterDxN* is:

$$H(z)=\frac{Y(z)}{X(z)}=1-\frac{1}{N}[z^{-D\frac{N-1}{2}}+z^{-D\frac{N-3}{2}}+\ldots+z^{0}+\ldots+z^{D\frac{N-3}{2}}+z^{D\frac{N-1}{2}}] \quad (3)$$

The equivalent transfer function in the frequency domain is:

$$H(\omega T)=1-\frac{1}{N}[e^{-D\frac{N-1}{2}j\omega T}+e^{-D\frac{N-3}{2}j\omega T}+\ldots+1+\ldots+e^{D\frac{N-3}{2}j\omega T}+e^{D\frac{N-1}{2}j\omega T}] \quad (4)$$

By applying the known relationship: $:e^{-j\omega T}+e^{+j\omega T}=2\cos\omega T$, we derive from (4):

$$H(\omega T)=1-\frac{1}{N}[1+2\sum_{k=1}^{(N-1)/2}\cos kD\omega T]\;=1-\frac{1}{N}[1+2\frac{\cos\frac{(N+1)D\omega T}{4}\sin\frac{(N-1)D\omega T}{4}}{\sin\frac{D\omega T}{2}}]. \quad (5)$$

Equation (5) is the general description of *FilterDxN* frequency response. From here, we can find the cut-off frequency, the slope, as well as the zeros of the filter.

The analysis of the zeros of the filter $H(\omega_0T)=0$, yielded the equation:

$$\sum_{k=1}^{(N-1)/2}\cos kD\omega_0 T=\frac{N-1}{2} \quad (6)$$

Since $\cos k2\pi$ (k is an integer 1,2,…) is a periodical function with a period of 2π, we could simplify equation (6), so that $D2\pi f_0/f_s = 2k\pi$, $\Rightarrow$ $f_0 = kf_s/D$. Therefore, *FilterDxN* is a comb filter with periodically distributed zeros at each frequency f_0, which is an integer ratio of the sampling frequency f_s to the number of samples D.

The analysis of equation (5) shows that for a fixed sampling period T, the frequency response could be easily adjusted by varying both D and N. One example of *FilterDxN* frequency response for fixed D and different N is presented in Fig.2.

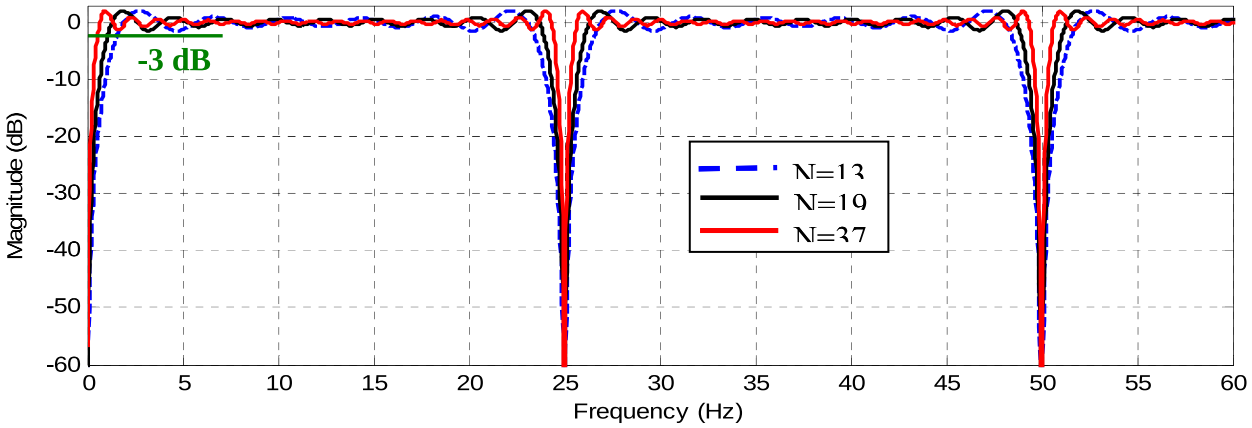

Fig.2.Frequency response of FilterDxN calculated for fs=250 Hz, D=10, and three different N-values - N=13, N=19, N=37, corresponding to low cut-off frequency of 0.5 Hz, 1 Hz and 1.5 Hz, respectively.

