CHAPTER 5

RESULTS AND DISCUSSION

5.1 ADAPTIVE FILTER APPLIED TO FETAL HEART RATE EXTRACTION

The frequency of an electrocardiogram signal is calculated directly from the abdominal signal. The heart rate of the fetus is usually higher than that of the mother, and as a result, the fundamental frequency of the fetus’ electrocardiogram signal is also higher. Filters to suppress mother’s higher harmonics and extract fetus signal were implemented in the previous chapters and the results are presented in this chapter.

The steps performed in this work are shown in Figure 5.1. In this, a simulated signal composed of a MECG signal, a FECG signal and random noise, to obtain the FHRV signal was used to check the accuracy of the technique.

Figure 5.1 Block diagram showing the different stages performed
The MECG simulated signal has two identical repeated parts, while the FECG simulated signal has three identical repeated parts. This ensures that the proposed method is capable of detecting FHR and FHRV correctly. The 1 Hz MECG signal, the 1.5 Hz FECG signal and the random noise signal were combined forming a mixed signal (Figure 5.2(a)) that exactly mimics the mother’s abdominal recording. The amplitudes of the three constituents of this signal are 1, 0.4, and 0.05 for the mother’s ECG, FECG and noise, respectively. These are shown in Figures 5.2(b), 5.2(c), and 5.2(d), respectively. The details of the simulated signals are given in Table 5.1.

Figure 5.2 The simulated signals used to verify the technique showing (a) the total signal (b) the mother ECG signal (c) the fetal ECG signal and (d) the noise signal
Table 5.1  Details of the simulated signals

<table>
<thead>
<tr>
<th>Signal characteristics</th>
<th>Nature of ECG</th>
<th>Description</th>
<th>Frequency Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated signal</td>
<td>Mother ECG</td>
<td>Heart rate = 60 bpm</td>
<td>1 Hz</td>
</tr>
<tr>
<td></td>
<td>Fetal ECG</td>
<td>Heart rate = 90 bpm</td>
<td>1.5 Hz</td>
</tr>
<tr>
<td>Type of waveform</td>
<td>Mother ECG and</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>fetal ECG same</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude</td>
<td>different</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>different</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.1.1  Cosine Wave Simulations

Passing the signal $|Y(j)|$ through the designed filter resulted in rejecting the 1 Hz signal. As a result, the output filtered signal ($y_o(t)$) has all the frequency components in $y(t)$ except the 1 Hz frequency. The 1.5 Hz signal and the filtered signal ($y_o(t)$) are plotted as a function of time (Figure 5.3(a)) for comparison. Figure 5.3(a) and the zoom in (Figure 5.3(b)) indicate that although the signal $y_o(t)$ (blue) consists of many frequency components, the peak-to-peak (or the zero-to-zero) values are exactly the same as those for the 1.5 Hz signal.
Figure 5.3  (a) Combined plot of the filtered signal and the 1.5 Hz signal and (b) zoom view
5.1.2 Filtering Results

The filtered output is compared with the simulated fetal ECG signal, as shown in Figure 5.4. The results indicate that the filtration process was successful in extracting the fundamental oscillation of the fetal ECG signal. To make sure that the beat-to-beat oscillations, (the $RR$ intervals), are preserved in the filtration process, the $RR$ intervals from the original fetal ECG signal, and the peak-to-peak (or zero-to-zero) values of the extracted fundamental signal, were evaluated and compared.

![The original fetal ECG signal and the extracted fundamental signal](image)

**Figure 5.4** A plot of the original simulated fetal ECG signal and the extracted fundamental frequency of the fetus’ ECG signal

Figure 5.5 shows a plot of those two evaluations along with the $RR$ plot for the mother’s simulated ECG signal. A clear similarity of the two fetal evaluations indicates that the beat-to-beat changes are preserved to a large extent.
Figure 5.5  Plot of the RR values as a function of time for the simulated mother ECG, the simulated fetal ECG and the filtered fundamental signal

5.1.3  Testing with Real Signals

A plot of a five second sample of one of the recordings is shown in Figure 5.6 with the R’s indicating the locations of the R wave for the mother’s signal. The mother has a heart rate of about 98.4 bpm, an RR value in the range of 0.61 sec, and a fundamental frequency of about 1.64 Hz. After passing the mother’s AECG signal through the first stage filters then followed with the second stage, the resultant output was obtained and logged for further processing.
The output was a cosine wave, oscillating at the fetus’ fundamental frequency, with some small amplitude harmonics carried in it. This is inferred from Figure 5.7(a). A zoom in for this signal is shown in Figure 5.7(b), indicating the \( R \) locations for the fetal ECG. For this case, the fetal heart rate was about 186 bpm and the fetus’ fundamental frequency was about 3.11 Hz.

Figure 5.6  A plot of a 5 second recording of a real abdominal pregnant mother ECG signal
Figure 5.7  (a) The filtered fundamental frequency of the fetus’s real ECG signal and (b) zoom view

It is shown in this work that the extraction of the FHR value and the FHRV signal is possible. The extraction process starts by determining the fundamental frequency of the mother’s ECG signal, using which the single extraction filters are designed. The system performance in frequency domain is shown in Figure 5.8.
5.2 MATERNAL QRS REMOVAL WINDOW

The extracted FECG using noise filter, maternal QRS and FECG signal after applying maternal QRS removal window are shown in Figure 5.9. It is noted that the maternal residual peaks are observed after the filter output and are eliminated after applying the maternal QRS removal window. After maternal residual peaks have been eliminated from the extracted FECG signal, a small amount of baseline wander has been observed. Therefore, notch filter centered at 1 Hz is adequate to attenuate this baseline wander.
5.2.1 Performance Evaluation

In this thesis, the proposed ANC and ICA methods are evaluated using sensitivity and positive predictivity. The effect of the lead position in the primary input of the reconfigurable ANC is also evaluated. Table 5.2 shows the performance using ICA and proposed methods at signal extraction stage. The average sensitivity of the proposed method is 85.5 % \((X_2\text{ as primary signal})\) as compared to 74.4% of the ICA based method. Similarly, the average positive predictivity of the proposed method is 67.6% \((X_2\text{ as primary signal})\) as compared with that of the ICA based method which is 64.1%. It shows that the reconfigurable filter based approach is more successful in detecting the FHR than ICA. The QRS removal window was performed to improve this detection.

