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Adaptive Tunable Notch Filter for ECG Signal Enhancement

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Abstract

In this paper, a high performance adaptive tunable notch filter algorithm for accurate estimation of ECG signal is proposed. The power line interference and muscle contraction noise is significantly suppressed using the proposed adaptive notch FIR filter with tunable notch frequency. An important aspect of the proposed filter scheme is that it preserves the selectivity and attenuation at the notch frequency. The filter is optimized and its coefficients are computed such that the noise in ECG signal is minimised in a specified frequency range. The proposed algorithm estimates the frequency of unwanted signal and updates accordingly the filter coefficients for optimum performance. Based on simulation results, it is demonstrated that the proposed technique can be used to accurately extract the ECG information such as heart beat rate from noisy ECG signal and significant improvement in output signal-to-noise ratio (SNR) can be achieved as compared to the normal adaptive notch filter technique.

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Keywords: Adaptive notch filter, FIR filter, ECG signal, tunable filter.

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1. Introduction

The ECG signal obtained from human being is a weak signal, which is mostly contaminated by noise signal such as power line interference and muscle contraction noise. It is highly desirable to remove such noise before further processing of ECG signal. The power line interference is represented by a narrow band (48-60 Hz) harmonic signals. On the other hand, the muscle contraction noise occurs at 38 to 45 Hz. In order to suppress these unwanted harmonic distortions from the ECG signal, one can use a highly selective notch filter designed at a particular frequency. Such type of notch filter can be useful for removing a particular frequency noise. In other words, many notch filters are needed to suppress noise signal present at different frequencies simultaneously. This approach will not only complicate the design but also attenuate the desired ECG signal. In order to over come this problem, we proposed the use of a tunable notch filter which can be tuned to the specified frequency range of power line interference and muscle contraction noise in the ECG signal. The proposed notch filter is so design that it preserves the ECG signal pulses containing useful information. These requirements lead to a notch FIR filter with a very narrow band. Varying frequency characteristic of the unwanted harmonic signal requires the use of adaptive filters in such cases. In the past, several adaptive notch filtering techniques have been reported [1,2,3,4,5,6] in literature. However, these approaches are not

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able to detect the ECG signal accurately in presence of harmonic noise. This is due to the fact that these techniques are based on LMS minimization or neural networks consisting of sub optimality in terms of the filter length related to its selectivity. Another disadvantage is that the attenuation of these adaptive filters at the notch frequency varies in the adaptation, and consequently a desirable attenuation of the noise signal at the notch frequency is not guaranteed. Therefore, motive of present work is to develop an adaptive notch filtering algorithm to efficiently detect the ECG signal information such as heart beat rate by suppressing harmonic noise. This approach is based on an adaptive notch FIR filter to have an optimal notch band width so that a strong attenuation is obtained at its notch frequency. The proposed adaptive notch FIR filter is optimal in terms of shortest possible filter length related to its frequency specification. Based on simulation results, it is demonstrated that accurate beat rate can be detected from the noisy ECG signal and 26% increase in output SNR can be obtained using proposed adaptive tunable notch filter (ATNF) when compared with conventional adaptive notch filter (ANF) technique[7,8,9,10].

2. Design and Optimization of Adaptive Tunable Notch Filter

Consider an adaptive predictive FIR filter whose output is written as[3].

$$\hat{v}(k+1) = h_k^T x_N(k) \tag{1}$$

where $h(k)$ and $x_N(k)$ vectors are given by

$$h(k) = [h_0(k)........h_{N-1}(k)] \tag{2}$$

$$x_N(k) = [x(k)x(k-1)........x(k-N+1)]^2 \tag{3}$$

The error signal, $e_p(k+1)$ is obtained as,

$$e_p(k+1) = x(k-1) - \hat{x}(k+1) \tag{4}$$

where $x(k+1)$ is noisy signal. For the filter coefficient vector fixed at h_0, an error transfer function can be defined as:

$$H_{e,o}(z) = \frac{E_p(z)}{X(z)} = 1 - \sum_{n=o}^{N-1} h_{0,n}(Z)^{-(N+1)} \tag{5}$$