2.2. Test signals

The *FilterDxN* output is presented for a set of signals:

- **Test ECG** – we use the standardized calibration signal ANE20000 from the ECG CTS-Test Atlas [11], which is part of the analytical ECGs designed to reproduce the 'normal' ECG waveform with a heartrate of 60 bpm.
- **Drift** – Sinusoid (0.5 Hz, 1 $mV_{p\text{-}p}$) is synthesized and added to Test ECG;
- **Powerline Interference** - Sinusoid (50 Hz, 1 $mV_{p\text{-}p}$) is synthesized and added to Test ECG;
- **Segments of real ECGs corrupted by extensive drift**, appearing during real recording conditions. These ECGs are part of AHA and MIT-BIH databases.

3. RESULTS

The signal processing is implemented in the software package MATLAB 7.0.

We focus our analysis on a particular application of *FilterDxN* for ECG signals sampled at 250 Hz. This is an ordinary sampling frequency preferred in fast and low-power resource ECG systems. Aiming at a zero at 50 Hz, we have 2 possible solutions for *FilterDxN*, i.e. D=5 (1st zero at 50 Hz) and D=10 (1st zero at 25 Hz, 2nd zero at 50 Hz – Fig.2). For D=5 and D=10 we estimate the low cut-off frequency of the filter and the time for averaging in dependence on the sample number N (Fig.3).

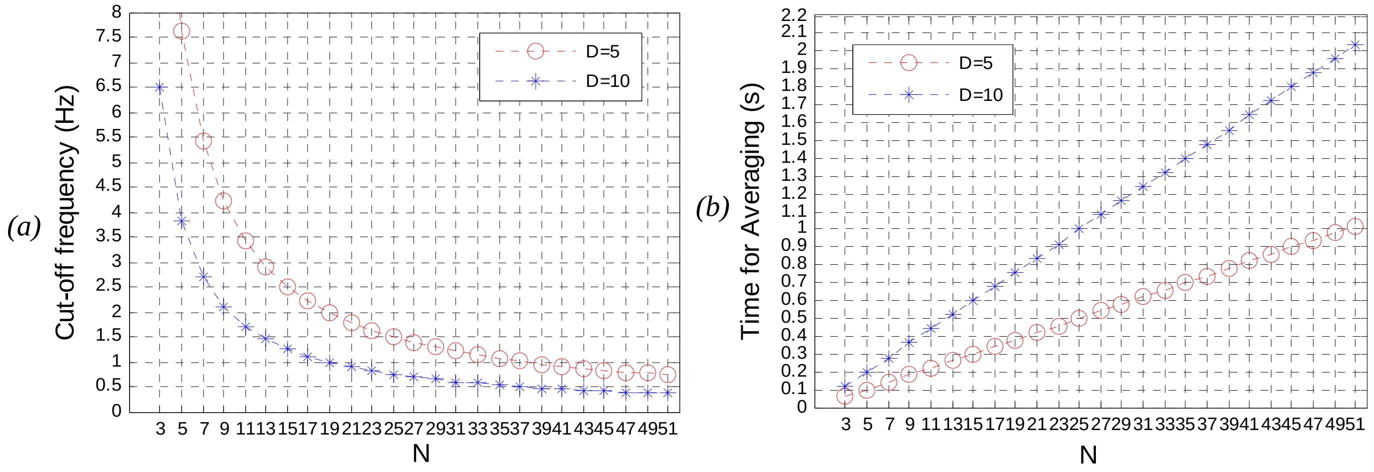

Fig.3. FilterDxN for fs=250 Hz and D=5, D=10: (a) Cut-off frequency vs.N; (b) Time for Averaging vs.N.

