THIRD-ORDER CUMULANT SIGNATURE MATCHING TECHNIQUE FOR NON-INVASIVE FETAL HEART BEAT IDENTIFICATION

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ABSTRACT

This paper utilises the distinctive transient pulse feature of the Third-Order Cumulant Diagonal Slice (TOCDS) of ECG signals to detect the number of occurrences of fetal heart beats during each of the maternal cycles. The fetal ECG signal is a comparatively weak signal (less than 20 percent of the mother ECG) and often embedded in noise. The fetal heart rate (FHR) lies in the range from 1.3 Hz to 3.5 Hz and it is possible for the mother and some of the fetal ECG signals to be closely overlapping. The paper also addresses the problem of false alarm situations often arising in diagonal-cumulant-slice recording during labour due to non-Gaussian impulsive or transient noise types and shows some results obtained after Volterra noise whitening and interpolation of the neighbouring fetal TOCDS samples.

1. INTRODUCTION

The Fetal Electrocardiogram (ECG) is an interesting and useful signal in the assessment of the condition of the fetal before and during labour. The extent of the scientific literature [1, and references therein] on techniques for recording and processing the fetal ECG amply testifies to the inherent difficulties encountered by every investigator. The basic problem results from the fact that the fetal signal is very weak relative to the maternal signal and to the competing noise arising, perhaps from numerous biological action potentials. This is particularly true in the case of abdominal wall recordings (transabdominal) which is a non-invasive method. Several techniques have been used to eliminate or minimise the maternal signal [1]. First the maternal peaks (R-wave) must be located accurately [2] then an average maternal template is developed, and subtracted from each complex leaving behind the fetal waves. There is a variety of approaches that can be used to locate fetal R-waves automatically [1]. The most straightforward is the use of an amplitude threshold. Another approach employs a matched filter whose impulse response is the time inverse of the fetal waveform. Unfortunately due to non-Gaussian noise and the non-linear nature of the media (human body) false peaks may show some of the characteristics of the actual fetal heart beat. This is even more serious than missing a beat because it usually prompts surgical intervention due to the apparently high fetal heart rate. We have carried out investigations to establish the relative performances of such well known techniques. The investigations involved 15 or more different transabdominal measurements taken from women during early and advanced stages of labour. The number of complexes involved range from 50000 to 100000 maternal ECGs and as twice fetal ECGs. We have enough evidence as a result of numerous investigations carried out over the last few years to show that the number of recoverable fetal ECGs using conventional techniques is about 60-70 per cent of the actual number for signal-to-noise ratios ranging from 2dB to 12dB. Our finding has been substantiated by most recent studies, which quote a failure rate of approximately 30 per cent as an almost unanimous norm [1]. Using non-linear filtering and appropriate HOS-based techniques [3-5] has, to date, reduced the failure rate down to less than 2 per cent in all 15 problematic labour cases. The actual number of successful 'hits', can be independently calculated from a synchronised recording of fetal ECGs using invasive scalp electrode together with the maternal transabdominal recording.

This paper presents a new HOS-based technique for non-invasive fetal heart beat identification. Higher-order ECG representative domains are free from Gaussian noise and can be carefully mapped to locate different non-Gaussian signal/noise support regions and characterise nonlinearity. ECG abnormalities can be clearly detected when comparing the third-order cumulants of healthy and heart patients [6,7]. The problem of separating overlapping, non-linearly

