An Approach to Successful Power-line Interference Suppression in ECG Signals

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Abstract: *The ECG signals acquisition is usually corrupted by presence of Power-Line Interference (PLI) induced by the electromagnetic field around us. Many methods for PLI suppression/elimination have been developed over the years. The easy to apply traditional notch filters suppress unacceptably the ECG spectrum around the rated PL frequencies of 50 or 60 Hz and their deviations, which are restricted by the standards within the range of ± 0.5 Hz. The changes are very slow but the current PL frequency has to be continuously checked to allow start and performance of adequate PLI suppression during any ECG recordings including the 24 hours Holter monitoring. According to the proposed approach, the corrupted ECG recording is bi-directional band-pass (BP) filtered. The resulting sinusoidal BP waves differ in amplitude from the PLI but their zero crossing points remain identical. The two out-sample distances located at both ends of each current sinusoidal curve are calculated and aided to the inter-sample distances. The obtained fractal wave period is converted into current PL frequency and used for bi-directional notch filtration with narrow stop-band. The results obtained demonstrate a very successful PLI suppression in ECG signals. The errors committed are within a few μV, except for the edges of the recordings due to the transition processes.*

Keywords: *ECG signals, Power line interference suppression, Subtraction procedure, Narrow notch filtration.*

Introduction

The ECG signals acquisition is usually corrupted by presence of Power-Line Interference (PLI). The electromagnetic field around us induces stray currents flowing through the patient cable capacitances, the unequal electrode-to-skin impedances and the patient body. As a result, the common mode voltage is transferred into false differential signal at the input of the amplifier [7] that cannot be suppressed by any high common mode rejection ratio.

Many methods for PLI suppression/elimination have been developed over the years [3].Various papers deal with versions of Least Mean Square algorithms: Recursive Least Square, Normalized Least Mean Squares and Constrained Stability Least Mean Square [13]. A lot of the algorithm performances are evaluated by Signal-to-Noise Ratio (SNR), Mean Square Error (MSE), Root MSE, and Peak SNR. Actually, similar measures are not the adequate metrics for PLI suppression assessment since the ECG analysis is known to be a time-amplitude interpretation.

Other investigations are devoted to Fast Fourier [19] and Discrete Wavelet Transforms [3], Recurrent Neural Networks [18], modified time-domain and regression subtraction methods [2], adaptive and Kalman filtration [1, 19]. Nevertheless, a few of authors show the differences between the original and the processed signals.

This is largely accepted in all publications on the subtraction procedure [4-6, 11, 12, 14-16]. As a rule the subplots of the figures show the original conditionally clean ECG signal, a synthesized variable PLI, the mixed signal, the processed signal and the difference between them, typically in the limits of ±20 μV. The subtraction procedure works as follows: comb filter with first zero at 50/60 Hz is applied on PQ and TP intervals usually with frequency band near to zero; the obtained clean values are further used to find out phase locked interference samples, which are subtracted from corresponding mixed samples in adjacent segments with QRS complexes and high T waves.

The PLI spectrum includes the fundamental harmonic (close to 50 or 60 Hz), a low-amplitude third, and negligibly small fifth harmonic. All conclusions about the fundamental are valid for the other harmonics as well. Even harmonics and DC component are not present in the PLI spectrum. The deviations of the rated PL frequency are restricted by the standards within the range of ±0.5 Hz. The changes are very slow but the current PL frequency has to be continuously checked to allow start and performance of adequate interference suppression during any ECG recordings including the continuous 24 hours Holter monitoring.

The early solutions of the problem, related to the subtraction procedure, are based on circuit for PL frequency monitoring and ongoing controlled AD conversion. The first samples of each PLI period are coupled to voltage level defined by Schmidt trigger, the other samples being shifted at the rated inter-sample distance thus contributing to small additional error [4]. It is later cancelled by measurement of the current period and calculation of the inter-sample distances for the next period. Nevertheless, the PLI tracking is not available in battery supplied and computer-aided ECG systems.

A software approach was reported by Dotsinsky and Stoyanov [5]. The PLI fluctuation is ongoing calculated. For the purpose, the signal is band-pass filtered and the intersections of interference and zero line are discovered using homogenous triangles formed by the samples around the zero. Then the contaminated signal is dynamically re-sampled to the rated PL frequency. The PLI is removed and the processed samples are shifted back, thus restoring the original timescale.

