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Power-line Interference Removal from ECG in Case of Power-line Frequency Variations

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Abstract: *The original version of the most successful approach for power-line (PL) interference removal from ECG, called subtraction procedure, is based on linear segment detection in the signal and hardware synchronised analogue-to-digital conversion to cope with the PL frequency variations. However, this is not feasible for battery supplied devices and some computer-aided ECG systems. Recent improvements of the procedure apply software measurement of the frequency variations that allow a re-sampling of the contaminated signal with the rated PL frequency followed by interference removal and back re-sampling for restoration of the original time intervals. This study deals with a more accurate software frequency measurement and introduces a notch filtration as alternative to the procedure when no linear segments are encountered for long time, e.g. in cases of ventricular fibrillation or tachycardia. The result obtained with large PL frequency variations demonstrate very small errors, usually in the range of ±20 μV for the subtraction procedure and ±60 μV for the notch filtration, the last values strongly depending on the frequency contents of the QRS complexes.*

Keywords: *ECG, Power-line interference removal, Software measurement of power-line frequency.*

Introduction

Each ECG analysis is preceded by pre-processing, which includes suppression or removal of residual power-line interference (PLI), muscle disturbances, physiological drift, and other artefacts, provoked by involuntary patient movements, bad electrode contact, electrostatic discharges, etc. The residual PLI is due to the parasitic currents flowing through the patient cable and body, and to the differences in the electrode impedances [8] and can not be influenced by the usually very high CMRR of the contemporary ECG amplifiers.

Since the ECG spectrum of interest is from 0.3 through 125 Hz, the traditional notch filters [11, 12, 14] used for PLI suppression affect also an overlapped ECG frequency band, which depends on the PL frequency variation that has to be compensated. Different types of adaptive filters were proposed [1, 7, 11, 13]. However, they introduce unacceptably long transient time response and/or "ringing" effect. The last one is found to be inherent also to signal reconstruction by inverse FFT transformation after deleting the PL frequencies of the spectrum [3].

A digital subtraction procedure was developed approximately two decades ago and continuously improved later on [2, 9, 10]. It does not affect any ECG frequency components including this coinciding with the PL frequency. The basic procedure principles are:

- The analogue-to-digital conversion (ADC) rate is synchronised with the PL frequency.
- Moving averaging (comb filtering) is applied on linear segments (usually PQ and TP intervals that have frequency band near to zero) to remove the interference. Phase locked interference components, called corrections, are calculated by subtracting the filtered samples inside the linear segment from the corresponding contaminated samples.
- These corrections are stored and further subtracted from the signal wherever non-linear segments (QRS complexes and some high and steep T wave) are encountered.

The subtraction procedure was tested carefully by comparing conditionally clean ECG signals with processed contaminated signals, which are obtained by mixing the clean signals with synthesised interference. The difference observed is usually in the limits of ±20 μV, but the real error committed is lower since in fact the conditionally clean signals contain inherent interference and tremor [4].

The PLI amplitude variations are taken in consideration by nearer update of the correction set using a less restrictive criterion for linear segment detection [3, 10]. The synchronised ADC allows small adjustments of the inter-sample intervals around their rated value that compensate the PLI frequency variations for an accurate PLI removal. According to an initial approach [3], each first sample inside the PLI period is locked to a given level of the PL voltage using Schmidt trigger connected to a secondary winding, the other samples being equally spaced at the rated inter-sample interval. The irregular distance between the first sample and the *n*-th sample of the previous period may results in a less than 2% additional error of the subtraction procedure for PL frequency change from 49 to 51 Hz. An improved version of the synchronised ADC cancels this error by measuring each PL interval followed by an equal sample allocation during the next period [3]. The time error introduced in the signal using both approaches is lower than 2% for a PL frequency deviation of ±1 Hz. However, the hardware measurement of the PLI frequency is not feasible in battery supplied devices and in some computer-aided ECG systems.

