IJIREEICE

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Eng

Nitte Conference on Advances in Electrical Engineering NCAEE-2016

NMAM Institute of Technology, Nitte

Vol. 3, Special Issue 2, Month 2016

NON- INVASIVE METHOD OF FETAL ECG EXTRACTION USING HILBERT TRANSFORM

Nivitha.M[1], Santhi.C[2]

Applied Electronics, Government College of Technology, Coimbatore, India[1]

Associate Professor, Electronics and Communication Engg., Government College of technology, Coimbatore, India[2]

Abstract: Fetal Electrocardiogram Extraction identifies the congenital heart problems at the earlier stage. One of the method for extracting fetal ECG is by using Noninvasive method but the noise and interference associate with the signal is more. So integrated approach for fetal heart beat detection from abdominal ECG signals is used. The signal is first processed by the first-order difference operation which remove the different types of noise in the signal, and then, the envelope of the differentiated signal is given by the Hilbert transform, which indicates both the maternal and fetal heart beats. After that, the non-linear state-space projections is applied to the envelope signal to remove the maternal heart beats, obtaining the fetal heart beats envelope. The validity and performance of the described method done by calculating SNR, MSE values and comparing with previous technique shows the proposed method provide better result. The Database for the ECG signal is taken from the Physionet Website[17].

Keywords: difference operation; Hilbert transform; NSSP; SNR; MSE.

I. INTRODUCTION

The fetal electrocardiogram (FECG) reflects the electrical activity of the fetal heart. By monitoring the FECG during perinatal period, physicians obtain important clinical information about the health condition of the fetus. The early diagnosis of any cardiac defects before delivery increases the effectiveness of the appropriate During the process of delivery, FECG is directly acquired by placing an electrode on the fetal scalp. However the technique is invasive and is only applicable when fetal membrane ruptured. To record the antepartum FECG, the non-invasive technique using electrodes positioned on the abdomen of the pregnant woman is widely accepted. However, there are various interference sources in the abdominal signal, such as the maternal electrocardiogram (MECG) component in the abdominal signal, 50 Hz power line interference, baseline wander and random noise etc. The MECG component in the abdominal signal is the main interference source and its amplitude is much higher than the FECG so that the FECG is often completely masked by the MECG. Monitoring of the fetal heart rate (FHR) has commonly been used as indirect indication of the fetal condition during gestation [1].

The most common technique for recording FHR is Doppler ultrasound, which has several disadvantages, such as repositioning of the transducer (only suitable for highly trained midwives) and active measurement (launching a 2 MHz signal towards the fetus, not recommended for long-time recordings). An alternative is utilising the abdominal electrocardiograph (ECG) signals which are acquired by some electrodes placed on the abdomen of the pregnant woman. This procedure is non-invasive and passive measurement, suitable for long-term recordings, which means that there would be no limitation of the time and frequency for FHR monitoring. However, FHR monitoring through abdominal ECG signal involves the detection of small amplitude fetal heart beat overwhelmed by a large amount of interference and noise.

The maternal ECG (MECG) is the predominant source of interferences. Various techniques have been employed to address this problem, including digital filtering and cross-correlation with template [2], template subtraction [3], matched filtering [4], linear combination of phase difference corrected signals [5], independent component analysis (ICA) [6, 7] and time-frequency analysis [8–12]. In this paper, an integrated approach for fetal heart beat detection is proposed, combining the Hilbert transform (HT) and non-linear state-space projections (NSSPs). The HT is widely used in signal processing and has been applied to the problem of R-wave detection in adult ECG signal [13–16]. The envelope of the ECG signal obtained by HT is an efficient method for heart beat detection. In [17], the HT has been presented for the fetal QRS detection from the fetal magneto cardiogram, where free of the MECG interference. NSSP has been proposed for fetal ECG estimation in [18], but its performance is easily influenced by its parameters selection in the strong noise situation, which makes it relatively less robust and inconvenient in real application especially in automated FHR estimation [19]. The signal-to-noise ratio (SNR) of signal envelope is higher than the raw ECG signal, if the signal envelope is regarded as the input of the NSSP process its performance could be improved significantly. For this reason, the HT and NSSP are combined to address the fetal heart beat detection problem in this work, and compared with the current popular method ICA using real fetal ECG database.