The PL frequency variation is special case of the non-multiplicity between sampling rate (SR) and rated frequency. The problem was overcome generalizing the structure of the subtraction procedure [14, 15]. The corrections are currently stored in a FIFO temporal buffer. Filter with linear phase response and unity gain in the PL frequency is specifically introduced to extrapolate the FIFO values before being used to compensate the amplitude errors introduced by the appeared phase differences.

Usually, a 250 Hz SR is acceptable for traditional ECG analysis [10]. However, some applications need higher SR [2]. When pacemaker's pulses have to be detected, the SR may reach 128 kHz [8]. In such cases the time for performing the subtraction procedure increases. To cope with the problem, Mihov [16] developed appropriate changes of some procedure stages. The efficiency achieved is manifested by ECG recordings with SR = 16 kHz.

Dotsinsky et al. [6] published a modified version of the subtraction procedure, which is based on counting the samples within the ongoing variable PLI intervals, extracted from the contaminated signal using bidirectional band-pass filter. The interference and the extracted amplitudes differ from each other but the phase error introduced by the forward filtration is canceled by the backward one thus preserving the actual positions of the intervals.

The two out-sample distances located at both ends of the sinusoidal wave are calculated and aided to the other distances. Thus, a fractional number of corresponding samples inside a wave is obtained to be used for exact moving averaging. The procedure is applied to paced ECG signals with 128 kHz SR. It includes pace pulse extraction, signal re-sampling down to 4 kHz and PLI elimination followed by adding back the removed pace pulses. The committed errors are usually in the range of 20 μV.

The traditional notch filters seem to be simple approach to cope the PLI but they suppress unacceptably the ECG spectrum around the rated PL frequency. The signal distortions can be avoided using filters with relatively narrow bandwidth but equating the filter central frequency to the interference one leads to a very long transition period. Quite logically, some researchers have experimented and continue to look for appropriate sophisticated notch filters that could cancel the 50 (60) Hz component with very limited affect to the informative ECG components, usually high and steep QRS complexes. Kher [9] introduced pair of complex-conjugated poles to a second-order FIR filter expecting to obtain a reliable selective bandwidth. Nevertheless, the presented figure shows reduced amplitudes of several R waves.

Recently, a recursive IIR band-pass filter for PLI extraction from ECG signal was developed and tested by Mihov and Badarov [17]. The filter is based on the Constantinides' transformation. One of the two coefficients is variable, linearly depended from the filter central frequency, and can be currently adapted to the PL frequency deviations to suppress the interference. The process is relatively fast going for SR of 250 Hz but is complicated in case of SR = 5 kHz due to the extended abscissa scale of the relationship between coefficient and SR. Therefore, the filter is "reduced" by processing samples spaced by 25 steps. The PL frequency assessment and the coefficient adaptation are performed using the so called "two-point" filter. The results obtained show low errors committed by the PLI extraction, generally in the range of 20 through 50 μV.

Materials and methods

Recordings taken from the AHA database, original and re-sampled up to 5 kHz, are mixed by synthesized interference with variable frequency from 49 through 51 Hz. They are used in MATLAB environment to test the method and evaluate the results obtained.

The corresponding algorithm consists of three steps:

- The mixed (corrupted) ECG recording (mix) is processed using bi-directional band-pass (BP) filter with central frequency **fo** at 50 Hz. The left **fl** and right **fr** cut-offs are 49 and 51 Hz, respectively. The resulting sinusoidal BP waves differ slightly in amplitude from the synthesized PLI but their zero crossing points remain identical.
- The two out-sample distances located at both ends of each current sinusoidal curve are calculated and aided to the inter-sample distances. The obtained fractal wave period is then converted in the corresponding PL frequency.
- The corrupted signal is subjected to bi-directional notch filtration with narrow stop-band. The coefficient, which is defined according to the central frequency, is continuously updated. The committed low error between original and processed ECG signal is reduced once more by a second backwards filtration.

Results and discussion

The subplots of Fig. 1 show the AHA1005d1 ECG signal, the synthesized PLI and the mixed signal, which is subjected further on to bidirectional band-pass filtration.

