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MUSIC Fetal Heartbeat Detection during Uterine Contraction

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***Abstract*:** *This paper is aimed at enhancing the spectral resolution of peaks identifying ECG signals contained in the transabdominally-measured QRS-complexes of the mother and the fetal. It is based on partitioning the subspace containing the ECG signal bearing the mother and fetal, and the orthogonal subspace containing the uterine contraction interference signal (UCS) plus noise. This is reminiscent of the multiple signal classification (MUSIC) estimator which exploits the orthogonality between the signal and noise subspaces provided that the noise is additive white Gaussian. In the proposed modified MUSIC, subsequent separation of the mother and fetal QRS-complexes is performed in their shared signal subspace*.

Keywords: *Fetal heartbeat detection, Spectral estimation, uterine contraction, non-invasive, MUSIC, HOS*

1. Introduction

The mother's QRS-complex principal spectral peak is found around 17 Hz, and the fetal QRS-complex principal spectral peak is found around 30 Hz [1]. Such spectral content can be exploited in the detection of either signal within the maternal cardiac cycle. The modified MUSIC algorithm has been devoted to identifying, in the frequency domain, anomalous QRS-complexes and P-waves such as P-on-T-waves and P-on-QRS-complex episodes for adult patients [1]. For fetal heart rate (FHR) detection in labour one has to overcome two problems; (i) poor signal spectral resolution, and (ii) the influence of the coexisting labour contraction signals [2] which exhibits a broad spectrum, and are characterised by having energy resonances, one of which is seriously overlapping with the fetal peaks which will be used as the fetal spike event. The fetal heartbeat detection is accomplished by thresholding the enhanced fetal spikes in the frequency domain. A challenging problem is to enhance the quality and resolution of the mother and fetal QRS-complexes' principal pseudo-spectral peaks, (MPPP) and (FPPP), respectively, and to nudge the UCS plus noise into a separate subspace which will be named the interference subspace (I-subspace), whereby orthogonalisation is forced between the I-subspace and the signal subspace (S-subspace) containing both the mother and / or the fetal QRS signature imprints. Two auxiliary methods have been used based on the concepts of *oriented energy* and *signal-to-signal ratio (SNR)*, and *the Gram-Schmidt orthogonalisation*. This is in addition to Generalised Singular Value Decomposition (GSVD) which deals with partitioning signal and coloured noise subspaces. This technique deals with the UCS during the strong peaks of labour contractions which have noise-like characteristics and are heavily contaminated with other noise artefact. The paper is organised as follows; Method is described in section 2. Results are shown in Section 3. Summary is discussed in Section 4.

2. Method

The mathematical formulation is based on [3-4]. A flowchart is given in [4]. The temporal window is restricted to 250 msec and is not aimed at a specific rank reduction. The Kaiser filter weights are applied to each of the 250 msec windows and the weights are optimised to enhance the principal peaks of either QRS-complex in their respective temporal domains. The data portions earmarked for the I_{noise} are falling mostly within segments III in the case of those maternal cardiac cycles that are free from coincident mother and fetal QRS-complexes in segments I, OR in segments II and IV for maternal cardiac cycles that do exhibit occurrences of coincident mother and fetal QRS-complexes in Segments I. An example is shown in Fig. 1.