II. METHODOLOGY

The block diagram of the proposed methodology is shown in Fig. 1. The acquired composite multi-channels abdominal signals are preprocessed firstly, eliminating the baseline wander, power line interference and other high-frequency nois. Next, calculating the first-order differential of the input signals to emphasise the maternal and fetal heart beat. After that, the envelope for each difference signal is obtained by HT, followed by the amplitude normalization. Then three signal envelopes are added together to make an information fusion in multi-channels. In order to remove the maternal heart beat, the NSSP process is applied to the summational envelope, and the result. At last, the envelope of the fetal heart beat could also be obtained by HT again. The detailed description of the HT and NSSP will be discussed in the following.

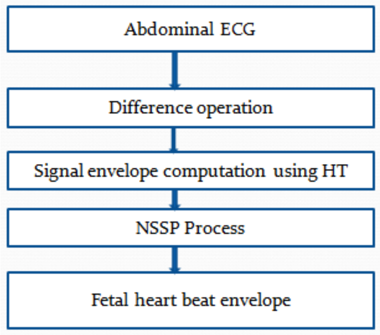

Fig. 1 Block diagram.

III. EXTRACTION OF FETAL ECG USING INTEGRATED APPROACH

Here the real ECG signal is obtained from the physionet database which contains both maternal and fetal ECG. The following section describe the integrated approach for extracting fetal ECG from maternal ECG.

A. Extraction of ECG

The Physio Net database contains a series of 55 multi-channels abdominal fetal ECG recordings, taken from a single subject between 21 and 40 weeks of pregnancy. Every recording includes two thoracic signals and three or four abdominal signals, and a 1 KHz sampling frequency and 16-bit resolution were employed. The database signal is shown in figure 2.

There are two method to extract the maternal ECG one is Invasive method under this fetal ECG is directly extracted from the fetus. But this method takes long time measurement and need well trained person and also it is very costly. Another method is non-invasive method is to extract FECG signal from signal recorded at blood pressure mother abdomen (AECG). AECG signal contains FECG signal, altered MECG signal and noises. The maternal components are distorted because it is travel from mothe’s heart to abdomen. This type of distortion can be taken as non-linear transformation of MECG signal.

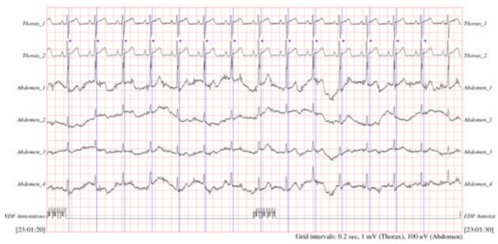

Fig. 2 Database signal

In order to improve the result of FECG signal, we need to weaken the power of MECG signal and decrease the effects of noises. We should able to recognize the altered MECG signal. By subtracting these MECG signal from AECG, we can get the FECG signal. Figure 3 shows the recording of thoracic and abdominal signals.

DOI 10.17148/IJIREEICE/NCAEE.2015.48

IJIREEICE
ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Eng
Nitte Conference on Advances in Electrical Engineering NCAEE-2016
NMAM Institute of Technology, Nitte
Vol. 3, Special Issue 2, Month 2016

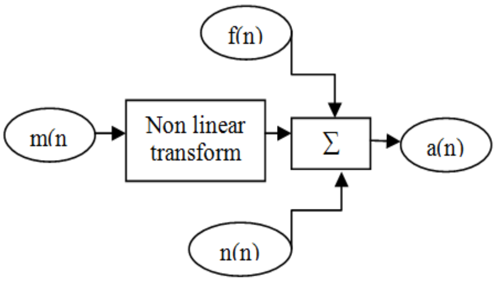

Fig.3 Block diagram

This method uses two recorded signal, one is recorded at thoracic region m(n) and another one is recorded at abdomen region a(n)of blood pressure mother. Figure 2 summarized the following equations:
a(n)=m~(n)+f(n)+n(n)
m~(n)=T{m(n)}

where m(n) and a(n) are the signals recorded at thoracic and abdominal areas respectively. n(n) indicates the sum of noises in the recorded signal. m~ (n) is the distorted version of m(n) signal due to non-linear transformation T. m~ (n) represents altered MECG signal components in the recorded AECG signal.