The written MATLAB program implements BF filter with the following **a1** and **a2** coefficients:

```
fl=48; fo=50; fr=52;
wo=2*pi*(fo/SR); wd=2*pi*(fr-fl)/SR; k=tan(wd/2); a=cos(wo);
a1=2*a/(1+k); a2=(1-k)/(1+k);
```

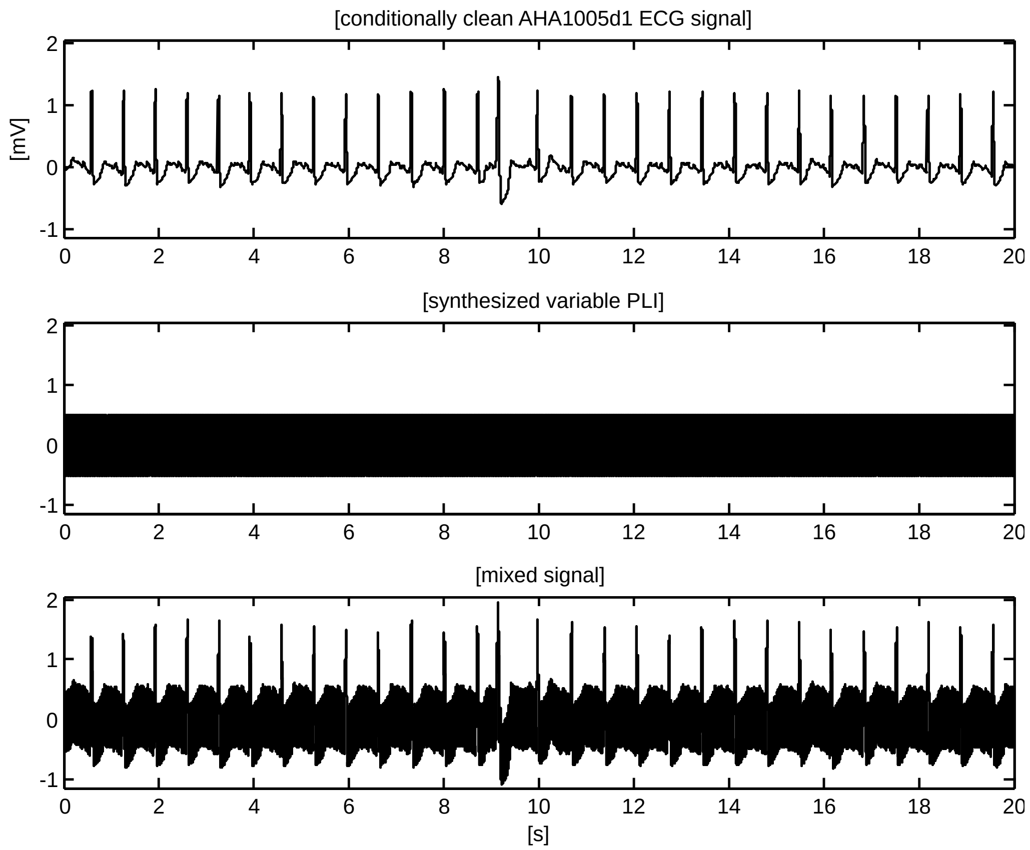

Fig. 1

The forward filtration **BPf** of the mix signal is completed by the instructions

```
BPf(1:2)=mix(1:2);
for i=3:1:length(mix)-1;
    BPf(i+1)=a1*BPf(i)-a2*BPf(i-1)+(mix(i+1)-a1*mix(i)*k-a2*mix(i-1))*k;
end;
```

while for the next backward (bidirectional) **BPb** filtration are used

```
for i=length(mix)-1:-1:2;
    BPb(i-1)=a1*BPb(i)-a2*BPb(i+1)+(BPf(i-1)-a1*BPf(i)*k-a2*BPf(i+1))*k;
end;
```

The efficiency of the bidirectional filtration is demonstrated in Fig. 2. The intersections of the **BPf** signal with the zero-line result in sine wavelengths (the red traces in first and third subplots), which differ from that of the PLI (the black traces) all over the recordings, except for a short epoch in the middle corresponding to the central PLI frequency at 50 Hz. The crossing points between the **BPb** signal and the PLI are identical (see the second and forth subplots).