Subsequent studies [4, 5, 6] are devoted to interference removal without hardware ADC synchronisation. The algorithm developed consists of:

- Software PLI frequency measurement.
- Re-sampling the contaminated signal so that the variable interference frequency is transformed into the rated constant PL frequency.
- Removal the interference.
- Back re-sampling the processed signal, thus restoring the original time scale.

The software PLI frequency is measured [4, 6] after an appropriate band-pass filtration of the contaminated signal. Then the amplitudes of two adjacent samples from a positive going slope of the interference located below and above the zero line are taken in consideration. Two homogenous triangles are obtained by the left and right sample amplitudes; the inter-sample interval; and the distance between the cross-point and the right amplitude, which can be calculated and used later on for PLI frequency determination. Generally, negative going slope can be used too. In particular cases one of the samples may be situated on the zero-line.

Four and eight point Lagrange's polynomials as well as linear interpolation were used for the two re-samplings [4, 5]. The results reported show that the advantage of the eight point before the four point polynomial is negligible. Both polynomials have smaller errors compared to these obtained by the linear interpolation, but the differences are not significant.

The papers dealing with PLI [4, 5] demonstrate tests with PL frequency changes of 0.5 Hz [5] and 1 Hz [4] for 8 seconds.

Larger frequency deviation from 12.5 through 18.8 Hz was accepted when ventricular fibrillation (VF) has to be detected in ECG signals recorded by public access defibrillators in environment of 16.7 Hz railway interference [6]. In such case the disturbances are suppressed by moving averaging (comb filtering) since the shape alternations introduced do not exceed the immense variety of original fibrillation patterns that must be recognised by the algorithm used.

Aim of the study

We found that the software track of the PL frequency deviations is the greater source of errors reflecting upon the successful PLI removal. Therefore, we tried to improve the software frequency measurement. Further, we extended the tests already reported [4, 5] with ±2 Hz deviations around the rated 50 Hz. and experimented automatic introduction of notch filtration if long time no linear segment was found, a case which is typical for the beginning of VF or ventricular tachycardia (VT) episodes. We choose the linear interpolation for the two re-samplings.

Algorithm

The contaminated ECG signal is band-pass filtered within 48 trough 52 Hz. Then its zero line crossings j = 1, 2… are detected. Sequences of four samples are taken in consideration (Fig. 1). The first two B_{LL} and B_L must be negative or zero, the next ones B_R and B_{RR} – with positive amplitude.

$$B_{LL}(j) \le 0;\ B_L(j) \le 0;\ B_R(j) > 0;\ B_{RR}(j) > 0;\quad j = 1, 2... \tag{1}$$

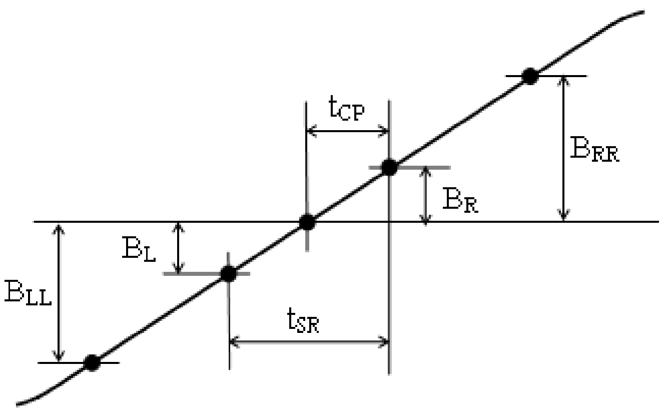

Fig. 1 PL frequency measurement

The increased number of the sequence, compared to the previously used [4, 5] two terms $B_L(j)$ and $B_R(j)$, reduces the errors caused by the residual QRS complexes, which may shift up and down the zero line. The distance between each cross-point and its right-hand amplitude is calculated by:

$$t_{CP}(j) = \frac{B_R(j)}{B_R(j) - B_L(j)} T_S \tag{2}$$

Here T_S is the inter-sample interval. The re-sampled T_S, $T_{RS}(j)$, is derived by:

$$T_{RS}(j) = \frac{n(j)T_S + t_{CP}(j) - t_{CP}(j-1)}{n(1)} \quad (3)$$

where $n(j)$, j = 1, 2… stand for the sample numbers inside two consecutive zero-line crossings. The initial value $n(1)$ is equal to the ratio between the sampling rate SR and the PL rated frequency. This study is carried out for 50 Hz interference and ECG signals with SR = 500 Hz. Then $n(1)$ equals 10 but the algorithm is working also with other SR and 60 Hz rated interference. The length of each inter-crossing interval is calculated by the product of the crossing number $n(j)$ and the inter-sample interval T_S that is corrected by the difference between the current and previous distances $t_{CP}(j)$-$t_{CP}(j-1)$. The re-sampled interval $T_{RS}(j)$ is derived by dividing the length of the inter-crossing interval by the initial number $n(1)$. Additional preventive measures are taken for suppressing the shift of the band-pass filtered signal. If the absolute value of the increment $inc=T_{RS}(j)-T_{RS}(j-1)$ divided by $T_{RS}(j)$ is higher than 0.016, the calculated $T_{RS}(j)$ is smoothed by:

$$T_{SRS}(j) = T_{RS}(j-1) + 0.25[T_{RS}(j) - T_{RS}(j-1) + T_{RS}(j) - T_{RS}(j-3)] \quad (4)$$

The calculated $T_{RS}(j)$ or smoothed $T_{RS}(j)$ are used further for the two re-samplings. The notch filtration introduced for PLI suppression when no linear intervals are encountered in the ECG signals (possible VF or VT) is implemented with low and high cut-offs equal to 45 and 55 Hz, respectively. These values, as well as the band-pass width from 48 through 52 Hz for the software PLI frequency measurement are defined heuristically.

Results

The algorithm is tested in MATLAB environment with recordings taken from the AHA database and re-sampled with SR = 500 Hz. Different frequency variable interferences are synthesised. The structure of the program written simulates a real going signal processing; therefore it is suitable for real-time implementation.

The consecutive steps of the PLI removal or suppression in case of PL frequency variations can be seen in Fig. 2 in zoomed time scale. The original AHA 7009 recording (blue trace, first subplot) is superimposed by interference. The contaminated signal (black trace, first subplot) is re-sampled according to the measured PL frequency (black trace, second subplot). The result of the processing is presented by the green trace, which is back re-sampled (red trace) and compared to the original signal (blue signal). Since the processed signal reproduces the original with very high accuracy, both traces are shown for better observation with small amplitude shift in the third subplot.

The next Figs 3a, 4÷6 demonstrate the results obtained by applying the subtraction procedure and the notch filtration on the AHA 6002 recording contaminated by PLI with variations from 49 through 51 Hz, from 51 through 49 Hz, from 48 through 52 Hz, and from 52 through 48 Hz. This signal is typical for rhythm disorder and is used for all combinations in order to give an opportunity for comparison. The errors committed with the subtractions procedure are below ±20 μV (see the red horizontal straight lines). The notch filtration introduces slightly higher peaks coinciding with the QRS complexes because of their high frequency spectrum.

The first subplot of Fig 3b shows the level of coincidence between measured and calculated (specified with the PLI synthesis) frequency variations. The PLI removal accuracy may be assessed in the lower subplots by the original (black trace) and the processed signal (red trace), which is shifted in time and amplitude by 20 ms and 20 μV, respectively.