B. Difference operation process
The difference operation is used to remove the noise in the maternal ECG signal when the fetal ECG is extracting from the maternal ECG it is affected by noise and interference due to the electrode or movement object and also due to electronic equipments.

The steps for performing difference operation is given below:
i. Download the original ECG signal x.
ii. Use a digital filter to cut out noises from ECG signals
iii. Obtain the difference signal xd
$x_d(n) = x(n) - x(n-1)$
iv. Applying any low-pass filter with a cut-off frequency 100 Hz to xd to eliminate the small amplitude but high frequency variation waveform and it is denoted by xdf.
v. Let the filtered signal xdf with the thresholds T1 and T2to get the final signalˆxdf

$$\hat{x}_{df} = \begin{cases} 0 & \text{if } 0 < x_{df} < T_1, \text{or } T_2 < x_{df} < 0 \\ x_{df} & \text{if } x_{df} \geq T_1, \text{or } x_{df} \leq T_2 \end{cases}$$

There are many different kind of noises are associated with maternal abdominal ECG signal and some of the noise and interference s are removed with the help of digital filters.
i. 60 Hz power-line interference.

It is due to the power line of the ECG signal measurement systems despite proper grounding. It is shown in figure. 4. Its frequency content 60 Hz is with harmonics. The 60 Hz notch filter can be used for rejecting the power-line interference

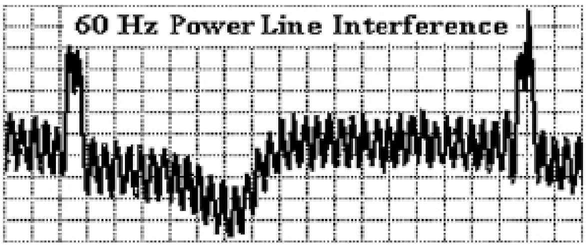

Fig. 4 60Hz power-line interference

ii. Baseline drift:
It is caused by patient breathing, bad electrodes, or improperelectrode site, etc. Its frequency range is usually below 0.5 Hz. The high-pass filter with cut-off frequency 0.5 Hz can be used to remove the interference by baseline drift. It is shown in figure 5 below.

IJIREEICE

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Eng

Nitte Conference on Advances in Electrical Engineering NCAEE-2016

NMAM Institute of Technology, Nitte

Vol. 3, Special Issue 2, Month 2016

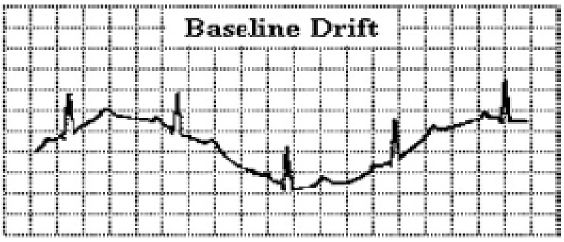

Fig. 5 Baseline drift

iii. Electromyogram (EMG):

It is produced by muscle electrical activity. In the ECG signal, EMG interference appears as rapid fluctuations which vary faster than ECG waves. Its frequency content ranges from dc to 10 kHz [20]. The morphological filter for a unit square-wave structuring (the best width is 0.07 s) can be used to remove the interference of EMG and it is shown in figure 6 below.

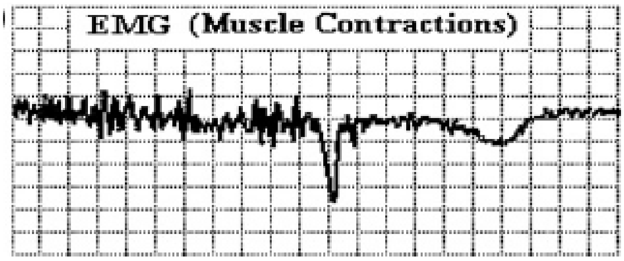

Fig. 6 Electromyogram

vi. Motion artifacts:

It results from motion of the electrode in relation to the patient's skin. It can produce larger amplitude signals in the ECG and its duration time is about 100–500ms. The adaptive filter can be employed to remove the interference of motion artifacts and it is shown in figure 7 below.