Note that $Eq.5$ is a notch filter which is to be tuned at the angle 0 such that the first pair of the zeros $(z_{0,1}, z_{0,2})$ are obtained and $H_{e,o}(z)$ can be written as:

$$H_{e,o}(z) = (1 - 2cos(\theta_0)z^{-1} + z^{-2}) \tag{6}$$

where $z_{0,l}, l = 3, ..., N$ are the remaining zeros of the polynomial. The proposed adaptive filter of $Eq.6$ is based on the parameter error transfer function given by:

$$H_e(z, \alpha) = (1 - \alpha z^{-1} + z^{-2})H_n(z) \tag{7}$$

where $\alpha = 2cos(\theta)$ whit θ as tuning angle and $H_n(z)$ denotes the product term in $Eq.6$, having constant coefficients of the powers of z. $Eq.7$, $H_e(z, \alpha)$ can be written using $Eq.5$ as:

$$H_e(z, \alpha) = 1 - \sum_{n=o}^{N-1} h_n(Z)^{-(n+1)} \tag{8}$$

The α filter coefficients can be obtained by expanding $H_e(z, \alpha)$ in $Eq.7$ as a power series. The filters are linear in α as given:

$$h_n(\alpha) = a_n + \alpha b_n \tag{9}$$

The filter will be optimal with respect to $\theta = cos^{-1}(\alpha/2)$. For initial value of tuning angle, $\theta_0, \alpha = \alpha_0 = 2cos(\theta_0)$. Filtered prediction error is defined as:

$$\hat{e}_p(k+1) = \sum_{n=0}^{N-1} h_{e,n} e_p(k+1) \tag{10}$$

where initial value of h_e is taken as h_0 at $\theta = \theta_0$. This error can also be written as difference of standard signal $x_0(k+1)$ and predicted signal as:

$$\hat{e}_p(k+1) \approx x_0(k+1) - \hat{x}(k+1) = x_0(k+1) - h^T(\alpha)x_N(k) \tag{11}$$

The standard signal can be defined as:

$$x_0(k+1) = h^T(\alpha)x_N(k) \tag{12}$$

where $\alpha_s = 2cos(\theta_s)$, and $Eq.11$ can be written as:

$$\hat{e}_p(k+1) = [h(\alpha_s) - h(\alpha)]^T x_N(k) = (\Delta h)^T x_N(k) \tag{13}$$

The correction in the coefficient vector is approximated by

$$\Delta h \approx \frac{\delta h}{\delta \alpha} \approx [-2sin(\theta_s)]\Delta\theta_s \tag{14}$$

where $b = [b_0.....b_{N-1}]^T$, and $\Delta\theta_s$ is the correction in the estimated angle. Substituting $Eq.14$ in $Eq.13$, the value of $\theta_s(K+1)$ is obtained

$$\theta_s(k+1) = \theta_s(k) - \mu(k)\frac{\hat{e}_p(k+1)}{[2sin\theta_s(k)]} \tag{15}$$

where μ may be taken between (0 to 1) as step size. Now, the coefficient vector of $Eq.9$ is updated as the value of term $b^T x_N(k)$ in $Eq.14$ is depending on θ_s. As θ_s is approaching its optimum value, $b^T x_N(k)$ be will be minimum as given by:

$$h(k+1) = h[\alpha(k+1)] = a + b\alpha(k+1) \tag{16}$$

where $\alpha(k+1) = 2cos(\theta_s(k+1))$.

$$|b^T x_N(k)| \leq 1 \tag{17}$$

where, ϵ is a threshold for successive updates. When ϵ is too small, it may lead to instability. On the other hand, a large value of ϵ may result in decreased tracking performance. Note that ϵ should be less than the maximum amplitude of $b^T x_N(k)$. Therefore, the update equation for θ_s depends upon $b^T x_N(k)$ as:

$$\theta_s(k+1) = \theta_s(k) - \mu\frac{\hat{e}_p(k+1)}{[2sin\theta_s(k)]b^T x_N(k)} \tag{18}$$

Where $\mu(k) = \mu|b^T x_N(k)| \leq \epsilon_0$ otherwise zero. In the implementation of the proposed adaptive filter, the angle range [0, π] is divided into eighteen intervals (L). The optimum filter coefficient vector is calculated at the centre angle $\theta_0(l), l = 1, ..., L$, of each interval. Fig. 1 shows the amplitude response of the optimized notch filter along with adaptive and basic notch filter. It can be seen that the proposed filter provides sharp notch characteristic with slightly reduced pass band gain. Further, the optimized adaptive notch filter is tunable in the frequency range where various noise occur in ECG signal. In contrast, the conventional filter is useful at a fixed notch frequency. Moreover, the large notch band of conventional filters is not desirable because it provides attenuation to the desired signal. Therefore, the proposed tunable filter is advantageous over the conventional filter. Considering various noise present in the ECG signal in the range 32 to 60 Hz, the center frequency of purposed notch filter is varied in a specified range. The optimized adaptive notch filter automatically search for noise signal present at a particular frequency and achieves a notch filter characteristic at that frequency to eliminate the noise. To best of our knowledge, a tunable notch filter concept is not applied to ECG signal. Therefore, the purpose of present work is to design and implement a tunable notch filter for removal of noise in a specified range of frequency in ECG signal.