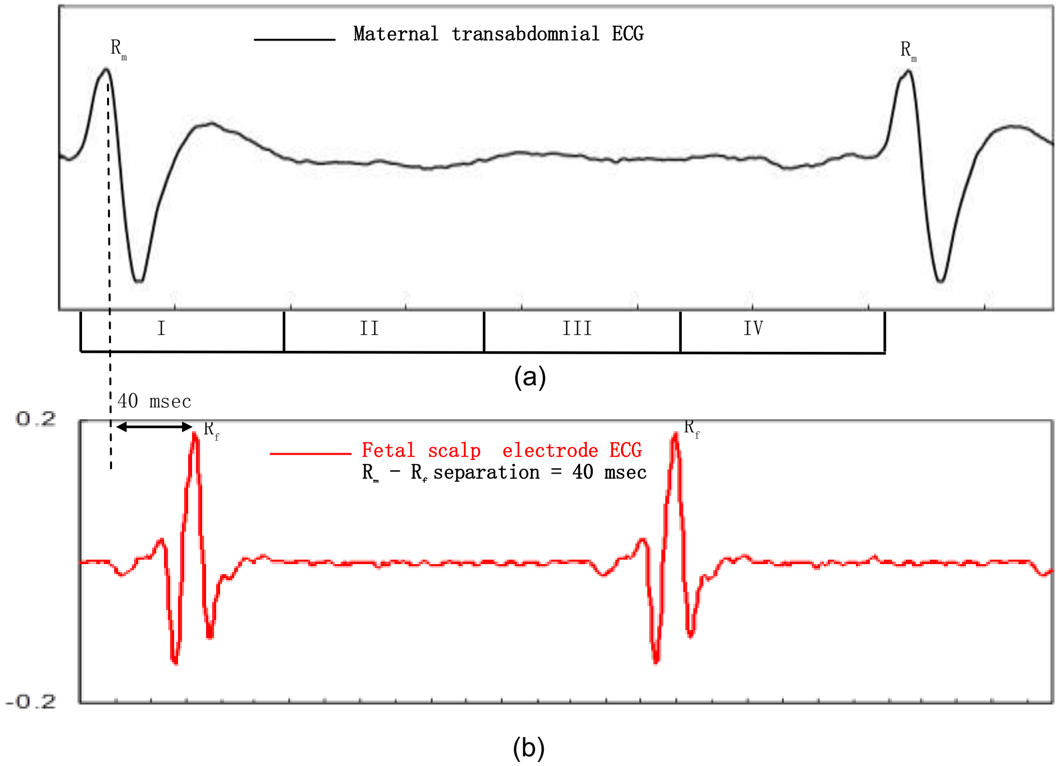


Fig. 1: Coincident mother's and fetal QRS-complexes. (a) A typical maternal transabdominal cardiac cycle, (b) the synchronised fetal ECG signal measured using two electrodes. The R-wave separation is 40 msec. The subject is at the first stage of labour, 40 weeks gestation. The maternal cycle has 500 samples at a rate of 0.5 KHz. Segment I: maternal QRS, segment II: the first fetal heartbeat with maternal contribution, segment III: QRS-free ECG, and segment IV: the second fetal heartbeat with maternal contribution.

To exploit a MUSIC methodology which incorporates a tailor-made subspace fitting for individual QRS spectral signatures based on *a priori* information, if we ignore the influence of the uterine contraction interference signals, the technique is based on weighting the covariance matrix of the transabdominally-measured signals, which in turn uniquely modifies the signal and noise subspaces to enhance and retain only eigenvectors that result in the mother QRS principal pseudo-spectral peak at 17 Hz, or the fetal QRS principal pseudo-spectral peak at 30 Hz as depicted in Fig. 2. In the absence of uterine contraction interference signals and assuming white Gaussian noise presence, this is a specially weighted MUSIC-like technique. The signal and noise subspaces will be reconfigured by two tailor-made weighting Kaiser functions, one is aimed at enhancing the mother QRS spectral peak and the other is aimed at enhancing the fetal QRS spectral peak.

2.1. Multiple overlapping windows

Up to five overlapping and optimised Kaiser weighted windows have been used in the detection of the mother's QRS-complex principal spectral peaks; 15-19 Hz. Up to ten overlapping and optimised Kaiser weighted windows have been used in the detection of the fetal QRS- complex principal spectral peaks; 28-38 Hz. The optimised Kaiser weights for the mother and fetal have been given in [4]. There are inevitable deviations in the 17 Hz and the 30 Hz of the mother and fetal QRS-complex pseudo-spectra, respectively.