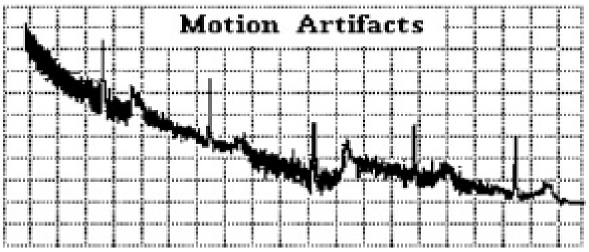

Fig. 7 Motion artifacts

C. Signal Envelope using Hilbert Transform

Hilbert transform of the product of a low-pass and a high-pass signal with non-overlapping spectra is given by the product of the low-pass signal and the Hilbert transform of the high-pass signal. A Hilbert transformer produces a -90 degree phase shift for the positive frequency components of the input x(t), the amplitude doesn't change.

Give a discrete-time signal x(n), n = 0,1,2, …, N–1, its HT ˆx(n), the unit sample response of the HT h(n) and its discrete Fourier transform (DFT), H(ejω). The HT causes a phase shift of all signal components, −90° for positive and +90° for negative frequency components

$$h(n) = \begin{cases} 0 & \text{even number for } n \\ \dfrac{2}{n\pi} & \text{odd number for } n \end{cases}$$

$$H(e^{j\omega}) = \begin{cases} -j & 0 < \omega < \pi \\ j & -\pi < \omega < 0 \end{cases}$$

Hilbert transform can be computed in a few steps:

1). Calculate the Fourier transform of the given signal x(t). 2). Reject the negative frequencies.

3). Calculate the inverse Fourier transform, and the result will be a complex-valued signal where the real and the imaginary parts form a Hilbert-transform pair.

IJIREEICE
ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Eng
Nitte Conference on Advances in Electrical Engineering NCAEE-2016
NMAM Institute of Technology, Nitte
Vol. 3, Special Issue 2, Month 2016

The concept of analytic signal or pre-envelope of x(n) is described as

$$z(n) = x(n) + j\hat{x}(n)$$

The analytic signal z(n) and HT ˆx(n) could be computed by DFT expediently by the following steps:
(1) Obtaining the DFT of the signal x(n), x(k), k = 0, 1…, N–1, notice that the k = N/2,…, N – 1 correspond to the negative frequency components.
(2) The analytic signal z(n), and its DFT, Z(k) can be obtained according to expression

$$Z(k) = \begin{cases} X(k), & k = 0 \\ 2X(k), & k = 1, 2, \ldots, N/2 - 1 \\ 0, & k = N/2, \ldots, N - 1 \end{cases}$$

$$z(n) = \mathrm{IDFT}(Z(k))$$

(3) HT ˆx(n) can be computed by expression

$$\hat{x}(n) = \mathrm{IDFT}[-j(Z(k) - X(k))]$$

$$\hat{x}(n) = -j[z(n) - x(n)]$$

The signal envelope e(n) is defined as the square of the analytic signal envelope as expressio, the squaring operation is in order to attenuate the effects of noise or artefacts.

$$e(n) = x^2(n) + \hat{x}^2(n)$$

The important property of Hilbert transform is the signal x(t) and its Hilbert transform $\hat{x}$(t) have
1. the same amplitude spectrum
2. the same autocorrelation function
3. x(t) and $\hat{x}$(t) are orthogonal
4.The Hilbert transform of $\hat{x}$(t) is -x(t)

The pre envelope of a real signal x(t) is the complex function
x+(t) = x(t) + j $\hat{x}$(t).
The pre envelope is useful in treating band pass signals and systems. This is due to the result

$$X_+(v) = \begin{cases} 2\,X(v), & v > 0 \\ X(0), & v = 0 \\ 0, & v < 0 \end{cases}$$

An important property of the signal envelope is that it is always positive, and a typical bipolar R-wave has a unipolar response with only one peak. This is useful because signals from multi-channels can be integrated (summation) without regard to their polarity, thus the fetal heart beat could still be detected even though it is missed in some channels, which improving the robustness of the heart beat detection over a single channel. The proposed method could be applied to both single-channel data and multi-channels data. The multi-channels inputs are preferred because of their more comprehensive description on the fetal heart beat.