Our tests with ECG test signals are performed on *Filter10x19* with 1 Hz cut-off, chosen to correspond to the 'monitor' type ECG. The results are presented in Fig.4-6. *Filter10x19* output is compared with two reference ECG filters - 1Hz RC High-pass 1-st order (HP), and comb filter for 50 Hz rejection (averaging on 5 consecutive samples) [8]. The error is calculated as the difference between the filter output and the pure ECG.

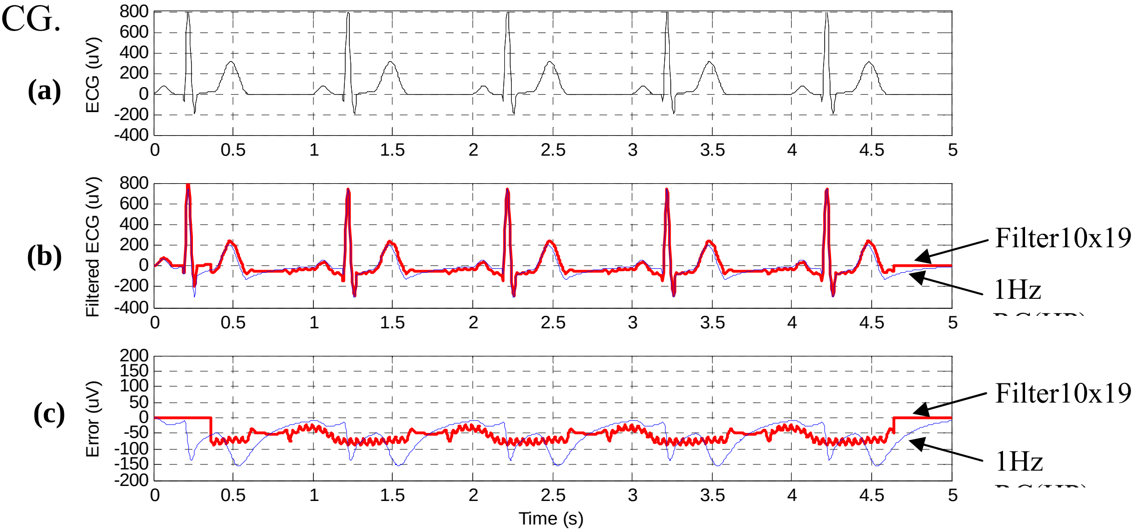

Fig.4. Pure ECG - ANE20000 passed through 2 filters: Filter10x19 and reference 1Hz RC(HP)

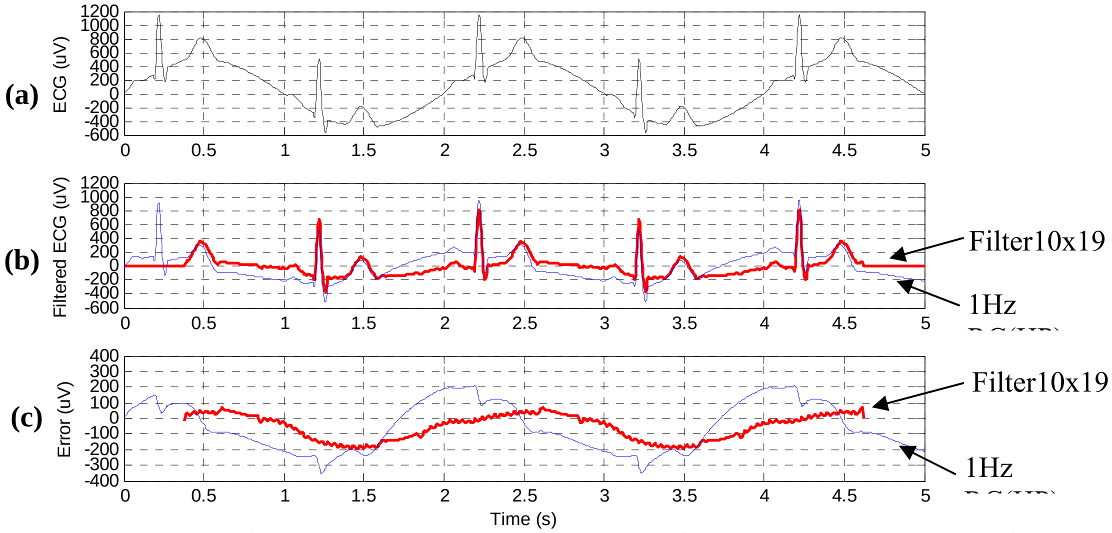

Fig.5. Pure ECG (ANE20000) + Drift (0.5Hz,1mV$_{p-p}$) - passed through 2 filters: Filter10x19 and a reference 1Hz