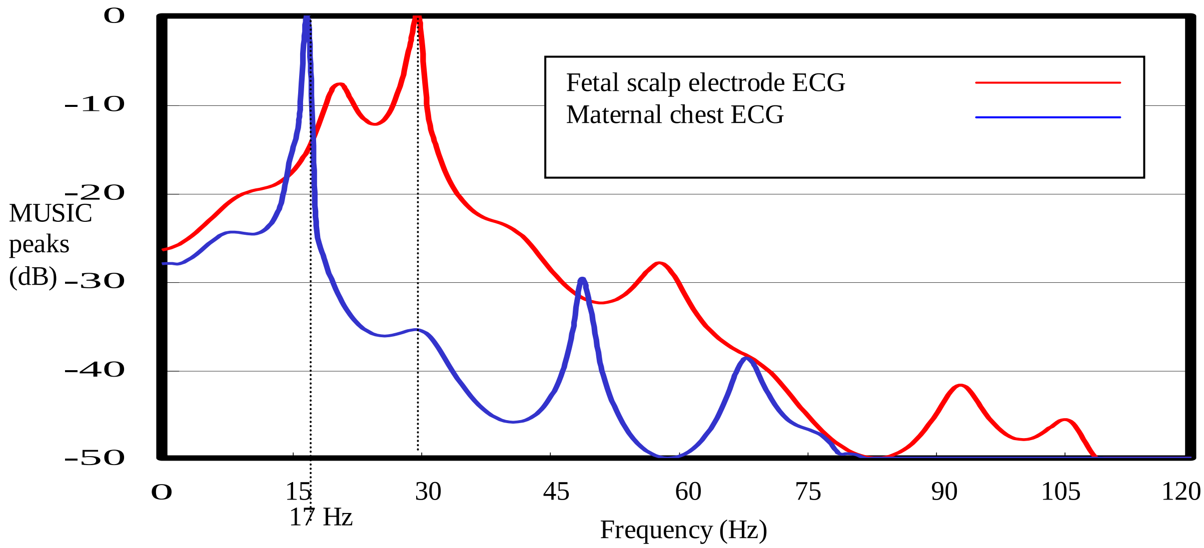


Fig. 2: Normalised weighted MUSIC pseudo-spectrum for fetal scalp electrode, and maternal chest full cardiac cycles. Optimised Kaiser weighting coefficients are used for the fetal and mother ECGs to enhance their spectral peaks at 30 Hz and 17 Hz, respectively. The maternal cardiac cycle begins 50 msec before the R-wave and ends 50 msec before the next R-wave. The subject is at end of term, 40 weeks. Model order is 11 and 4, respectively, for the signal and noise subspaces.

2.2. The choice of the model order

The model order has to be chosen carefully. The optimum model order is eleven for the signal and four for the noise. The method presented is not sensitive to small deviations in the model order.

