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Monitoring of fetal heart rate using sharp transition FIR filter

Niyan Marchon [a,*], Gourish Naik [b], Radhakrishna Pai [a]

[a] Padre Conceicao College of Engineering, Goa, India
[b] Goa University, Goa, India

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ABSTRACT

We propose a novel technique which uses a linear phase sharp transition finite impulse response filter with reduction in band edge ripples due to Gibb's phenomenon. This is accomplished by a slope matching technique. This design can be used for processing a wide variety of signals irrespective of their bandwidth. This paper includes the mathematical design analysis of the band pass filter with slope matching which used fetal frequency fiduciary edges to filter the raw abdominal ECG signals. Our filter design displayed a fairly good magnitude response in all passband, stopband and transition regions with very little computation time and thus is suitable for real time processing of numerous records at a time. The magnitude responses of our finite impulse response filter design was compared to Parks-McClellan algorithm. It was observed that our algorithm showed better results in the passband and stopband at lower filter orders. The peak passband in conventional finite impulse response designs is about 18% which is reduced to around 1.5% with the use of trigonometric functions in the proposed filter model combined with slope equalization technique. The QRS detector effectively extracts the fetal R-peaks to display the fetal heart rate variability which diagnoses the mother-fetus health status. The accuracy of the noninvasive fetal heart rate measurement using our technique is found to be impressive and matches closely with the fetal scalp records. The obtained results show that the sensitivity ranges from 88.36% to 100%, the positive predictive value ranging from 92.31% to 100% and an overall average accuracy recorded at 95.19%.

1. Introduction

The most common filtering objectives include improving the signal to noise (SNR) ratio, separate the frequency components or extract certain information from signals for applications in biomedical, speech, image signal processing or other research areas. Due to the obvious merit of finite impulse response (FIR) filters with respect to linear phase (LP) and stability, FIR design was chosen over infinite impulse response (IIR) for designing LP filters with sharp transition width. However the limitations of the former such as more processing time with memory storage, longer delays and more computations are easily handled today by fast computers or DSP processors for real time implementations.

One of the important problems in digital filtering that has been considered by a number of authors in the past is the design of linear phase FIR filters with a very flat passband response and an equiripple stop band response. Several methods are available such as the window method, frequency sampling and optimal methods and all three lead to LP FIR filters. Truncation of the infinite series reduces the complexity and leads to the Gibbs phenomenon of about 18% overshoot and ripple at the discontinuity points at the transition regions [1]. The demerit of the window method is its lack of flexibility and also the passband and stopband edge frequencies cannot be precisely specified. In the optimum method, the main objective is to find the impulse response h (n), such that the value of the maximum weighted error |E (ω)| is minimum in the stop and pass bands expressed as min [max |E(ω)|]. An iterative process known as Remez algorithm is used which locates the optimal set of extremal frequencies, thus obtaining the actual H (ω) and h (n) of the filter [2]. Parks McClellan (PM) routines can be used for designing the LP FIR filters based on Chebyshev approximation criterion, implemented with the Remez exchange algorithm.

The author in [3], proposed a method of designing an equiripple LP FIR phase with linear constraint by carrying out the Remez exchange technique and that the design is optimal in the minimax sense. Two methods were presented in [4], the first one used Remez multiple exchange and optimized the shaping filter and the interpolator of the interpolated FIR filter. This method efficiently reduced the arithmetic hardware and delays. In the 2nd method the interpolator was derived based on the recursive running sums which further reduced the number of multiplier and adders in the implementation. The author in [5], presented an optimal design of LP FIR filter for flat passband and equiripple stopbands using Remez algorithm for the design of weighted Chebyshev FIR fil-

* Corresponding author.
E-mail address: niyan@pccegoa.org (N. Marchon).