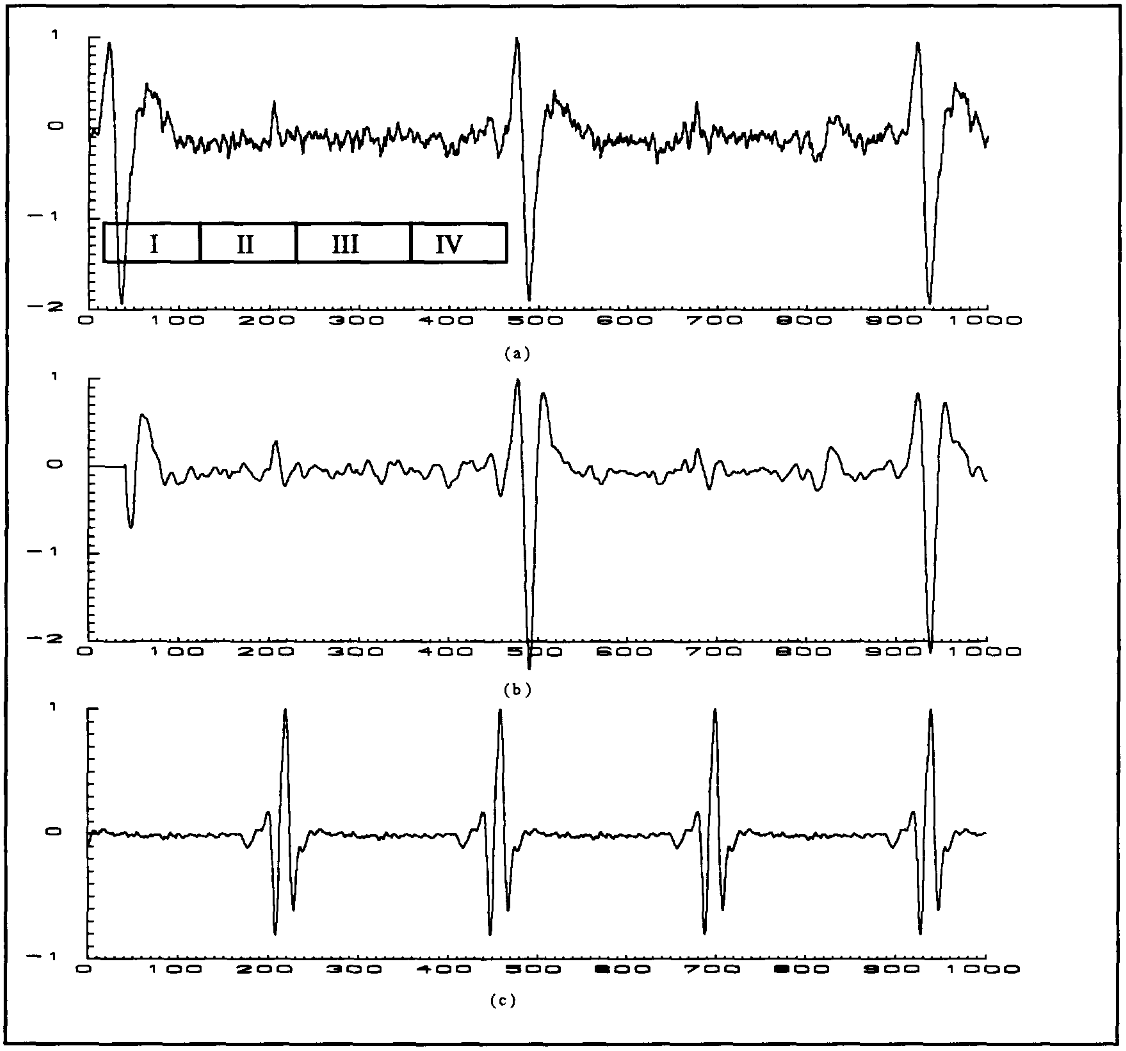

Figure 1: Two typical cycles of Transabdominally measure ECG signals of a woman in a late stage of labour, (a) before, and (b) after LMF filtering. (c) Synchronised and amplified fetal ECG measured using two electrodes; one electrode is clipped to the fetal scalp, and the other is attached to her thigh.

coupled, and noise contaminated mother and fetal complexes is a formidable task and can only be solved with the aid of an HOS domain library code pattern of several hundred ECG signals (mother/fetal). The key feature of the third-order cumulant domain can only be recovered if appropriate choice of temporal segmentation of the maternal ECG cycle (based on an estimate of the ratio of FHR/mother HR) and the subsequent whitening of non-linearity of any suspected transient noise are successfully carried out. Then the distinctive features of the third-order cumulants of mother and fetal ECG can be used in a number of ways to detect the fetal complexes. In the following, we show that having whitened the constituent mother/fetal cumulant slices, a simple thresholding detection scheme can be implemented to give a highly accurate account of FHR.

The motivation behind the use of the one dimensional TOCDS instead of multi-dimensional sequences in the identification of mother, fetal and noise events is due to excessive number crunching in the latter which can take a CPU time in excess of 100 seconds. The CPU time for a diagonal slice is of the order of 200 msec. For a sampling rate of 0.5 KHz and an FHR of the order of 2 Hz a real-time system can be easily implemented.