D. Non linear state space projection

In general, linear filter is used to separate signals based on their difference in frequency domain. However, even the optimal linear filter, the Wiener filter, cannot be successful in this case because ECGs of the pregnant include both maternal and fetal signals which have the same spectral contents, and the noise coming from the electric equipments has a broad band and random.

So nonlinear filter which offers some superior features to linear projection in this case.
In nonlinear filter, though the fetal signal and maternal signal are similar in shape and spectral contents, we can separate the components by a very natural way: the magnitude and the heart beat. In fact, because the fetal heart is much smaller than the maternal heart, the fetal signal is much smaller than the maternal signal. Generally, the heart beat of the fetus is about one-third of the mother. In fact, our method is used for noise reduction, we just consider fetal signal as a contaminated noise.

i. Algorithm:

In the delay representation of E(n) in state space, utilizing the geometrical information provided by the maternal and fetal heart beat, removal of the maternal heart beat by NSSP algorithm consists of five main steps:

IJIREEICE
ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Eng
Nitte Conference on Advances in Electrical Engineering NCAEE-2016
NMAM Institute of Technology, Nitte
Vol. 3, Special Issue 2, Month 2016

(1) Determine the points set representing the maternal beats in state space, denoted by Cm.
(2) Project each point of Cm orthogonally onto approximation to the attractor to produce the Cˆ m, which representing the cleaned maternal beats.
(3) Removal of the maternal beats by Cmr= Cm− Cˆ m.
(4) Update the original points set C by Cm→Cmr to obtain the new delay representations Cf in the state space, only representing the fetal heart beat.
(5) Convert C_f back to the scalar time series f (n) using
Expression given below when t = 1, m = 10

$$f(n) = \frac{\sum_{i+j-1=n} C_f(i,j)}{\min\{n,\ 10,\ N-n+1\}}$$

$$n = 0, 2, \ldots, N-1$$

The technique we apply below is actually based on phase space reconstruction. The post transient trajectory of the system is frequently confined to a set of points in state space called an "attractor". By using the delay coordinates, attractor is then empirically found to be constrained to a low-dimension manifold. Hence, by estimating the attractor, noise can be reduced by projecting onto it. Whenever a multidimensional reconstruction of a signal can be approximated by a low-dimensional surface (or attractor), a projection onto this surface can improve the signal-to-noise ratio. In the present application, the fetal component is first treated as a contamination of the maternal ECG, hence noise reduction techniques are suitable for signal separation.

IV. RESULT AND DISCUSSION

The experimental results shows that of fetal ECG extraction from maternal ECG using Non-invasive method. The parameter signal to noise ratio, Mean square error is used to measure the quality of the proposed method by comparing with other method. This section describes the results of individual stage in process.

E. Abdominal ECG

The PhysioNet database contains a series of 55 multi-channels abdominal fetal ECG recordings, taken from a single subject between 21 and 40 weeks of pregnancy. Every recording includes two thoracic signals and three or four abdominal signals. Fig. 8 is a segment of the signal 'ecgca323' recording at 23 gestational weeks plus 6 days. Ch1 and Ch2 are thoracic signals and Ch3–Ch5 are abdominal signals. The non-stationary noise, such as electromyogram by uterine contraction, is very strong in these abdominal signals. The noise of this data is relatively strong, which is useful for testing signal separation algorithms.

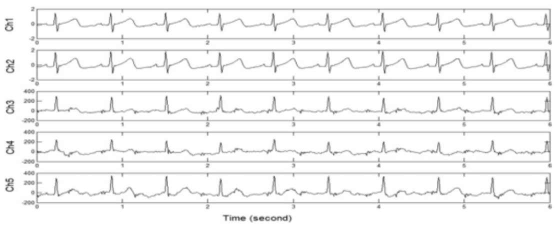

Fig. 8 Ch1–Ch2: thoracic signals and Ch3–Ch5: abdominal signals

F. Difference operation process

The extracted maternal ECG has fetal ECG, maternal ECG, noise and interference and noises are due wrong electrode placement, motion, due to electronic equipment. This noise and interferences are removed by using different digital filters as shown in(III B).