Figure 5.9 (a) Extracted FECG using reconfigurable filter (b) MQRS and (c) FECG signal after applying MQRS removal window
Table 5.2 Performance of ICA and proposed method

<table>
<thead>
<tr>
<th>Weeks</th>
<th>No Signal</th>
<th>EHW based ANC method (Proposed)</th>
<th>ICA method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X₂ as primary signal</td>
<td>X₃ as primary signal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Se (%)</td>
<td>P (%)</td>
</tr>
<tr>
<td>35</td>
<td>2</td>
<td>79.0</td>
<td>54.5</td>
</tr>
<tr>
<td>36</td>
<td>13</td>
<td>88.4</td>
<td>77.8</td>
</tr>
<tr>
<td>37</td>
<td>6</td>
<td>91.1</td>
<td>68.9</td>
</tr>
<tr>
<td>38</td>
<td>9</td>
<td>84.8</td>
<td>69.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>85.5(%)</td>
<td>67.6(%)</td>
</tr>
</tbody>
</table>

Since, there is an availability of the multi-lead system for the ICA, it is possible to evaluate the lead position for the primary signal that gives optimum results. Hence, a comparison is made between X₃ (the primary signal) and X₂ and is shown in Table 5.2. From this table it can be observed that the average sensitivity of the proposed algorithm from the primary signal X₂ is 85.8 % as compared to 82.5 % with primary signal X₃. Also the average positive predictivity of the proposed algorithm is 67.6% with primary signal X₂ as compared to X₃ with 66.7%. The locations of the abdominal electrodes are shown in Figure 5.10.

Figure 5.10 Locations of the abdominal electrodes.

The locations are chosen such that the effect of noise is uniform. The performance of the algorithm was better than ICA for both locations, although electrode location p2 (associated with X₂) is better than p3. This
infers that the location of the electrode plays an important role in FHR detection. Figure 5.11 shows the results obtained in this case, confirming that the algorithm used performs well in extracting the original signal from a noisy input.

**Adaptive Filter Input (Noisy Signal)**

![Adaptive Filter Input (Noisy Signal)](image)

**Figure 5.11 Test results**

Various tests were carried out to determine the filter order to be used such that, it provides the best efficiency at the data input speed. From the graph shown in Figure 5.12, it is concluded that a filter order of 10 gives the best results. Other system tests were performed for different convergence factor values until the value of 0.0589 yielded best convergence results. This is close to the value of 0.0602 obtained through simulation.
5.3 **FIR FILTER COEFFICIENTS**

A number of simulation runs are performed for different FIR filter orders. The simulation includes both, the filter with its original coefficients and with its new coefficients (i.e. after applying the proposed algorithm). Figure 5.13(a) shows the simulation results for N-tap (medium number of taps) raised cosine pulse-shaping filter with a roll-off factor of 0.22. Figure 5.13(b) shows the frequency and phase response of the filter with its new set i.e. after applying the proposed algorithm. From these two plots it is observed that the phase response of the filter improves after applying the proposed algorithm. Also, as seen from the frequency response the ripples in the cutoff region is also reduced, and a smoother response is obtained. The new set of coefficients are obtained by multiplying the original coefficients with a constant value and then rounded to the nearest integer.
Figure 5.13(a)  Phase and frequency response of the filter with its original coefficients

Figure 5.13(b)  Phase and frequency response of the filter after using the proposed algorithm
5.3.1 ADVANTAGES OF PROPOSED CONTEXT SWITCHING EHW ARCHITECTURE

The number of coefficients for an N-tap filter is N+1. However, after applying the proposed algorithm, the number of non-zero coefficients reduces to N/2+1. This means that Fig. 5.13 (b) is obtained with only N/2+1 coefficient. As a result, the number of addition operations needed gets reduced by half. This highly influences the system speed and hardware complexity requirement. The proposed algorithm has also been tested on a square root raised cosine pulse shaping filter. The phase and frequency responses of this filter are shown in Figures 5.14.(a) and 5.14 (b).

![Figure 5.14(a) Response of the N tap square root RC filter with its original coefficients](image)

The frequency and phase response of a Higher order FIR filter with its original coefficients is shown in Figure 5.15 (a), whereas, the response with new coefficients is shown in Figure 5.15 (b).
Figure 5.14(b) Response of the N-tap square root RC filter after using the proposed algorithm

Figure 5.15(a) Phase and frequency response of the filter with its original coefficients
In this case also, a constant value is multiplied with the original filter coefficients. However, comparing the constant values in this case with that of medium order filter, the value is much greater. The reason behind this increment is that enough signal power (usually >90\%) cannot be achieved with small constants as the filter order becomes high (e.g. 512-tap filter). Therefore, as the filter order increases, the constant value will probably increase. On the other hand, the value of the first and last coefficients is not a function of the filter order; rather it is a filter specification dependent value. As it can be seen, the value of the 1st and last coefficient in the case of a higher order filter can be slightly less than for a Medium order filter.