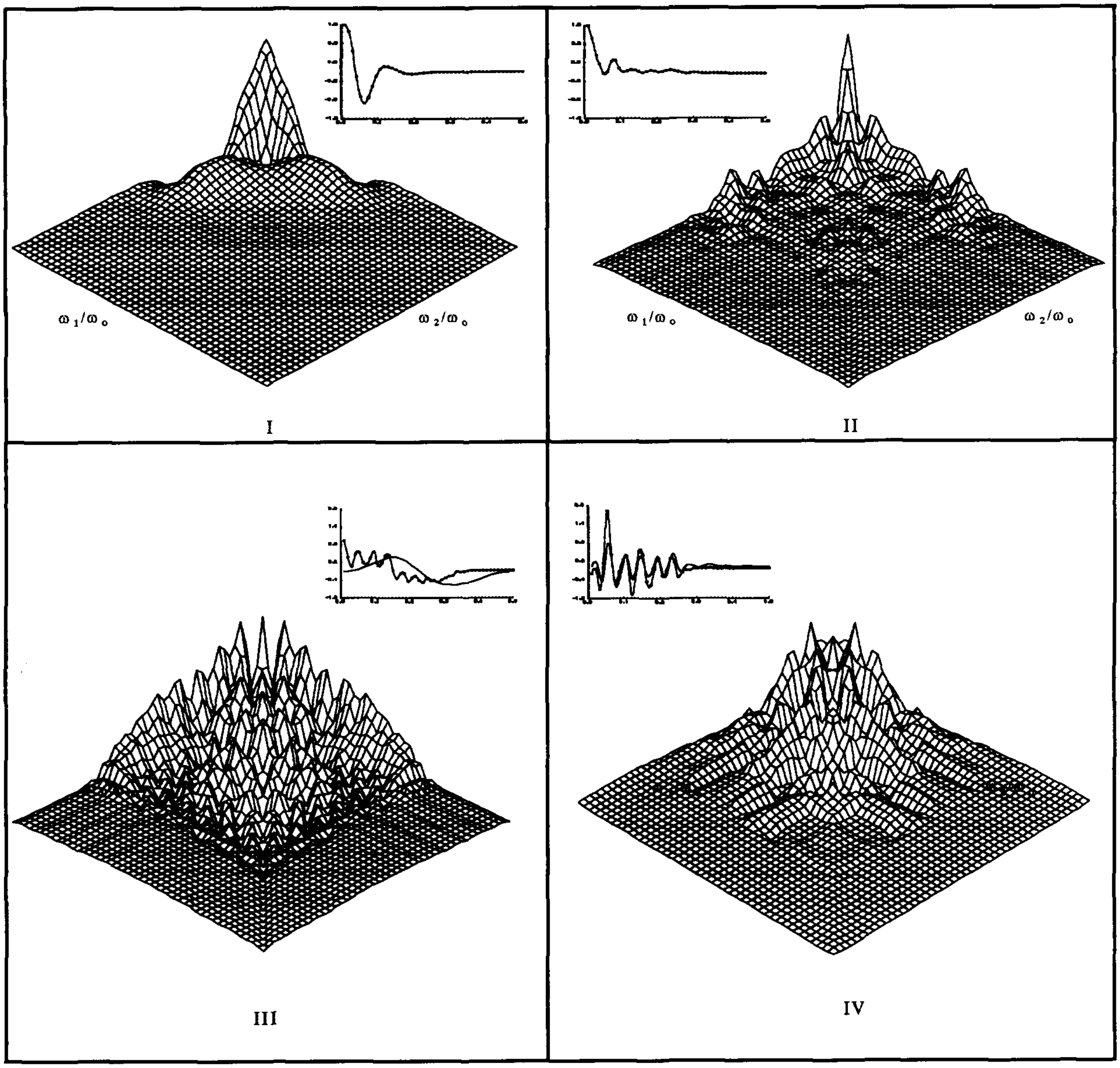

Figure 2: The third-order cumulants I, II, III, IV corresponding to the segments I, II, III, IV of figure 1, and their normalised diagonal slices shown in the insets before (dotted) and after (solid line) whitening quadratic and cubic nonlinearities using adaptive Volterra filter.

2. THEORY

Consider a non-Gaussian process $\{X(k)\}$ with third-order cumulants given by [8]:

$$C_3^x(\tau_1,\tau_2) = Cum\{X(k), X(k+\tau_1), X(k+\tau_2)\}$$

One-dimensional slices of $C_3^x(\tau_1,\tau_2)$ can be defined as: $r_{2,1}^x(\tau)\underline{\underline{\nabla}}Cum\{X(k), X(k), X(k+\tau)\} = C_3^x(0,\tau)$

$$r_{1,2}^x(\tau)\underline{\underline{\nabla}}Cum\{X(k), X(k+\tau), X(k+\tau)\} = C_3^x(\tau,\tau)$$

the right hand side of the above equations represent two straight lines with slopes of $90^{o}$and 45^{o}, respectively. Although the diagonal (45^{o}) and the wall (90^{o}) slices usually exhibit different features. In this paper only the former is considered. However, additional information can be extracted from the latter to assist in other applications.