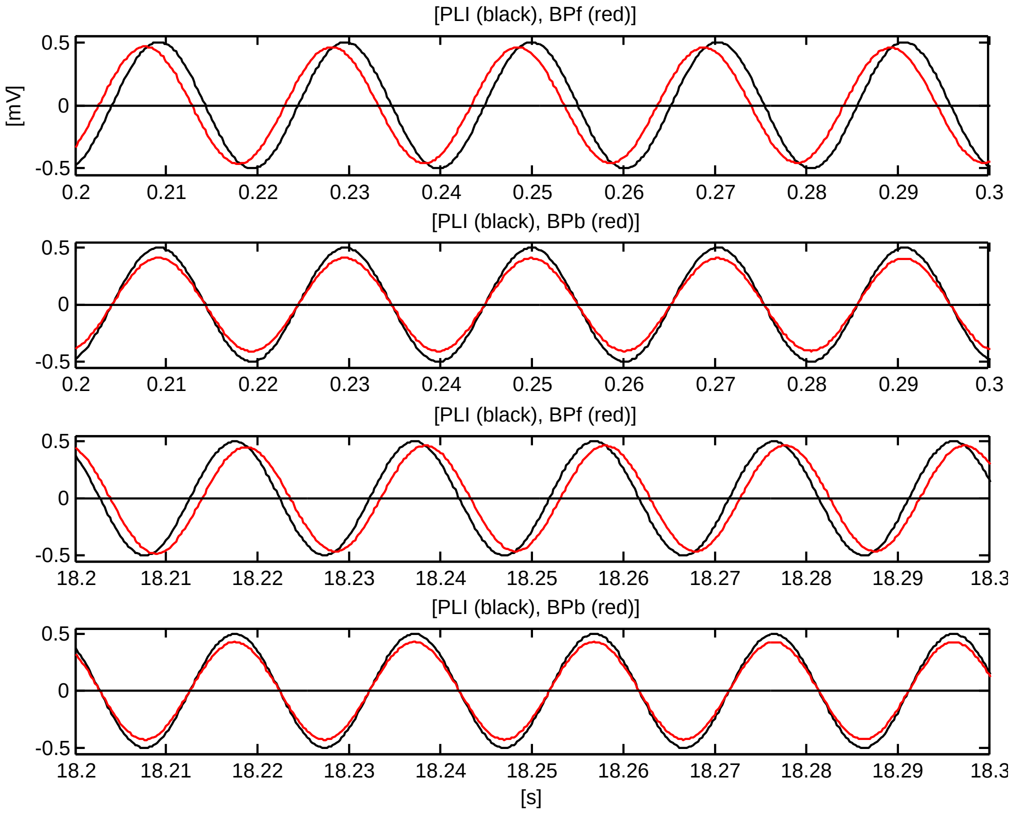

Fig. 2

The variable sine wavelengths are defined by detection of each first positive bi–directional BP sample following a series of negative ones. The number of samples N_i in a current wavelength shown in Fig. 3, is given by

$$N_i = t_{\ell+1} - t_\ell$$

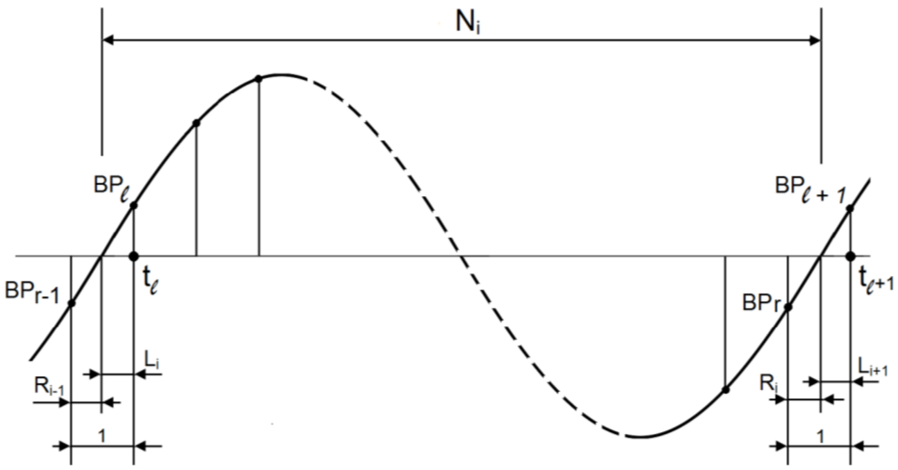

Fig. 3

The inter-sample distances are equated to unity. The left lateral distances are calculated using similar triangles, e.g.