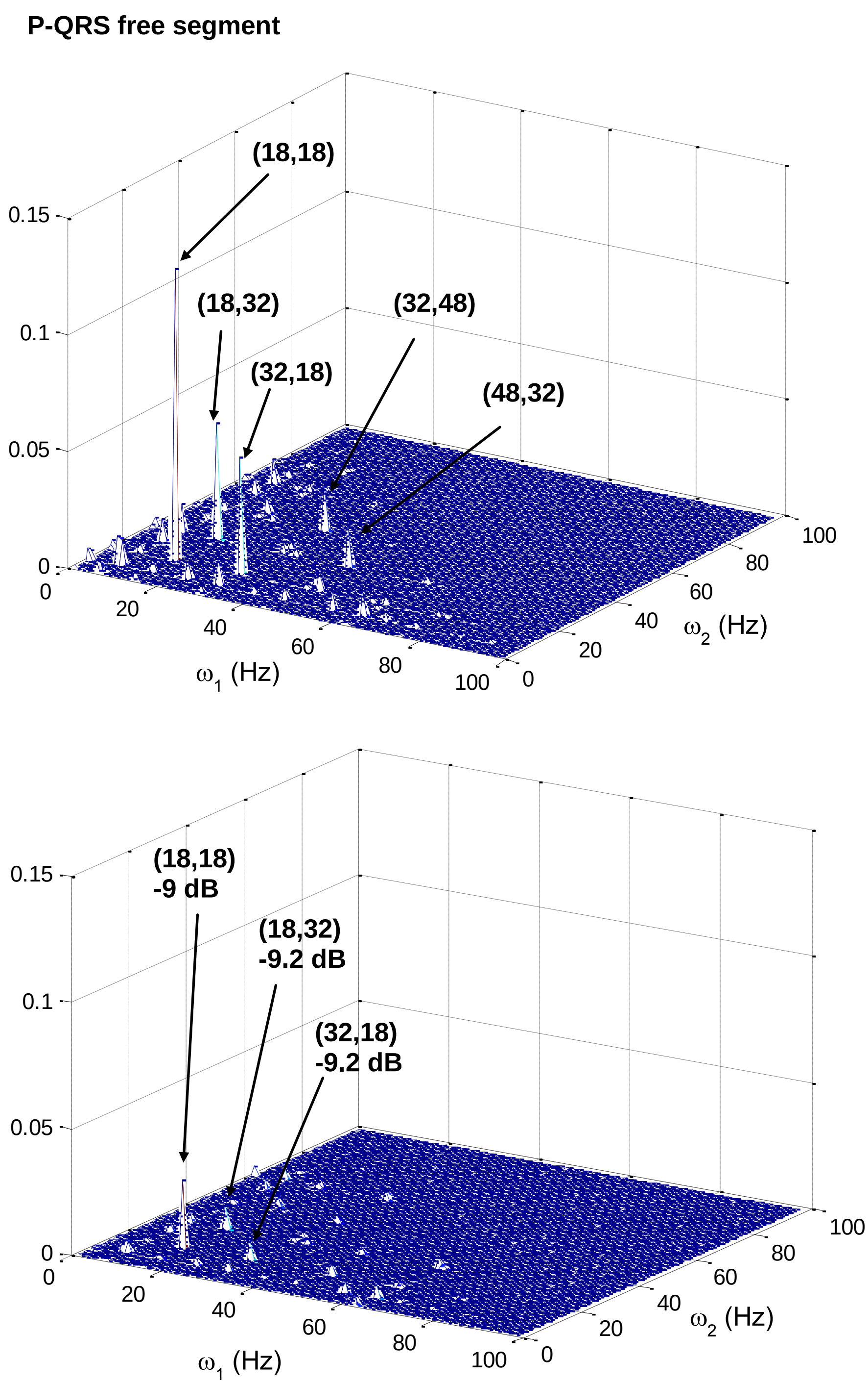
2.3. The bias and variance

Each maternal cardiac cycle has been divided into four segments of 250 msec each. If the mother's heart rate reaches 100 bpm the individual segmentation length is reduced by 100 msec reducing the segment length to 150 msec. And this would result in an increase in the variance of 15%. The effect on the QRS interval is marginally small as a normal interval is from 90 msec to 110 msec. The segmentation usually starts at 50 msec before the mother's R-wave and continues until the end of the first segment, albeit 250 msec or 163 msec. The other three equal segments are increased or decreased according to the mother's heart rate. A decrease in the temporal window can increase the variance by up to 15% of the value assigned to the critical 250 msec.

The bias [5] is defined as the averaged differences in frequencies, over 10,000 cases, of the transabdominally-measured fetal MUSIC peaks and those of the fetal scalp electrode. It was shown that the proposed MUSIC has a bias of 1.23 and 2.15 for MPPPs and FPPPs, respectively. This is lower than that of the conventional MUSIC by approximately 45%. The improvement in the bias is because the PPP of the fetal heartbeat segment are closer to that calculated from the fetal scalp electrode segment. For the mother's QRS-complex, the more deviation of the detected frequency of the MPPP around 17 Hz from that of the mother's chest ECG, the higher the bias will be. Similarly, for the fetal QRS-complex, the more deviation of the detected frequency of the FPPP around 30 Hz from that of the fetal scalp electrode, the higher the bias will be. The variance [5] is defined as the averaged squared differences in frequencies, over 10,000 cases, of the transabdominally-measured fetal MUSIC peaks and those of the fetal scalp electrode. The variance of the FPPPs ranges from 0 to 8, with an average value of 4.127.