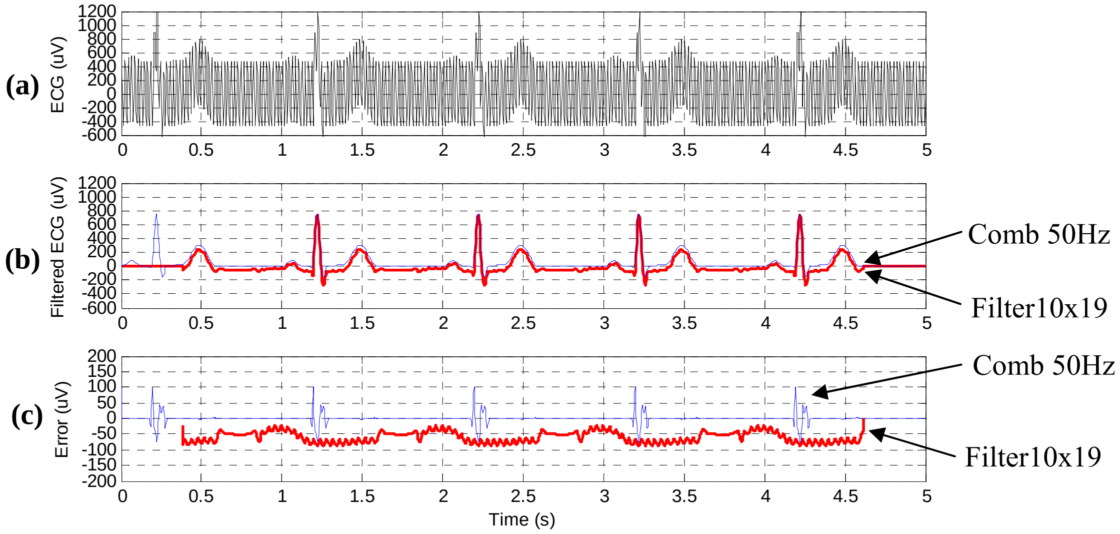

Fig.6. Pure ECG (ANE20000) + Powerline Interference (50 Hz,1mV$_{p-p}$) - passed through 2 filters: Filter10x19 and a reference averaging filter on 5 samples (50 Hz rejection)

The performance of *Filter10x19* (1 Hz cut-off) with real ECG recordings disturbed by extensive baseline drift, is shown in Fig. 7.