$$L_i = BP_\ell / [BP_\ell + abs(BP_{r-1})].$$

The right lateral distances are

$$R_i = 1 - L_{i+1}$$

The sine interval T_i and the corresponding fractal frequency f_i are given by

$$T_i = N_i - 1 + L_i + R_i; \quad f_i = SR/T_i$$

The corrupted signal mix is processed by narrow notch filter using the detected variable central frequency f_i. The -3 dB cut-off frequencies are $f_i \pm 0.5$, the first coefficient **A1(i)** is a function of f_i, while **a2** remains constant.

```
k=0.5; fi=SR/Ti; fl=fi-k; fr=fi+k;
wo=2*pi*(fi/SR); wd=2*pi*(fr-fl)/SR;
A1(i)=2*cos(wo)/(1+tan(wd/2)); a2=(1-tan(wd/2))/(1+tan(wd/2));
```

The forward and backward filtrations are performed by

```
NFf (1)=mix(1); NFf (2)=mix(2);
for i=3:1:length(mix)
    NFf (i)=A1(i-1)*NFf (i-1)-a2*NFf (i-2)+.5*(1+a2)*mix(i)-
    -A1(i-1)*mix(i-1)+.5*(1+a2)*mix(i-2);
end;
```

and

```
for i=length(mix):-1:1;
      NFb(i)=A1(i+1)*NFb(i+1)-a2*NFb(i+2)+.5*(1+a2)*NFf(i)-
      -A1(i+1)*NFf (i+1)+.5*(1+a2)*NFf (i+2);
end;
```

The results of the PLI suppression achieved by both notch filtrations are demonstrated in Figs. 4 and 5 using the 5 kHz sampled AHA1005d1. The processed signals are compared to the original and the differences are presented in normal and zoomed scales. The maximum absolute errors except for the edges of the recordings are 7 μV for the forward filtration (Fig. 4) and practically imperceptible for the bi-directional one (Fig. 5).

Generally, the accuracy of the proposed approach depends of the sampling rate. Higher the SR, shorter the lateral distances L and R (Fig. 3) that leads to higher precise in approximating the ends of the sinusoidal curve with straight lines. Fig. 6 shows experiments with the AHA7009d1signal sampled with 1 kHz, 500 Hz and 250 Hz. The maximum errors committed are near to zero, 3 μV and 19 μV, respectively.

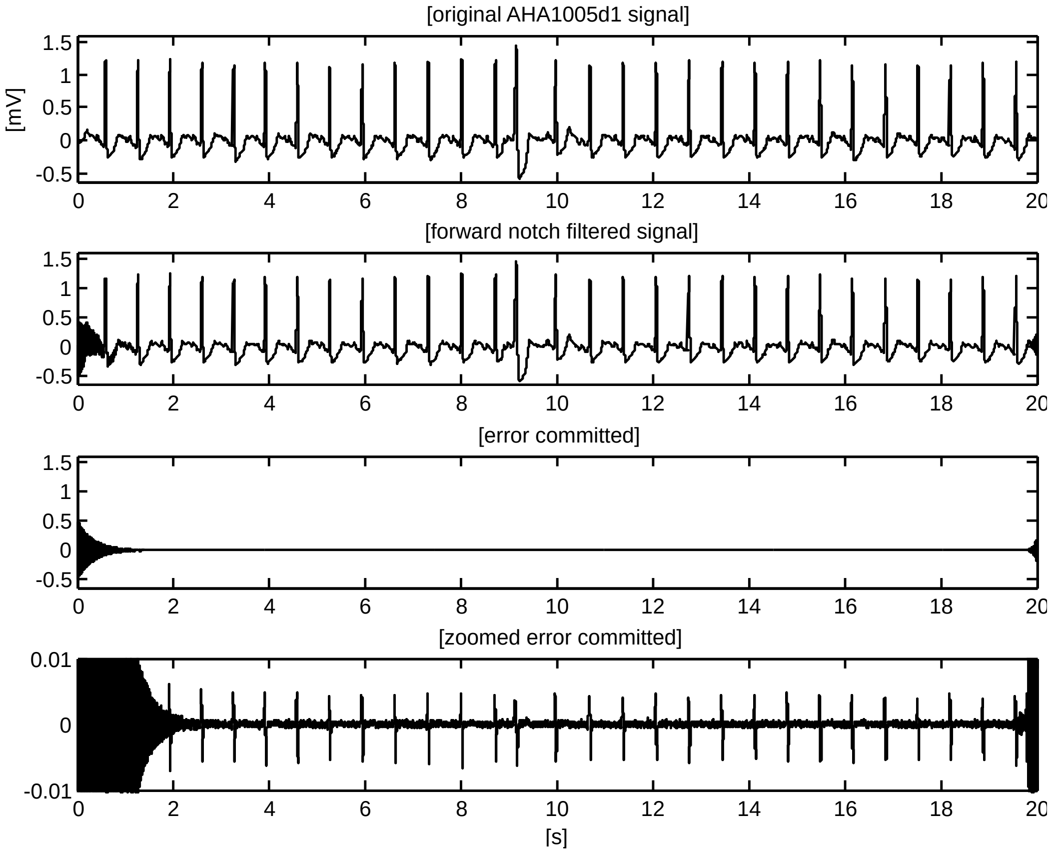
[original AHA1005d1 signal]
[mV]
[forward notch filtered signal]
[error committed]
[zoomed error committed]
[s]