3. Results

The spectrum of the UCS may include comparatively strong narrowband spectral components centred around 5 Hz, 30 Hz, 45 Hz, 60 Hz, and 90 Hz in addition to some broadband components. Fig. 3 depicts the effect of linearisation on the UCS's bicoherence squared. Linearisation has resulted in an average reduction of about 9 dB in spectral peaks at frequency pairs of (32 Hz,18 Hz), (32 Hz,48 Hz), and (48 Hz,32 Hz). The uterine



(b)

Fig. 3: The bicoherence squared of the transabdominally-measured ECG 250 msec segment which is free from both the P-waves and the QRS-complexes (a) before and (b) after linearisation using a third-order Volterra synthesiser. Retaining only the linear part results in a significant reduction in artefact. The direct method was used to calculate the bispectrum and then normalised with the Welch averaged periodogram to obtain the bicoherence squared. The Volterra synthesiser parameters are: filter length = 6, delay = 2, step-size parameters =0.001, 0.0001, 0.00001, for linear, quadratic and cubic parts, respectively.

contraction component at 30 Hz usually masks the principal spectral components of the fetal. A challenge is isolating the FPPP at 30 Hz in the presence of the UCS peak at the same frequency. Using a new pseudo-spectral localiser which incorporates the modified covariance matrix representing the UCS plus coexisting noise artefact, and seeks to reduce the influence of background uterine activities in the pseudo-spectral MUSIC localisation procedure by partitioning the two subspaces; one contains the desired signal parameters and the other contain the UCS parameters, is proposed. An accurate estimate of the UCS modified covariance matrix is needed to be incorporated in the pseudo-spectral localiser. A portion of the data that contains only noise fields, and does not contain any signal information such as the P-waves or the QRS-complexes, is utilised. When such a segment of the data that is P-wave- and QRS-complex-free is sufficiently long for the MUSIC pseudo-spectral localiser (in this case 250 msec or 250 samples at 1 KHz sampling rate), an accurate estimate of the UCS modified covariance matrix can be obtained.

The proposed localiser is applied to the segments. The UCS modified covariance matrix is calculated using the data portion in the segments. The results are shown in Fig. 4. The maternal MPPP is detected at 17 Hz as shown at the top of the Figure. The FPPP of the first fetal heart beat, which is coincident with the maternal QRS-complex in segment I, is detected at 30 Hz and can be seen at the top of the Figure. The FPPP of the second fetal heartbeat is detected at 32 Hz as can be seen in the bottom of the Figure.

The effect of proximity of the mother's and fetal R-wave on the frequency deviation of the FPPP around 30 Hz, and on the fetal heart detection rate, in all observed cases of coincident mother and fetal QRS-complexes has been studied. The proposed algorithm has been applied to approximately 50,000 maternal cardiac cycles, including 4,873 coincident QRS-complexes cases. The results are tabulated in Table 1. For a fixed model order of 11 and 4 for the signal and noise subspace, respectively, the new MUSIC algorithm is capable of detecting fetal heartbeats, at a rate of almost 92%, when the mother and fetal R-waves are almost synchronised, provided that appropriate sequential weightings for the mother and the fetal are maintained throughout. As the separation between the mother and fetal R-waves is increased, a slight increase in the corresponding detection rate and a decrease in the FPPP frequency deviations is observed.

