ABSTRACT

An Enhanced Signal Processing Strategy For Fetal Heart Rate Detection

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The goal of the research was to improve the signal processing strategy for an acoustic fetal heart rate monitor. The theory, implementation, and testing of several possible signal processing strategies for fetal heart rate detection are presented. The enhanced signal processing strategy implemented is discussed and justified with off-line Matlab simulations and real-time experiments. A FIR matched filter was used as a preprocessor to increase the SNR of the acoustic fetal heart signal. The Teager energy operator and autocorrelation, used in the previous version of the monitor, were combined with a matched filter. Linear prediction and quadratic energy detection were investigated and are discussed as methods for improving the signal processing but were not effective enough for implementation in the real-time system. Other modifications, which were implemented, such as improving the audio feedback signal, fetal heart rate range selection, and real-time FFT option, are described. Comparisons of the enhanced signal processing strategy in the acoustic fetal heart rate monitor are made with the results of ultrasound fetal monitoring. The experimental tests indicate that the modifications in the signal processing lead to more accurate fetal heart rate detection.

AN ENHANCED SIGNAL PROCESSING STRATEGY FOR FETAL HEART RATE DETECTION

by

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I am thankful for the continued support and love my family has given. I would like to dedicate this thesis to my wife and son.

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INTRODUCTION

1.1 Fetal Heart Rate Monitoring

Acoustic fetal heart rate (FHR) monitoring captures the beating activity of the fetal heart valves opening and closing using an acoustic sensor placed on the mother's abdomen [1]. As long ago as 1818, a physician detected fetal heartbeats by listening to a fetus from the mother's abdomen. In 1833, a textbook on "Obstetric Auscultation" mentioned the possible connection between FHR patterns and fetal health [2]. In 1906, Cremer first measured the fetal electrocardiogram (FECG) by using abdominal electrodes [3]. Since Cremer, FHR monitoring has been used clinically for assessing fetal health. Fetal cardiograms can predict fetal distress allowing doctors to prevent irreversible harm to the fetus. The motivation for working on an acoustic fetal heart rate monitor (FHM) is to make long term, at home fetal heart rate monitoring possible. At home monitoring will be convenient for doctors and pregnant women. With long term monitoring, more fetal heart rate data will be collected, resulting in better fetal diagnostics.

There are two primary methods used for FHR monitoring which are the fetal electrocardiogram (FECG) and fetal phonocardiogram (FPCG) methods. The FECG method observes the electrical activity of the fetal heart within the mother's abdomen by using electrodes attached to the fetal scalp or outside the mother's abdomen. Ultrasound is an external FECG method of FHR monitoring. Both the internal and external FECG are considered invasive methods of fetal monitoring. The FECG method limits the amount of fetal monitoring because it is invasive and potentially hazardous. The FPCG method uses a passive microphone placed on the mother's abdomen to detect fetal heartbeats. Therefore, the FPCG method is an uninvasive method of fetal monitoring and can be used for long term, at home monitoring. Recorded signals from FPCG methods have a lower signal to noise ratio (SNR) than FECG methods due to the low acoustic energy of the fetal heartbeats at the wall of the mothers abdomen. Also contributing to a low SNR in FPCG methods is the high acoustic energy of the movements in the amniotic fluid and the heartbeat of the mother relative to the fetal heart beats. Three advantages of the FPCG method over the FECG methods are the low cost, simplicity of equipment, and uninvasive nature of monitoring. One disadvantage of the FPCG is the difficulty of the signal processing, which could result in less accurate FHR detection compared to the FECG method.

1.2 Previous Work on the Fetal Heart Rate Monitor

There are three phases through which work on the FHR monitor project has been performed. The first phase was initiated by Donald Baker (MD) in 1986. Dr. Baker contacted NASA and suggested that long term fetal monitoring of a maternal mother could prevent significant fetal problems such as hypoxic brain damage. Dr. Baker suggested a passive acoustic device using the FPCG method would make it possible to perform long term fetal monitoring. NASA agreed to fund a project to develop the FHR monitor recommended by Dr. Baker. NASA developed and fabricated the acoustic sensors for the FHM. The sensors were produced using a polyvinylidene fluoride film which had been used to detect vibrations in wind tunnels at NASA. The Department of Electrical and Computer Engineering at Old Dominion University (ODU) was selected to develop the signal processing hardware and software for the FHM. The Eastern Virginia Medical School (EVMS) agreed to assist in the clinical data collection and testing of the acoustic FHM system. Dr. Pretlow and Dr. Stoughton from Old Dominion University developed a prototype monitor and demonstrated the feasibility of Dr. Baker's idea, which concluded phase 1.