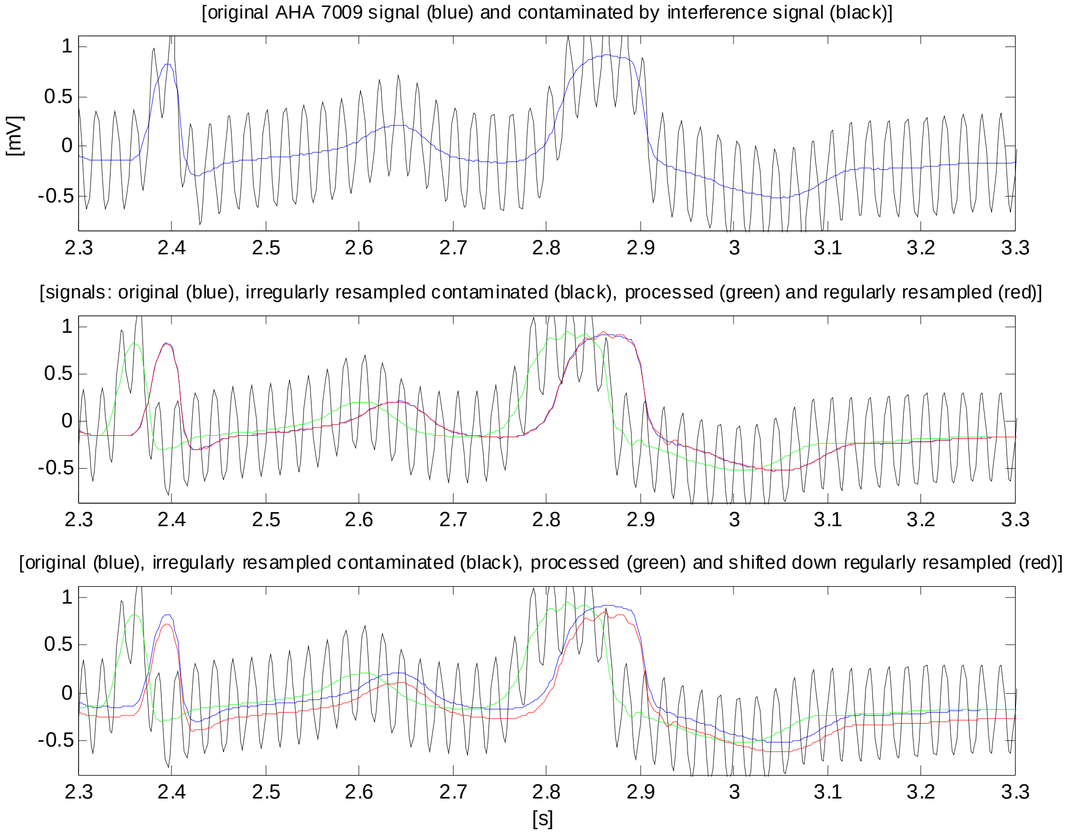

Fig. 2 Re-sampling, PLI suppression and back re-sampling of AHA 7009 recording

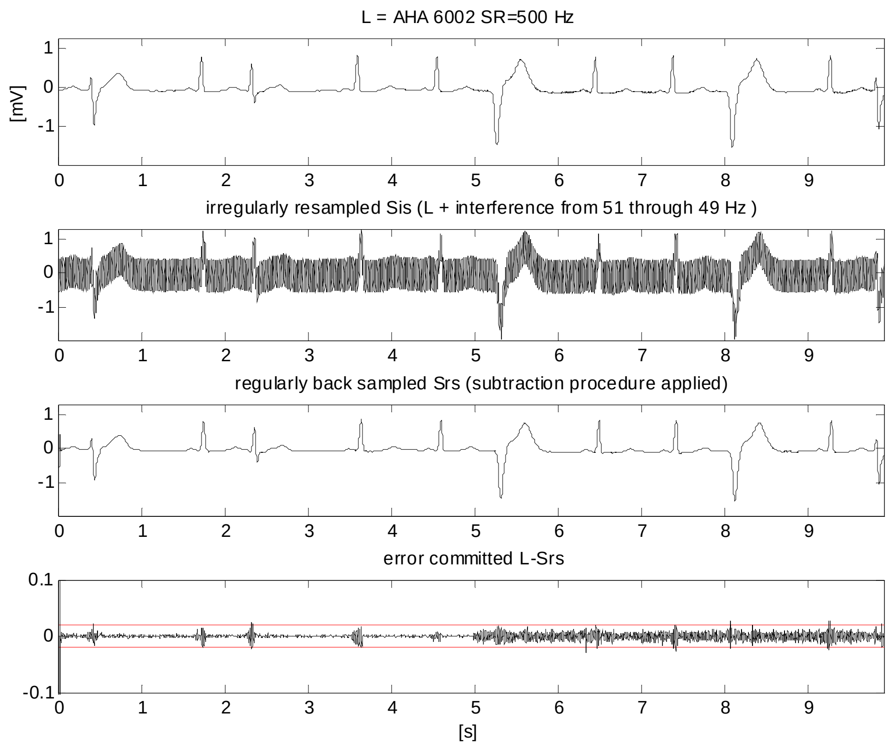

Fig. 3a Result of applying the subtraction procedure on the AHA 6002 recording contaminated by interference, which decreases from 51 through 49 Hz for 10 s