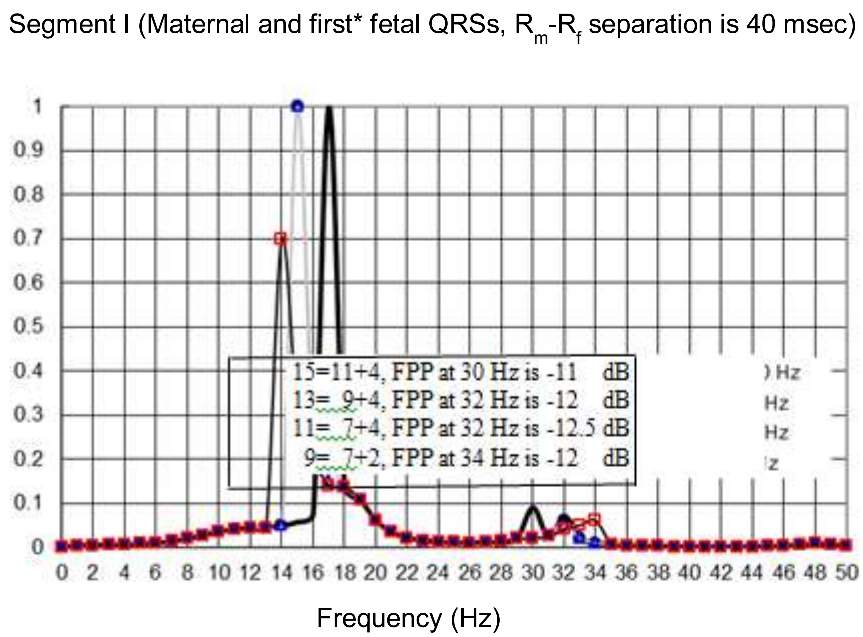
TABLE 1: The Effect Of Proximity Of The Mother's And Fetal R-Wave On The Frequency Deviation Of The FPPP Around 30 Hz, And On The Fetal Detection Rate.

Averaged R_m-R_f separation (msec)	40	35	25	20	15	7	0
Frequency deviation $\pm$ (Hz)	1.73	1.92	2.09	2.17	2.31	2.52	2.74
Number of overlapping windows	5	5	5	5	8	9	10
Average detection rate (%)	93.81	93.63	93.56	93.49	93.24	92.35	91.83

From the overall results, note that:

1. The algorithm is capable of detecting fetal heartbeats, at a rate of 92%, when the mother and fetal R-waves are synchronised, provided that appropriate sequential weightings for the mother and the fetal are maintained throughout. As the separation between the mother and fetal R-waves is increased, there is a slight increase in the corresponding detection rate and a decrease in the FPPP frequency deviations.
2. The incorporation of the covariance matrix of the UCS helps to strengthen and sharpen the FPPPs in some cases and hence improves the resolution, and reduces the sensitivity of the FPPPs to any small deviations from the optimal model order.
3. The modified MUSIC has resulted in the following fetal heart detection rates: (i) 89.23%, 97.51%, and 91.20% for coincident, non-coincident mother and fetal QRS-complexes, and overall average, respectively. The proposed MUSIC has resulted in the following fetal heart detection rates: (i) 93.52%, 99.35%, and 95.50% for coincident, non-coincident mother and fetal QRS-complexes, and overall average, respectively. The results have been verified by the recording of the instantaneous scalp fetal heart rate.

The expected values of the estimates are those obtained using the 250 msec segments from the maternal transabdominal ECG signal for a predominantly maternal QRS segment and a fetal heartbeat with maternal contribution. Those true values and estimates were calculated for 1000 segments. The results are 1.23 and 2.15 for MPPPs and FPPPs, respectively. For the mother's and fetal QRS-complex, the more deviation of the detected