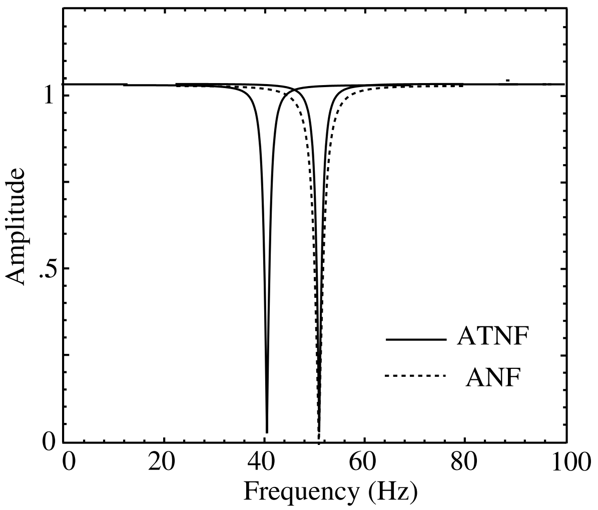

Fig. 1. Frequency response of normal adaptive notch filter and adaptive tunable notch filter.

3. Application to ECG Signal Enhancement

Electrocardiogram (ECG) is an important clinical tool for investigating the activities of heart, which is one of the signals of vitality. Interpretation of these details allows diagnosis of a wide range of heart conditions. These conditions can vary from minor to life threatening. A typical ECG tracing of a normal heart beat (or cardiac cycle) consists of P-wave, QRS-complex and T-wave. From various artifacts contaminate ECG recording, the most common are power line interference and muscle contraction. Power line interference is easily recognizable since the interfering voltage in the ECG may have frequency 48 to 60 Hz. This interference may be due to stray effect of the alternating current fields due to loops in the patient's cables. Other causes are loose contacts on the patient's cable as well as dirty electrodes. When the machine or the patient is not properly grounded, power line interference may even completely obscure the ECG waveform. The most common cause of 50/60 Hz interference is the disconnected electrode resulting in a very strong disturbing signal. Electromagnetic interference from the power lines also results in poor quality tracings. Electrical equipments such as air conditioner, elevators and X-ray units draw heavy power line current, which induce 50/60 Hz signals in the input circuits of the ECG machine. Electrical power systems also induce extremely rapid pulse or the spike on the trace due to switching action. For the meaningful and accurate detection, steps have to be taken to filter out or discard all these noise sources. With the advance technology, digital filters are now capable of being implemented easily and efficiently for large number of applications. The work on design and implementation of digital filter on the ECG signal is in progress. In the past, various approaches have been used to design digital filter for removing power line interference[4,7]. Further, the advantage of using adaptive algorithms for ECG signals is very well demonstrated[9]. The main advantage of the developed method in comparison with other simpler and faster approaches is the accurate interference reduction in cases when the harmonic noisy frequency deviates from the nominal 48 to 60 Hz. Superior performance is observed in terms of effective elimination of noise under conditions of varying harmonic interference frequency. An improved adaptive approach for ECG signal enhancement has been reported in[10]. These methods were based on designing a notch filter at fixed frequency and therefore may not be suitable for removing power line interference and muscle contraction noise simultaneously from a ECG signal.

In order to test the performance of proposed algorithm for extracting useful information such as beat rate from ECG signal corrupted by power line and muscle contraction noise, we have taken a clean ECG signal as shown in Fig. 2(a). This signal is corrupted by the known sinusoidal harmonics at 38 Hz, 41 Hz, 48 Hz, and 51 Hz as represented by Fig. 2(b) to (e) resulting the noisy ECG signal given in Fig. 2(f). As seen from Fig. 2(g), the beat rate detected from the noisy ECG signal without use of any filter is 89 which is much higher than the actual value. The beat reduces to 78 when the noisy ECG signal is passed through a normal ANF algorithm as given Fig. 2(h). On the other hand, as shown in from Fig. 2(i), the ECG signal is obtained using the proposed ATNF algorithm and the beat rate is accurately