Fig. 4

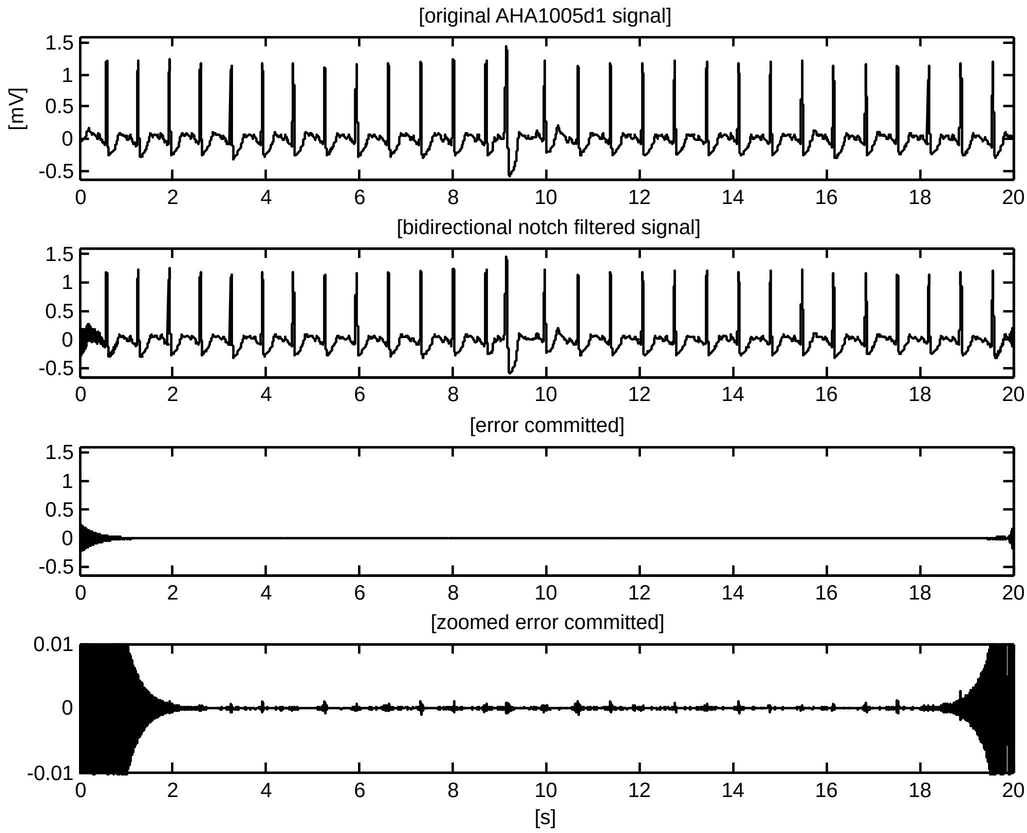
[original AHA1005d1 signal]
[mV]
[bidirectional notch filtered signal]
[error committed]
[zoomed error committed]
[s]