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ters. The flatness of the passbands is to a prescribed degree. The overall filter is designed for even order N. Rabiner, in his paper [6], described in detail the designing of LP FIR filters mainly the Chebyshev approximation. The paper used special techniques to obtain optimal low pass or band pass filter (BPF). Norbert in his paper [7] describes an FIR filter design based on the desired H (ω) and the iteratively reweighted Chebyshev error minimization which is suitable for high filter orders. In [8], the author presents in detail, the design of an optimal FIR filter based on the Chebyshev approximation. The algorithm converges and requires $0(M^2)$ computations per iteration, where M is the filter length. Another author described a computer program by Park McClellan to design optimal FIR BPF. Here the order of the filter is the input to the program. The task was to find the lowest order filter which satisfies certain maximum ripple requirement [9].

2. The realization of the proposed linear phase sharp transition (LPST) BPF model

In this section, the design of an LPST FIR BPF is presented. For the proposed filter model, the five regions of the filter response are modelled using trigonometric functions of frequency. The BPF model magnitude response H (ω) is shown in Fig. 1.

The frequency response for the five regions are listed in Eq. (1).

$$\left.\begin{aligned}
&\text{Region 1}: H(\omega) = -\frac{\delta s}{2}\cos(k1\ \ \omega) && 0 \le \omega \le \omega_{s1}\\
&\text{Region 2}: H(\omega) = k2(\omega - \omega s1) && \omega_{s1} \le \omega \le \omega_{p1}\\
&\text{Region 3}: H(\omega) = 1 + \frac{\delta p}{2}\sin(k3(\omega - \omega p1)) && \omega_{p1} \le \omega \le \omega_{p2}\\
&\text{Region 4}: H(\omega) = 1 - k4(\omega - \omega p2) && \omega_{p2} \le \omega \le \omega s_2\\
&\text{Region 5}: H(\omega) = -\frac{\delta s}{2}\sin(k5(\omega - \omega s2)) && \omega_{s2} \le \omega \le \pi
\end{aligned}\right\} \tag{1}$$

Using Eq. (1), the filter design parameters k_1, $k_{2,}$ $k_{3,}$ k_4 and k_5 for the five regions of the band pass filter are evaluated and listed in Eq. (2)

$$\left.\begin{aligned}
k1 &= \frac{2\pi m1 + \frac{\pi}{2}}{\omega s1}\\
k2 &= \frac{1}{(\omega p1 - \omega s1)}\\
k3 &= \frac{(2\ m3+1)\pi}{(\omega p2 - \omega p1)}\\
k4 &= \frac{1}{(\omega s2 - \omega p2)}\\
k5 &= \frac{2\pi m5 + \frac{\pi}{2}}{(\pi - \omega s2)}
\end{aligned}\right\} \tag{2}$$

where, ω_{s1} and ω_{s2} are the stopband edge frequencies while ω_{p1} and ω_{p2} are the passband edge frequencies. δ_s and δ_p are the stopband attenuation and passband ripple respectively, while m_1, m_3 and m_5 are integers. Based on the magnitude response H (ω) and the design parameters for each of the 5 regions, the impulse response coefficient h (n) is given by Eq. (3).

$$\begin{aligned}
h(n) = &\left\{\left(\frac{\delta s}{4\pi}\right)\left[\frac{\cos((k+\ k1)\omega s1)-1}{(k+\ k1)} + \frac{\cos((k-\ k1)\omega s1)-1}{(k-k1)}\right]\right\}\\
&+ \Big\{\left(\frac{k2}{k\pi}\right)[(-\omega p1)\cos(k\omega p1)+(\omega s1)\cos(k\omega s1)] - \left(\frac{k2}{k^2\pi}\right)[\sin(k\omega p1)-\sin(k\omega s1)] + \left(\frac{k2\omega s1}{k\pi}\right)[\cos(k\omega p1)-\cos(k\omega s1)]\\
&+ \left(-\frac{1}{\pi}\right)\left[\frac{\cos(k\omega p2)-\cos(k\omega p1)}{k}\right] + \left(\frac{\delta p}{4\pi(k-k3)}\right)[\sin[(k-k3)\omega p2 + k3\omega p1] - \sin(k\omega p1)] + \left(\frac{-\delta p}{4\pi(k+k3)}\right)[\sin[(k+k3)\omega p2 - k3\omega p1] - \sin(k\omega p1)]\\
&+ \left(\frac{1}{k\pi}\right)[-\cos(k\omega s2)+\cos(k\omega p2)] + \left(\frac{k4}{k\pi}\right)[(\omega s2)\cos(k\omega s2) - (\omega p2)\cos(k\omega p2)] + \left(\frac{k4}{k^2\pi}\right)[\sin(k\omega s2)-\sin(k\omega p2)] + \left(\frac{k4\omega p2}{k\pi}\right)[-\cos(k\omega s2)+\cos(k\omega p2)]\\
&+ \left\{\left(\frac{-\delta s}{4\pi}\right)\left[\left(\frac{\sin((k5-k)\pi - k5\omega s2) +\ \sin(k\omega s2)}{(k5-\ k)}\right) - \left(\frac{\sin((k5+k)\pi - k5\omega s2) - \sin(k\omega s2)}{(k5+\ k)}\right)\right]\right\}, \text{ where,} k = \left[\left(\frac{N-1}{2}\right) - n\right].
\end{aligned} \tag{3}$$