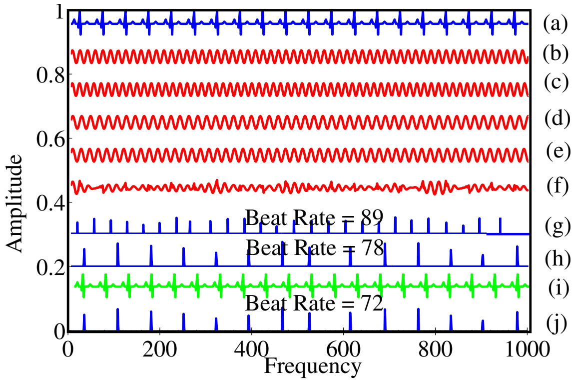

Fig. 2. Beat rate detection using normal adaptive notch filter and adaptive tunable notch filter from ECG signal corrupted by known harmonic noise.

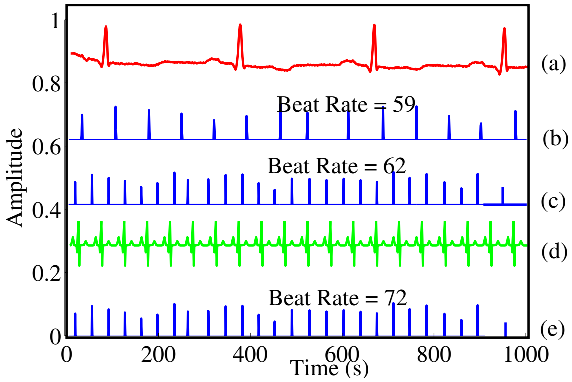

Fig. 3. Beat rate detection using normal adaptive notch filter and adaptive tunable notch filter from ECG signal containing muscle contraction noise.

detected to 72 as given in Fig. 2(j). Fig. 3 shows another example of detection of beat rate from a noisy ECG signal. Fig. 3(a) gives the noisy signal containing muscle contraction noise. The heart beat rate are found to be 59, 62, and 72 without any filter, with ANF, and ATNF algorithms, respectively as shown in Fig. 3(b), (c) and (e). Fig. 3(d) represents the ECG signal at output of ATNF algorithm. This shows that the proposed ATNF technique can be used to accurately extract the useful information from a noisy ECG signal. Further, the SNR performance of the proposed adaptive tunable notch filter compared with that of the normal adaptive notch filter is demonstrated in Fig. 4. The input SNR and output SNR for the ECG signal are defined as: SNR (dB) at input,

$$SNR_{dB} = 10log_{10}\frac{(ECG_{pure})^2}{(ECG_{noisy} - ECG_{pure})^2} \tag{19}$$

SNR (dB) at output,

$$SNR_{dB} = 10log_{10}\frac{(ECG_{pure})^2}{(ECG_{filtered} - ECG_{pure})^2} \tag{20}$$

where ECG$_{pure}$ is the pure ECG signal, ECG$_{noisy}$ is the noisy ECG signal, and ECG$_{filtered}$ is the filtered ECG signal at output terminal. The SNR calculated from above equations are plotted in Fig. 4 for both ANF and ATNF algorithms. It can be seen that for the entire range of input SNR, the proposed ATNF technique provides significantly higher out SNR as compared to the normal ANF algorithm.

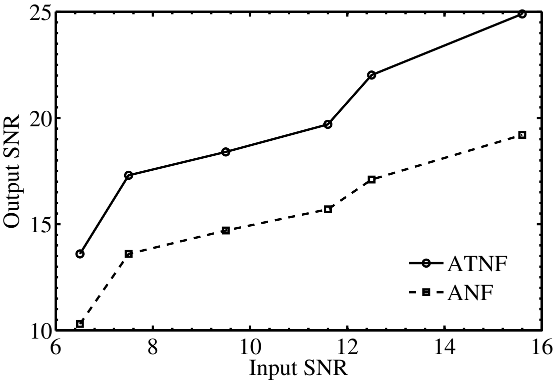

Fig. 4. Input and output SNR performance of the adaptive notch filter and adaptive tunable notch filter.

4. Conclusion

In this work, we have developed adaptive tunable notch filter (ATNF) to reduce the noise present in ECG signal. The proposed adaptive tunable notch filter technique has been exploited for the design of adaptive noise cancellation scheme. The ATNF algorithm is optimized to enhance ECG signal containing power line interference and muscle contraction noise. Our simulation results show that the information such as heart beat rate can be very accurately detected from the noisy ECG signal with the proposed scheme. The superiority of the proposed method as compared to the conventional adaptive notch filter is also demonstrated by determining the SNR fidelity parameter. Therefore, ATNF can be an alternative superior approach for ECG enhancement process.

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