Fig. 5

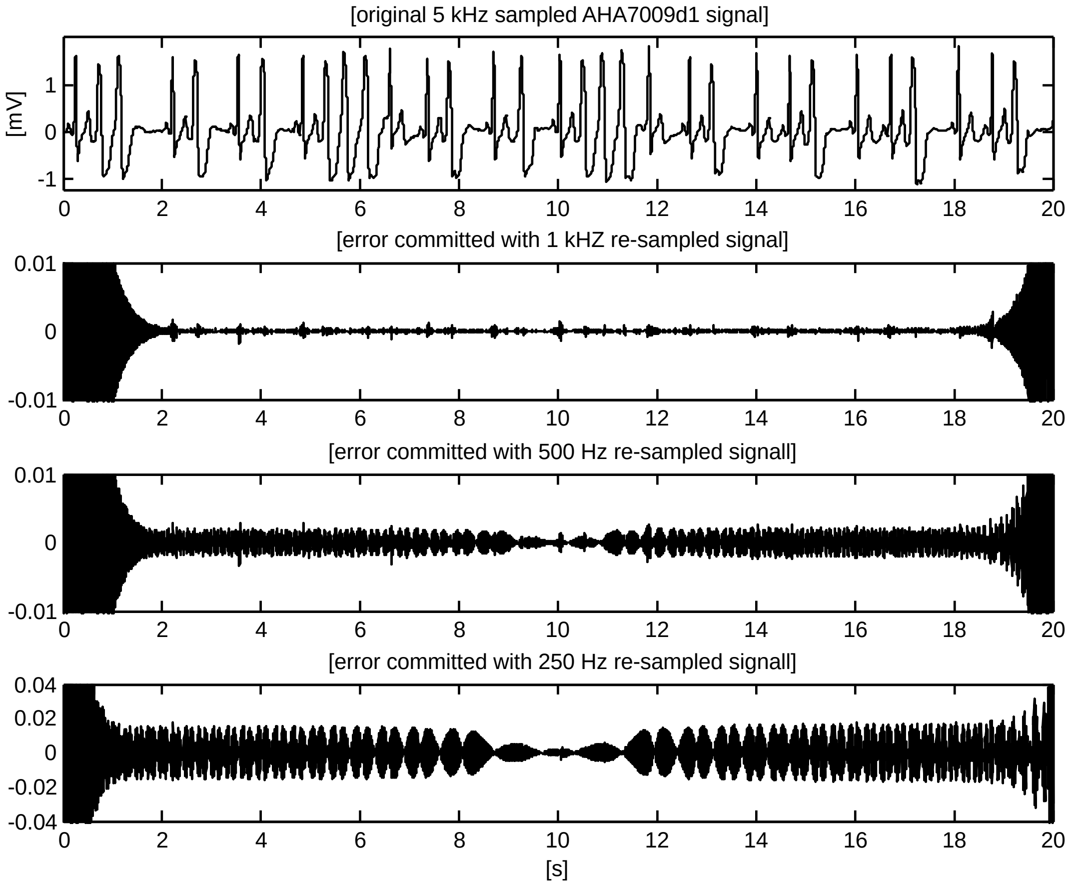

Fig. 6

Conclusion

The proposed approach demonstrates a very successful PLI suppression in ECG signals. The used for testing interference is with variable frequency of 0.1 Hz/s that significantly exceeds the real cases. Its amplitude is also higher than normal. These parameters are selected to highlight the extreme accuracy obtained.

As usually, the synthesized frequency does not contain third harmonic, the influence of which is practically unclear. The amplitude of fifth harmonic can be considered as negligible. Basically, the presence of harmonics in PLI has to be carefully investigated by simulating the human body together with parasitic currents flowing through the patient cable and electrodes.

The transition process is within the range of 1÷1.5 s. It can be slightly reduced expanding the boundaries of the cut-off frequencies from **`fi ± 0.5`** trough **`fi ± 1`** but this is accompanied by small accuracy degradation for signals with SR < 1 kHz.

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