The second phase began when Dr. Stephen Zahorian, an ODU professor and researcher, was asked to improve the FHM and develop a working portable medical research instrument [1]. Zongyao Zhou, an ODU graduate student, began working with Dr. Zahorian and a portable FHM system was developed. EVMS provided patients for testing of the portable acoustic FHM.

The third phase is documented in this thesis. The third phase goals are to improve the FHM accuracy and aid in making the acoustic FHM a commercial product. To improve on the accuracy of the FHM system the signal processing, the "heart" of the FHM system, was to be improved. Actually the acoustic sensors are the most important aspect of the acoustic FHM with the signal processing the next most important aspect of the acoustic FHM. Because the acoustic sensors were developed by NASA and ODU's task was to develop the FHM system using NASA's acoustic sensors, improving the signal processing was the next logical place to begin. The signal processing has been taken one step further than that of phase 2. The signal processing in phase 2 used only the periodic information in the fetal heart beat signal for fetal heart rate detection. The enhanced signal processing implemented in phase 3 uses a matched filter preprocessor together with the signal processing in phase 2 to improve the SNR before fetal heart rate detection. Modifications requested by the nurses and doctors using the FHM system were also made. A typical modification requested by the nurses using the FHR monitor was to improve the audio feedback of the system to help in positioning the acoustic sensor belt.

1.3 Objective of Research

The main research objective of this thesis is to enhance the signal processing strategy for detecting the fetal heartbeats in the FHR monitoring system. By enhancing the signal processing strategy, the fetal heart rate detection becomes more reliable and compares to ultrasound methods. Because the data from the FHM will be used as the basis for important decisions by the doctors, the detected heart rates should be as accurate as possible. Another objective of the FHM project is to modify the FHM system to accommodate the doctors and nurses who use the FHM system. Modifications to the FHM system are as follows: fetal heart rate range selection, audio feedback enhancement, and real-time FFT. Clinical testing in order to collect data from EVMS and compare the acoustic FHM to ultrasound methods is another important part of the thesis research.

1.4 Overview of Thesis

Chapter 2 begins by giving a summary of the previous acoustic FHM research performed during phase 2 of the FHM project. Also, Chapter 2 contains a literature review of signal processing techniques considered for the FHM but not chosen as part of the signal processing in the FHM. Chapter 3 discusses the enhanced signal processing strategy chosen for the real-time version of the acoustic FHM including a theoretical background of the signal processing components that make up the enhanced signal processing strategy. Chapter 4 describes important refinements to the FHM system including audio feedback enhancements, fetal heart rate range selection, and a real-time FFT display. Chapter 5 discusses the experimental data collected using the acoustic FHM. A comparison of the acoustic FHM data with ultrasound data and the previous acoustic FHM system from phase 2 is done in Chapter 5. Chapter 6 concludes by summarizing important results gathered during the thesis and points out where future research efforts should be focused.

C H A P T E R   2

BACKGROUND AND LITERATURE SUMMARY

2.1 Introduction

A summary of the research performed in phase 2 by Dr. Stephen Zahorian and Zongyao Zhou is presented in this chapter. In the summary, an overview of the FHM system is presented. The fetal heartbeat detection algorithm used in phase 2 is discussed. Chapter 2 is concluded with a discussion of the signal processing components investigated but not implemented in the FHM system.

2.2 The Acoustic Fetal Heart Beat Signal

The fetal heart beat signal results from vibrations produced in the opening and closing of four valves which control blood flow through the heart and from vibrations of the fetal heart muscle. The two primary components of the fetal heart beat signal are referred to simply as the first heart sound and the second heart sound. The first heart sound is due to closure of the mitral and tricuspid valves (MT). The second heart sound is due to closure of the aortic and pulmonary valves (AP). Figure 2-1 shows a recording of an acoustic fetal heart beat signal. In figure 2-1, the heart beats are the large spikes due to the combined effects of the AP and MT. Resolution of the individual components of the heart beat is not possible for this tracing because of the overall noise level of the acoustic FHM system.