3. RESULTS AND CONCLUSIONS

The ECG signals contain linear and non-linear components and are considered to be highly non-stationary. However, they have a quasi-periodic repetitive structure which permits the pre-setting of snapshot segmentation and future interpolation [9]. Therefore most signal complexes re-occur with some varieties. Figure 1 shows two typical cycles of transabdominally measured ECG signals of a woman in the late stage of labour, (a) before, and (b) after Least-Mean Forth (LMF) filtering. Figure 1 (c) shows synchronised fetal ECG measured using two electrodes; one electrode is clipped to the scalp and the other is attached to the woman's thigh (It was deemed necessary to use the scalp electrode since the fetal FHR lacked variability and from our viewpoint this has provided the vital information for performance analysis.)

Each maternal cycle is divided into four equal segments I, II, III, IV (figure 1a). Each segment contained 125 samples and was zero-padded prior to cumulant calculations to provide an additional length to the data. This has the effect of compressing key features of the TOCDSs and can be advantageous if the receiver is designed to have a bank of correlators for different feature matching. It is worth mentioning that both ECG signals are sampled at 0.5 KHz. The use of an adaptive LMF line enhancer [10] is optional in this case as we are working in higher-order domains.

Figure 2 shows the corresponding third-order cumulants and their diagonal slices (insets). In the cumulant domains figure 2 (I) depicts a typical mother impulse response. Figure 2 (II and IV) shows the fetal first and second impulse responses respectively, and III corresponds to an eventless time interval between the two fetal complexes but for the appearance of a transient noise response.

It is much simpler to use an amplitude thresholding operation instead of a bank of TOCDS correlators as diagonal slices usually have peaks exceeding 6dBs above the mean level of ringing (figure 2) and can easily raise the flag in a detector circuit as they pass through it. In this case it is necessary to whiten the transient noise using a Volterra filter (inset of figure 2 (III)) to bring down its level below the pre-set threshold level.

Observe the inset of figure 2 (IV), the neighbouring fetal samples in the third-order domain were irrevocably distorted due to the above whitening operation and had to be discarded and replaced by using another Volterra interpolator. The interpolator was tuned to the fetal TOCDS [9].

In conclusion the cumulant signature technique has proven to be very successful even in cases of severely distorted signals and non-resolvable mother and fetal differential time delays (figure 1 (a,c) segment IV). In this segment the differential time delay is of the order of 40 msec.

4. REFERENCES

[1] Bailliere's; Clinical Obst. & Gynae.- Intrapartum Surveillance- Int. Practice & Research, 1996.

[2] Q. Xue, Y. Hu, and W. J. Tompkins, " Neural network-based adaptive matched filtering for QRS detection," IEEE Trans. on Bio. ENG., Vol. BME-39, NO.4, pp. 317-328, April 1992.

[3] M. Sabry-Rizk, "Transabdominal fetal mother ECG signals deinterleaver using a neural network," accepted in NNESMED'96, 2nd International conference on neural networks and expert systems in medicine and healthcare.

[4] M. Sabry-Rizk, W. Zgallai, P. Hardiman and J. O'Riordan, "Application of Higher-Order Cepstral Techniques in Problems of Fetal Heart Signal Extraction," Proceedings of International Symposium on Optical Science and measurements, vol. SPIE 2846, pp. 395-411, Colorado, 1996.

[5] W. Zgallai and M. Sabry-Rizk," Distinctive 3-D super-resolution bispectrum templates for fetal heart complexes", submitted to IEEE Signal Processing Letters.

[6] M. Sabry-Rizk, W. Zgallai, P. Hardiman, and J. O'riordan, "Blind Deconvolution - Homomorphic Analysis of Abnormalities in ECG Signals," IEE Colloquium on Blind Deconvolution, London, UK, Sept. 1995.

[7] M. Sabry-Rizk," Third-order cumulant characterisation of some abnormalities in ECG signals", submitted to IEEE Signal Processing Letters.

[8] C. L. Nikias and A. P. Petropulu," Higher Order Spectral Analysis: A Nonlinear Signal Processing Framework". A. V. Oppenhein Series editor, 1993.

[9] W. Zgallai and M. Sabry-Rizk," Volterra modelling and interpolation of ECG signals in the second and third higher order statistical domains," submitted to ISDSP97.

[10] E. Walach and B Widrow, "The Least-Mean Forth (LMF) adaptive algorithm and its family," IEEE Trans. on Information Theory, vol. IT-30, No. 2, pp.275-283, March 1984.