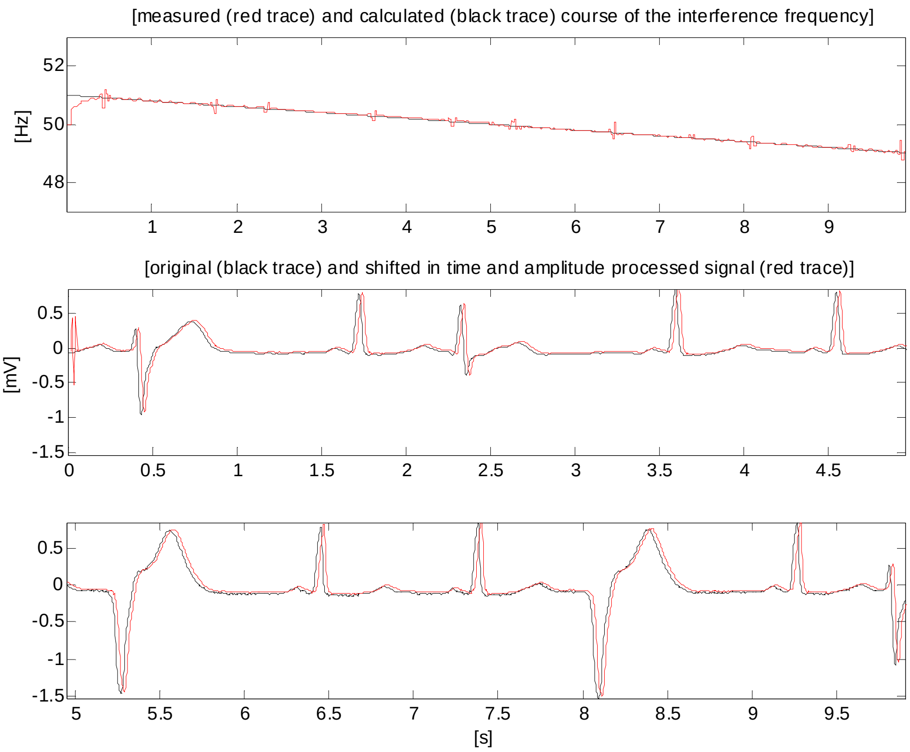

Fig. 3b Upper subplot: coincidence between measured and calculated (specified with the PLI synthesis) frequency variations; lower subplots: comparison of original (black trace) and processed signal (red trace), shifted in time and amplitude by20 ms and 20 μV, respectively