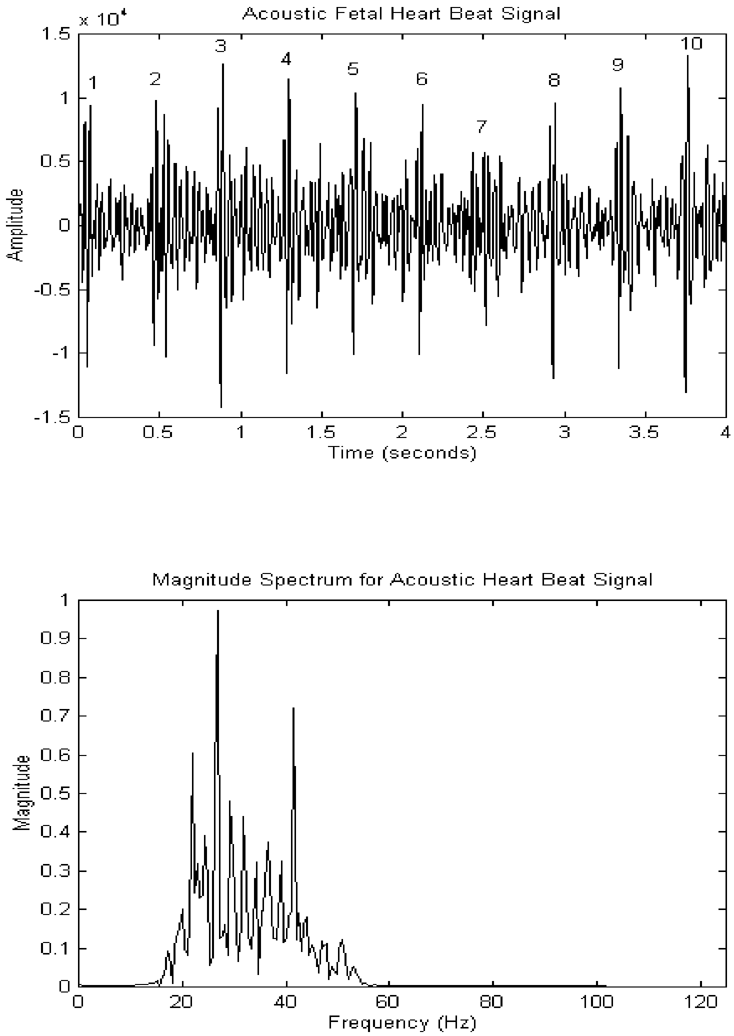

Figure 2-1 Acoustic Fetal Heart Beat Signal and Spectrum

The acoustic fetal heart beat signal has relatively low energy. The mother's heart beat is anywhere from 10 to 100 times stronger than the fetal heart beat [1]. In most cases, the fetal heart beat can be heard in a 3 cm diameter area on the mothers abdomen. The 3 cm diameter area where the fetal heart beat signal can be heard can be located anywhere within a 12 cm diameter area.

An important basic concept is determining the FHR from a frame of the acoustic fetal heart signal. In figure 2-1, there are 10 heart beats over 4.0 seconds. Using equation 2-1, the FHR can be calculated.

$$FHR = \frac{\#\_of\_beats}{frame\_time(s)} * 60 \frac{\sec onds(s)}{\min ute} \tag{2-1}$$

The unit for the FHR is beats per minute (BPM). The resulting fetal heart rate for the 4.0 second frame in figure 2-1 is 150 beats per minute (BPM). Figure 2-1 also displays the shape of the magnitude spectrum of the fetal heart beat signal.