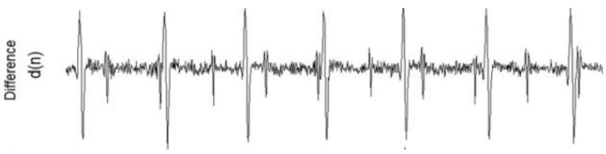

Fig.9 Result of difference operation

The figure 9 shows the maternal ECG after applying difference equation.

G. Signal envelope using hilbert transform

The Hilbert transform is used to produce both the amplitude and frequency domain of the signal. In many measurement the time signal contains rapidly oscillating movement. The amplitude of the oscillation slowly varies with time and shape of the slow variation with time is called envelope. This envelope contains important information about the signal.

IJIREEICE
ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Eng
Nitte Conference on Advances in Electrical Engineering NCAEE-2016
NMAM Institute of Technology, Nitte
Vol. 3, Special Issue 2, Month 2016

By using Hilbert transform the rapid oscillation is removed form the signal to produce the direct signal envelope alone. In Hilbert transform the negative frequencies are zero and maintaining only the positive frequency. The figure 11 show the signal envelope after applying Hilbert transform.

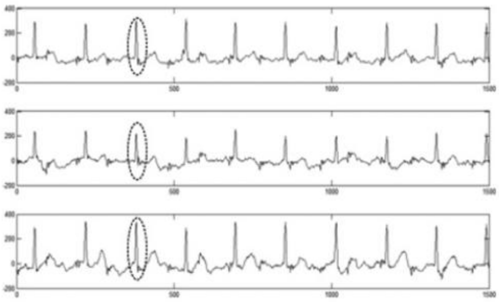

Fig.10 Abdominal ECG signals (ch3:ch5)

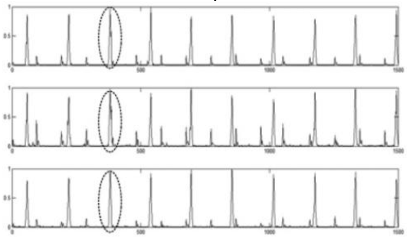

Fig.11 Signal envelopes

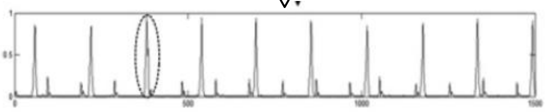

Fig.12 Summational envelope

The figure 10 shows the Abdominal ECG of ch3-ch4 signal. Which shows the three different channel signal and figure 11 shows the signal envelope after performing Hilbert transform which removes the negative frequency and maintaining only positive frequency. The figure 12 shows the summational of three signal into one signal.

H. NSSP PROCESS

The nonlinear state space projection method is used to extract the fetal ECG from the Maternal ECG. To remove the maternal heart beat in the summational envelope, it is processed by the NSSP algorithm, and the result has been shown in Figure 13.

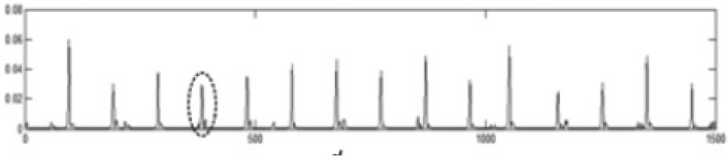

Fig.13 Fetal heart beat detection

Although the maternal and fetal heart beat are a very probable overlap in real situations, it is possible to separate them by this non-linear process, the overlapping fetal heart beat could be recovered by the NSSP method successfully after eliminating the corresponding maternal heart beat.

I. Comparision

To further assess and validate the described method, a comparison has been made with the well-known ICA method. A fast fixed-point algorithm for ICA described in [17] is applied to the same data. For comparison, Hyvarinen's fast fixed-point algorithm for ICA is applied to the Ch1–Ch5 signals including the thoracic and abdominal signals, and the result is shown in Fig. 14.