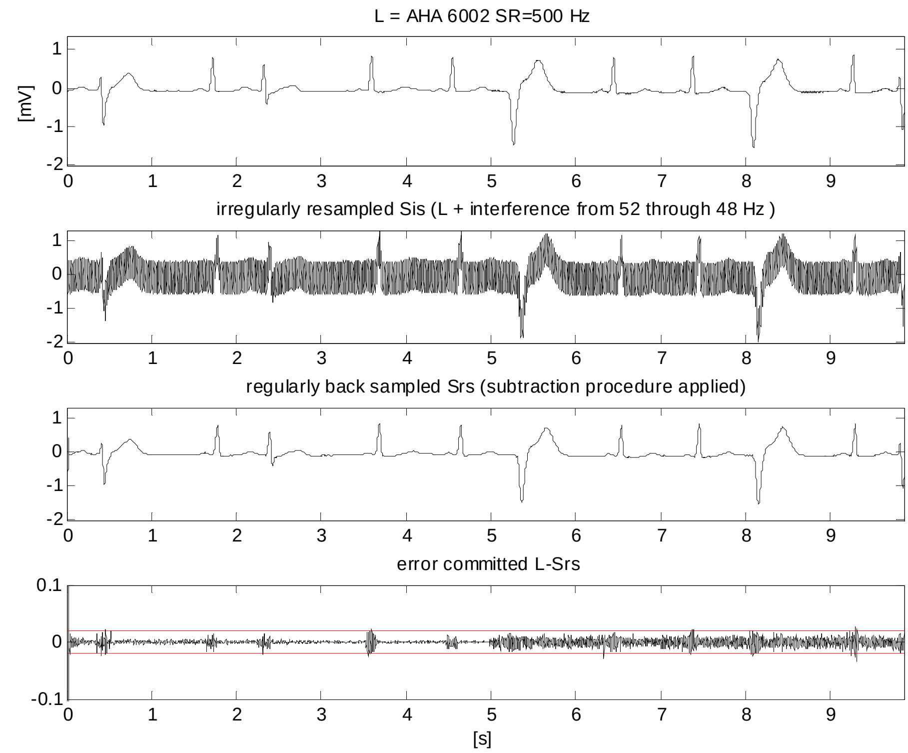

Fig. 4 Result of applying the subtraction procedure on the AHA 6002 recording contaminated by interference, which decreases from 52 through 48 Hz for 10 s

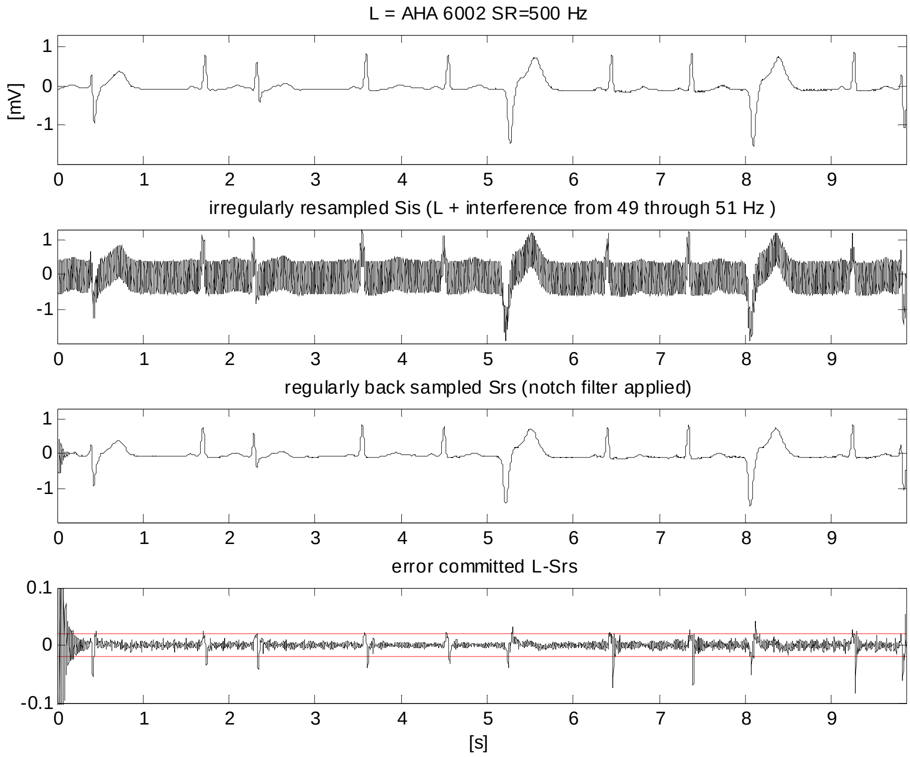

Fig. 5 Result of notch filtration of the AHA 6002 recording contaminated by interference, which increases from 49 through 51 Hz for 10 s