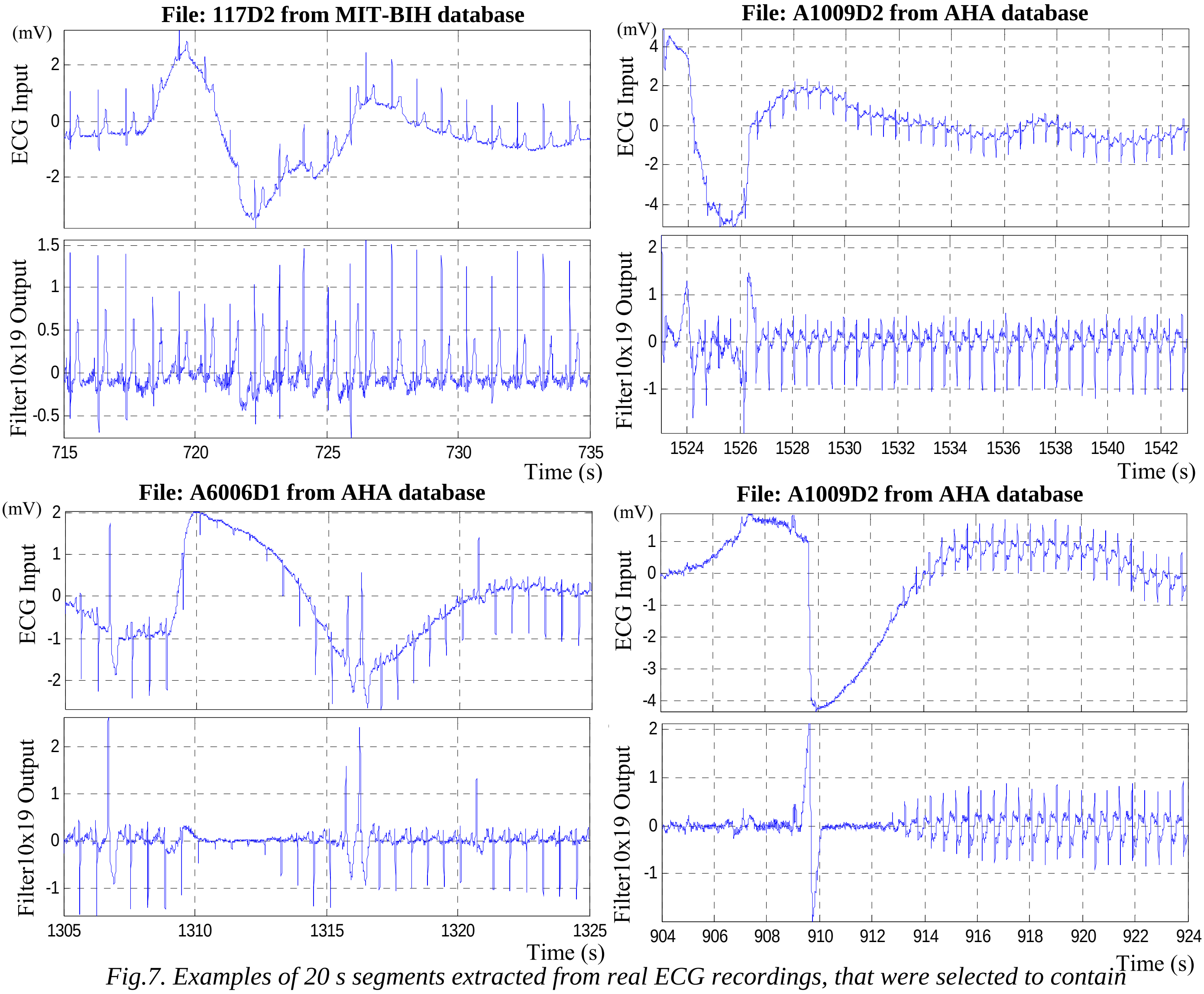

Fig.7. Examples of 20 s segments extracted from real ECG recordings, that were selected to contain intensive baseline drift. The Filter10x19 output (1Hz) is shown in the bottom subplot.

4. DISCUSSION AND CONCLUSIONS

The proposed *FilterDxN* for combined high-pass and power-line interference filtration is designed by linear difference equation with integer coefficients (see Equ. 1), that hasten the computations for online operating ECG systems. The number of the add instructions is defined by the number of the averaged samples N. Other important parameter is the time-interval for averaging DN/fs, which defines the operational time-delaying of the filter's output sample to the last input sample considered in the filter's equation. For the particular application of *FilterDxN* with sampling frequency of 250 Hz and zero at 50 Hz, we calculate time interval for averaging between 0.1 s and 2 s (time-delaying between 0.05 s and 1 s), to achieve low cut-off frequency between 6.5 Hz and 0.5 Hz, respectively (Fig.3b).

The frequency response of *FilterDxN* resembles a comb filter (Fig.2). The number of the averaged samples N defines the high-pass cut-off frequency as well as the number of the ripples in the pass-band. The integer ratio fs vs. D defines the locations of the zeros in the frequency characteristic. Our analysis applied over the particular application of *FilterDxN* for fs=250 Hz, shows only two possible D-values that could provide zero at 50 Hz, i.e. D=5 and D=10. By varying the number of the averaged samples N between 3 and 51, we can achieve cut-off frequencies between 8 Hz and 0.74 Hz (for D=5) and between 6.5 Hz and 0.37 Hz (for D=10). This implies that D=10, N>25 are the only solutions applicable in diagnostic ECG systems for which cut-off below 0.74 Hz is demanded.