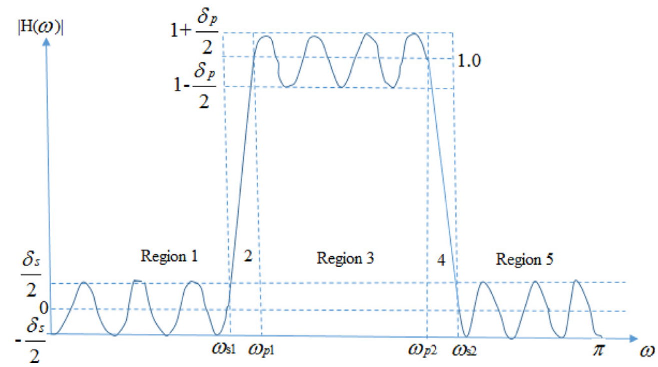

Fig. 1. LPST FIR BPF magnitude response H (ω).

We can choose the effective pass band width ($\omega_{p2} \sim \omega_{p1}$) such that ($\omega_{s1} \sim \omega_{p1}$) = ($\omega_{s2} \sim \omega_{p2}$), is as small as possible for sharp transition of passband edge. Once ω_{p1}, ω_{p2}, ω_{s1} and ω_{s2} are chosen k_1, k_2, k_3, k_4 and k_5 are determined.

In this paper, we have proposed the design of a LPST FIR BPF design for lower orders with arbitrary passband and not necessary an equiripple filter. Our proposed technique eliminates the need for a centre frequency nor the fixed passband width as it is used in [10]. Our design allows the user to set the cut off frequencies for a narrow pass band width for any filter order. It also incorporates a very linear sharp transition width while reducing the effects due to Gibb's phenomenon thereby reducing the passband ripple of the filter. To study the merits of our filter design, the magnitude response of our proposed filter design was compared to the PM algorithm for a range of filter orders. To evaluate our filter designs, we first applied the single lead non-invasive abdominal ECG (aECG) signal to the LPST FIR BPF using the designated fiduciary edges with a sharp transition width. In the second stage, a QRS detector based on Pan Tomkins QRS detector algorithm [11] detected the fetal R-peaks from the non-invasive aECG to compute fetal heart rate (FHR) which in turn can be used to assess the fetal health status at labor [12–14]. This method can also be extended to obtain simultaneously the heart rate of an adult mother [15].

The filter response functions of a filter design are discontinuous at the passband edge which leads to ripples at the points of discontinuity. Normally the points of discontinuity for the BPF will be at four points, they are: (a) At the end of the stopband region and start of the transition region (ω_{s1}) (b) At the end of transition region and start of the passband region (ω_{p1}) (c) At the end of the passband region and start of the transition region (ω_{p2}) and (d) At the end of the transition region and start of the stopband region (ω_{s2}). In this paper, a novel slope matching technique is proposed in Section 2.1 and the frequency response of the two models (with and without slope matching) are also compared.

2.1. LPST FIR BPF model with slope matching technique (LPST BPF_{slope})

In this technique, the slopes of the magnitude response are equalized at the fiduciary edges of fetal frequency spectrum, i.e