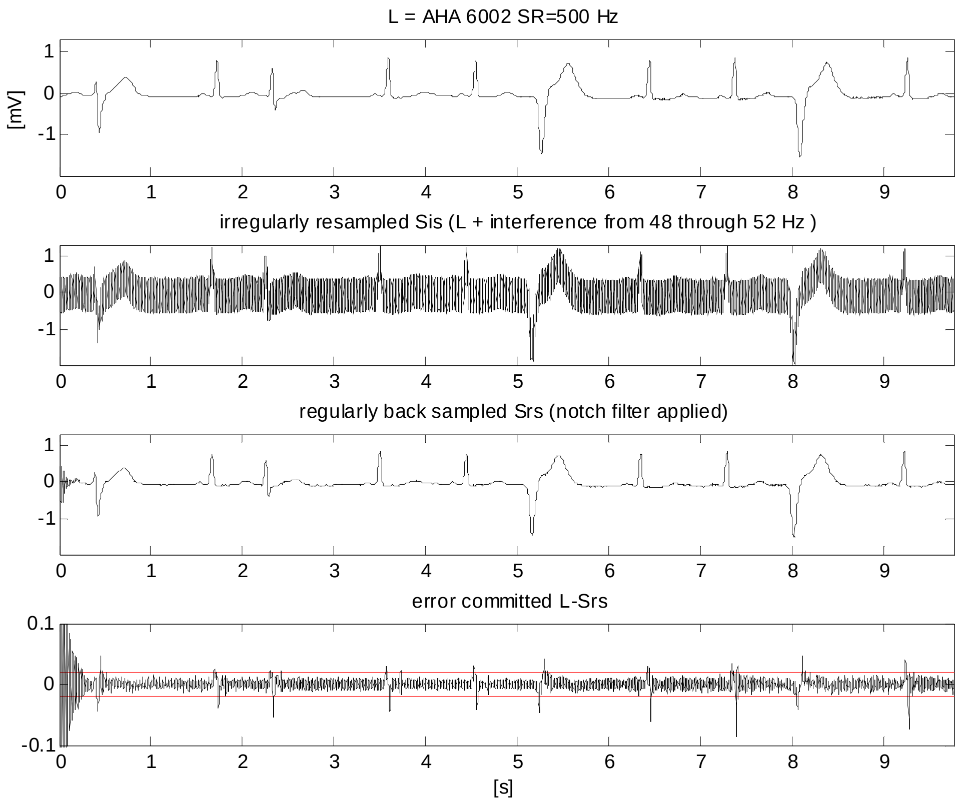

Fig. 6 Result of notch filtration of the AHA 6002 recording contaminated by interference, which increases from 48 through 52 Hz for 10 s

Conclusions

The improved software measurement of the PL frequency variations, compared to the previously used approach [4, 5], contribute to an efficient interference removal using the subtraction procedure or suppression by notch filtration. The written MATLAB program was tested with large number of AHA database recordings. The program structure allows real time implementation. The results obtained demonstrate very small errors, which are assessed by subtraction the original signal from the processed. It is necessary to have in mind that the original signals contain inherent noise, which is added to the calculated difference. It remains below ±20 μV when the subtraction procedure is applied on extended PL frequency variations up to ±2 Hz for 10 s, except for very rare cases. The errors introduced by the notch filter are higher, usually about ±40÷60 μV depending very closely on the frequency content of the QRS complexes. However, they have no impact on the interpretation accuracy since this filtration is called by the program when no linear segments are detected, i.e. in cases of VF and VT.

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