We demonstrate the performance of *Filter10x19*, with cut-off of 1 Hz, corresponding to the common frequency in the long-term monitoring ECG devices. The test with the calibration ECG signal (Fig.4) shows an error about 50 μV_{p-p} that is not changing after the steep QRS and T-wave, such as the error of an ordinary 1-st order HP RC filter, presenting peaks of 150 μV_{p-p}. The only disadvantage of *Filter10x19* is the ripples in the pass-band, visible as small waves at the zero-line, which however, could be suppressed by the mandatory LP filter in the ECG systems.

Tests with 0.5 Hz sine drift (Fig.5) present the better suppression of *Filter10x19* vs. 1Hz HP RC filter, so that the error range is 300 μV_{p-p} vs. 500 μV_{p-p}. In general, *FilterDxN* has improved robustness to drift because of its steep slope 11.5 dB/oct.

Tests with 50 Hz sinusoid (Fig.6) show its full rejection without suppressing the QRS amplitude, such as the comb 50 Hz filter with 200 μV_{p-p} error below QRS.

The drift suppression in real ECGs is adequate (Fig.7). *Filter10x19* is capable to restore even small amplitude QRS complexes hidden within the strong baseline drifts. This proof together with the easy implementation makes *FilterDxN* very attractive, especially for real-time applications and autonomous ECG monitoring systems.

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5. REFERENCES

[1] Faes, Th., H. Govaerts, B. Tenvoorde, O. Rompelman., *Frequency synthesis of digital filters based on repeatedly applied unweighed moving average operations*, Med. Biol. Eng. Comp., Vol. 32, pp 698-701, 1994.

[2] Christov, I., I. Dotsinsky, I. Daskalov, *High-pass filtering of ECG signals using QRS elimination*, Med. Biol. Eng. Comp., Vol. 30, pp 253-256, 1992.

[3] Dotsinsky, I., T. Stoyanov, *Optimization of bi-directional digital filtering for drift suppression in electrocardiogram signals,* J. Med. Eng. Technol., Vol. 28, pp 178–180, 2004.

[4] Łęskia, J., N. Henzel, *ECG baseline wander and powerline interference reduction using nonlinear filter bank*, Signal Processing, Vol. 85, pp 781-793, 2005.

[5] Thakor, N., Y. Zhu, *Applications of adaptive filtering to ECG analysis: Noise cancellation and arrhythmia detection*, IEEE Trans. Biomed. Eng., Vol. 38, pp 785-794, 1991.

[6] Xu, L., D. Zhang, K.Wang, *Wavelet-based cascaded adaptive filter for removing baseline drift in pulse waveforms*, IEEE Trans. Biomed. Eng., Vol. 52, pp 1973–1975, 2005.

[7] Ma, W.K., Y.T. Zhang, F.S.Yang, *A fast recursive-least-squares adaptive notch filter and it is applications to biomedical signals*, Med. Biol. Eng. Comp., Vol. 37, pp 99-103, 1999.

[8] Lynn P.A., *Online digital filters for biological signals: some fast designs for a small computer*, Med. Biol. Eng. Comp., Vol. 15, pp 534-540, 1977.

[9] Levkov, Ch., G. Mihov, R. Ivanov, I. Daskalov, I. Christov, I. Dotsinsky, *Removal of power-line interference from the ECG: a review of the subtraction procedure*, BioMed. Eng. OnLine 4:50, 2005.

[10] Tompkins W., *Biomedical digital signal processing: C-Language examples and laboratory experiments for the IBM PC*, Englewood Cliffs, NJ: Prentice Hall, 1993.

[11] Zywietz Chr., *CTS-ECG Test Atlas*, Center for Computer Electrocardiography. Biosignal Processing. Medical School. Hannover, 1999.