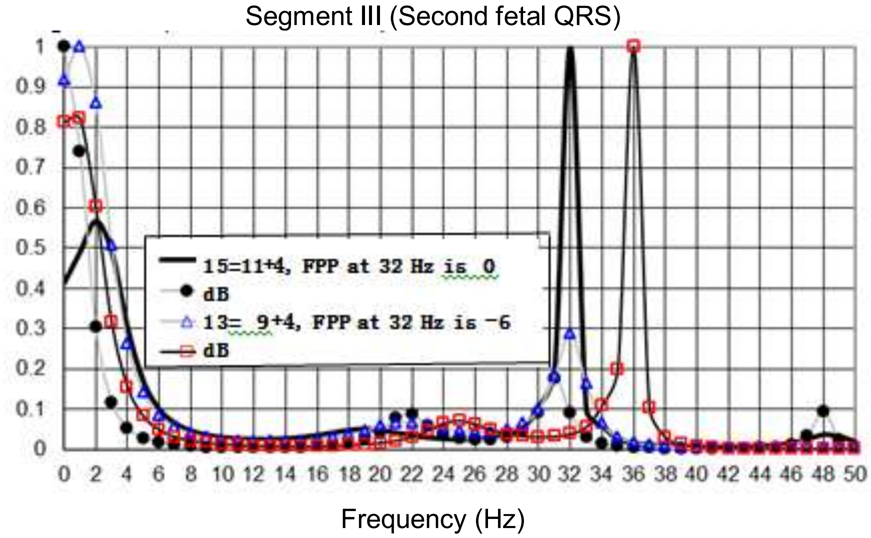


Fig. 4: The proposed MUSIC for the transabdominally-measured ECG signal. Both mother's and fetal QRS-complexes coexist in segment I with their respective R-wave separation at 40 msec. FPP at 32 Hz indicates the presence of a second fetal QRS in segment III, while segments II and IV contain noise artefacts within the maternal cardiac cycle. FPPs at 30 Hz and 32 Hz in segments I and III, respectively. When I_{noise} is incorporated the MUSIC peaks are less sensitive to small deviations in the model order. By incorporating the I_{noise} the FPPs tend to be sharper at 32 Hz when there are small deviations in the model order such as 13=9+4 and 11=7+4 frequency of the MPPP at around 17 Hz and the FPPP around 30 Hz, respectively, from the respective actual frequency, the higher the bias will be. The variance ranges from 0 – 8, average = 4.127, when calculated for 120,000 FHBs

4. Summary

Assuming a mother's heart rate of 60 bpm yielding a cardiac cycle length of 1000 msec. Each maternal cardiac cycle has been divided into four equal segments of 250 msec. The average rate by which the first fetal event coincides with the QRS-complex of the mother is 9.8%, based on 50,000 maternal cardiac cycles. When the two QRSs of the mother and fetal coincide in segment I, segment II is usually free from such events and may be taken as the UCS plus noise artefact segment. On average, the second fetal heartbeat occurs in segment III. And if there is a third fetal heartbeat, then it is likely to occur over both the fourth segment of the present cycle and the first segment of the next cycle. In most cases, two fetal heartbeat occurrences within each maternal cardiac cycle were encountered, even when the mother's heart rate goes up during labour contractions. The deceleration of the fetal heart rate after the peak of labour contractions is normal and not proven to be related to the mother's heartbeat as her heart will still be racing for a while after the peak of contractions.

Successful detection of coincident mother and fetal QRS-complexes has resulted in an increase of 9.3% and 5.4% over and above the cumulants and the bispectrum template matching techniques, respectively [7-8]. The mother and fetal QRS-complexes coincide making it difficult to separate them using any time-domain technique. With the cumulants method [7] there is a 13.8% failure rate, partially due to 9.8% rate of QRS-complex coincidences, and the rest, 4% rate, is due to overlapping fetal QRS-complex and maternal T-wave. The bispectrum method [8] failure rate of 9.8% is purely due to QRS-complex coincidences as there is a shortcoming in acquiring sufficiently high resolution to separate the bispectral peaks of the mother and fetal QRS-complexes. The overlapping of the fetal QRSs and the maternal T-waves can be resolved by the bispectrum template matching technique. The above percentages of QRS-complex coincident episodes have been found in the 50,000 maternal heartbeat database. The alternative is to try to resolve them in the frequency-domain.

The incorporation of the covariance matrix of the UCS helps to strengthen and sharpen the FPPPs for the optimum model order and in some cases it appears to be tolerant to a change in the model order from 11 and 4 to 9 and 4 for the signal and noise subspace, respectively. It has also resulted in a significant noise artefact reduction in the QRS-free segments. The method has resulted in the following fetal heart detection rates: (i) 93.52% for coincident mother and fetal QRS-complexes, (ii) 99.35% for non-coincident mother and fetal QRS-complexes, and (iii) 95.50% overall average. Without the incorporation of the UCS modified covariance matrix into the mathematical formulation of the sequentially optimised, weighted MUSIC, the following fetal heart detection rates have been obtained: (i) 89.23% as opposed to the 93.52% for coincident mother and fetal QRS-complexes, (ii) 97.51% as opposed to the 99.35% for non-coincident mother and fetal QRS-complexes, because in the former no appropriate noise model was assumed in the analysis, and (iii) 91.20% overall average.

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