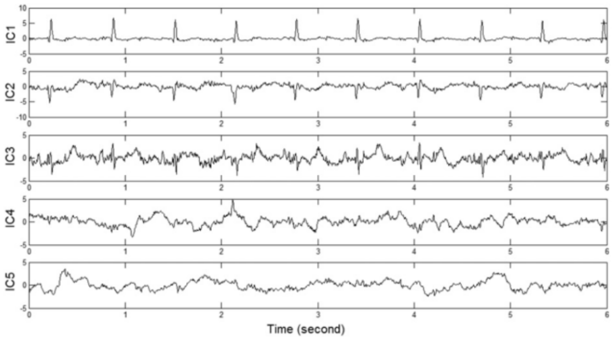

Fig.14 Fetal heart beat detection by ICA method using Ch1–Ch5 signals

IC1– IC3 signals are obvious the MECG components, but it is hard to find the fetal heart beat in IC4 and IC5 signals. Five input mixed signals are probably not enough for the ICA method. The number of estimated sources is confined to the dimension of the input mixture, so that different dimensions of the input mixture may bring out different results of estimated sources.

In this section the proposed method is compared with the very well known method of independent component analysis method. For both the method the same data base is used for the analysis. The figure 14 shows the result of independent component analysis method and figure 15 shows the result of integrated approach by using Hilbert transform and nonlinear state space projection.

Fig.15 Fetal heart beat detection

The proposed method takes the signal envelopes as inputs, which are the high-pass filtered data. This will naturally attenuate the lower frequency MECG and enhance the higher frequency fetal ECG. The ICA is applied directly to the unfiltered raw data. This could be a flaw for comparison.

J. Quality measurement

i. Signal to noise ratio

Signal-to-noise ratio is defined as the ratio of the power of a signal (meaningful information) and the power of background noise (unwanted signal)

$$\mathrm{SNR} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}}$$

TABLE I: QUALITY PARAMETER

Database record name	**SNR Ratio**	
	ICA	**Proposed method**
ecgca323	8.58	8.96
ecgca826	8.64	8.71
ecgca906	8.45	8.55

V. CONCLUSION

In this paper describes an integrated approach for fetal heart beat detection using Hilbert transform and Nonlinear state space projection. The maternal and fetal heart beats are separated in the envelope of the abdominal signal, not in the original signal. Its main advantage is that the signal envelope is clearer than original signal, which will improve the robustness of separation process. This paper introduces the signal envelope to replace the ECG signal as the input of the NSSP process, which could improve the SNR of the input and the performance of the NSSP. The validity and performance of the described method are confirmed by real experiments using the fetal ECG data from PhysioNet. The trans-abdominal fetal heart beat detection algorithm is simple and promising, without the limitations of any particular recording technique. Here the signal to noise ratio and Mean square error is used to compare the result of proposed method to other method. By comparing the different record values of SNR value to ICA. The table shows that the proposed method provide the better quality than other method.

REFERENCES

[1]. K. Parer, J.T.: 'Nonstress testing', in Schmitt, W. (Ed.): 'Handbook of fetal heart rate monitoring' (Saunders, Philadelphia, PA, 1997, 2nd edn.), pp. 8–9
[2]. Ibrahimy, M.I., Ahmed, F., Mohd Ali, M.A., Zahedi, E.: 'Real-time signal processing for fetal heart rate monitoring', IEEE Trans. Biomed. Eng., 2003, 50, (2), pp. 258–262
[3]. Vullings, R., Peters, C.H.L., Sluijter, R.J., Mischi, M., Oei, S.G., Bergmans, J.W.M.: 'Dynamic segmentation and linear prediction for maternal ECG removal in antenatal abdominal recordings', Physiol. Meas., 2009, 30, pp. 291–307
[4]. Pieri, J.F., Crowe, J.A., Hayes-Gill, B.R., Spencer, C.J., Bhogal, K., James, D.K.: 'Compact long-term recorder for the transabdominal foetal and maternal electrocardiogram', Med. Biol. Eng. Comput., 2001, 39, pp. 118–125
[5]. Peters, C.H.L., van Laar, J.O.E.H., Vullings, R., Oei, S.G., Wijn, P.F.F.: 'Beat-to-beat heart rate detection in multi-lead abdominal fetal ECG recordings', Med. Eng. Phys., 2012, 34, pp. 333–338
[6]. Najafabadi, F.S., Zahedi, E., Mohd Ali, M.A.: 'Fetal heart rate monitoring based on independent component analysis', Comput. Biol. Med., 2006, 36, (3), pp. 241–252
[7]. Vullings, R., Peters, C.H.L., Hermans, M.J.M., Wijn, P.F.F., Oei, S.G., Bergmans, J.W.M.: 'A robust physiology-based source separation method for QRS detection in low amplitude fetal ECG recordings', Physiol. Meas., 2010, 31, pp. 935–951
[8]. Karvounis, E.C., Papaloukas, C., Fotiadis, D.I., Michalis, L.K.: 'Fetal heart rate extraction from composite maternal ECG using complex continuous wavelet transform', Comput. Cardiol., 2004, 31, (31), pp. 737–740
[9]. Karvounis, E.C., Tsipouras, M.G., Fotiadis, D.I., Naka, K.K.: 'An automated methodology for fetal heart rate extraction from the abdominal electrocardiogram', IEEE Trans. Inf. Technol. Biomed., 2007, 11, pp. 628–638
[10]. Karvounis, E.C., Tsipouras, M.G., Fotiadis, D.I.: 'Detection of fetal heart rate through 3-D phase space analysis from multivariate abdominal recordings', IEEE Trans. Biomed. Eng., 2009, 56, pp. 1394–1460
[11]. Rooijakkers, M.J., Rabotti, C., Oei, S.G., Mischi, M.: 'Low-complexity R-peak detection for ambulatory fetal monitoring', Physiol. Meas., 2012, 33, pp. 1135–1150
[12]. Sahin, I., Yilmazer, N., Simaan, M.A.: 'A method for subsample fetal heart rate estimation under noisy conditions', IEEE Trans. Biomed. Eng., 2010, 57, (4), pp. 875–883
[13]. Bolton, R.J.,Westphal, L.C.: 'ECG display and QRS detection using the Hilbert transform', in Ripley, K.L. (Ed.): 'Computational Cardiology' (IEEE Computer Society, Washington DC, 1985), pp. 463–466
[14]. Benitez, S., Gaydecki, P.A., Zaidi, A., Fitzpatrick, A.P.: 'A new QRS detection algorithm based on the Hilbert transform', Comput. Cardiol., 2000, 27, pp. 379–382
[15]. Benitez, S., Gaydecki, P.A., Zaidi, A., Fitzpatrick, A.P.: 'The use of the Hilbert transform in ECG signal analysis', Comput. Biol. Med., 2001, 31, pp. 399–406
[16]. Hyvarinen, A., Oja, E.: 'A fast fixed-point algorithm for independent component analysis', Neural Comput., 1997, 9, (7), pp. 1483–1492
[17]. [17] Madeiro, J.P.V., Cortez, P.C., Marques, J.A.L., Seisdedos, C.R.V., Sobrinho, C.R.M.R.: 'An innovative approach of QRS segmentation based on first-derivative, Hilbert and wavelet transforms', Med. Eng. Phys., 2012, 34, pp. 1236–1246
[18]. [18] Wilson, J.D., Govindan, R.B., Hatton, J.O., Lowery, C.L., Preissl, H.: 'Integrated approach for fetal QRS detection', IEEE Trans. Biomed. Eng., 2008, 55, (9), pp. 2190–2197
[19]. [19] Richter, M., Schreiber, T., Kaplan, D.T.: 'Fetal ECG extraction with nonlinear state-space projections', IEEE Trans. Biomed. Eng., 1998, 1 pp. 133–137
[20]. Wei, Z., Hongxing, L., Jianchun, C.: 'Improving local PCA in pseudo phase space for fetal heart rate estimation from single lead abdominal ECG', Biomed. Tech., 2011, 56, pp. 309–319.