2.3 Summary of Previous Research

A working real-time FHM system was developed by Dr. Zahorian and Zongyao Zhou in 1994, during phase 2 of the FHM project. Subsections of this section summarize chapter 3 titled, Fetal Heart Rate Monitoring System, in Zongyao Zhou's master thesis [1]. An overview of the FHM system is shown in figure 2-2. The elements of the system are as follows: a seven sensor array sensor belt, an analog electronic front-end system, a speaker, and a portable personal computer (PC) with an ELF DSP board inside which contains a Texas Instrument TMS320C31 digital signal processing (DSP) microprocessor. The real-time DSP algorithm runs on the ELF DSP board while the graphical user interface

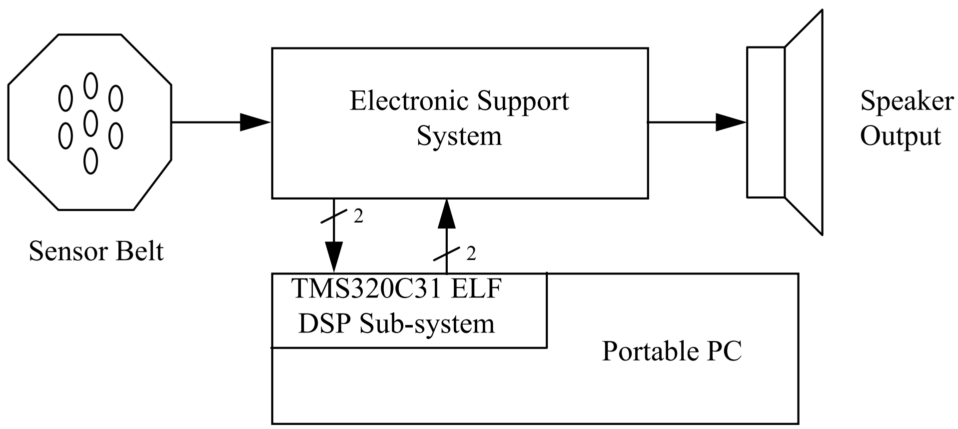

Figure 2-2 An Overview of the Fetal Heart Rate Monitor

software runs on the PC. The PC code is synchronized with the ELF code to allow data and command transfers between the PC and ELF code. The ELF code computes the fetal heart rates and passes the rate information along with the acoustic fetal heartbeat signal to the PC for displaying.

2.3.1 Acoustic Sensor Belt

The acoustic sensor belt contains a seven-element sensor array which covers the twelve centimeter diameter site expected for fetal heart tones to be found on the mothers abdomen. Each of the seven sensors covers a 4 cm diameter area. The design of the sensor belt ensures that fetal movement during monitoring will not cause the system to fail. Each of the seven sensors is processed individually resulting in a fetal heart rate computation for each channel. The fetal heart rate that the FHM system is "most confident in" is chosen as the fetal heart rate for that time interval. A diagram of the acoustic sensor belt is shown in figure 2-2.

The acoustic sensor belt has been designed to accomplish five functions: signal detection, acceleration cancellation, acoustical isolation, electrical shielding, and electrical isolation of the mother. Each of the seven sensor elements are made of two sensors which are PVF2 elements arranged in a bimorph structure, that is mechanically in series and electrically in parallel [1]. The internal sensor detects pressure pulses on the maternal abdomen. The external sensor is designed to enable cancellation of accelerations due to rigid body motion of the mother. The belt material is nylon parachute webbing which gives the belt a high degree of stiffness. The belt must have high stiffness to resist displacement by the incident pressure pulses which ensures sufficient compression of the PVF2 foil. The acoustical isolation is achieved by using kevlar wool to attenuate signals due to ambient noise. Electrical shielding is accomplished by grounding a foil of copper coated kapton which completely surrounds the sensor array. A layer of RTV silicone rubber completely covers the copper shielding and isolates the mother from earth ground. Refer to reference [4] for further details on the acoustical sensors.

2.3.2 Front-end Electronic System

The purpose of the front-end electronics is to amplify the acoustic sensor signals to span the dynamic range of the A/D converter and increase the SNR before digital processing. The data from all seven sensor elements is processed in parallel inside the front-end electronics system and multiplexed onto the ELF DSP subsystem. The electronic system contains the following parts: instrumentation amplifiers, band pass filters, two time-division multiplexor channels, two final-stage amplifiers, and an audio amplifier circuit. Figure 2-3 illustrates the layout of the front-end electronics system. The front-end electronic system has three input connections and three output connections. The input connections are as follows: 25 pin male dB connector from the acoustic sensor belt, a stereo jack containing the control signal and one playback signal from the ELF board, and one push button switch. The output connections are as follows: 25 pin female dB connector which routes the push button signal to the parallel printer port on the PC, one stereo jack for the acoustic signals to be multiplexed onto, and a mono audio jack for playing the playback audio signal.

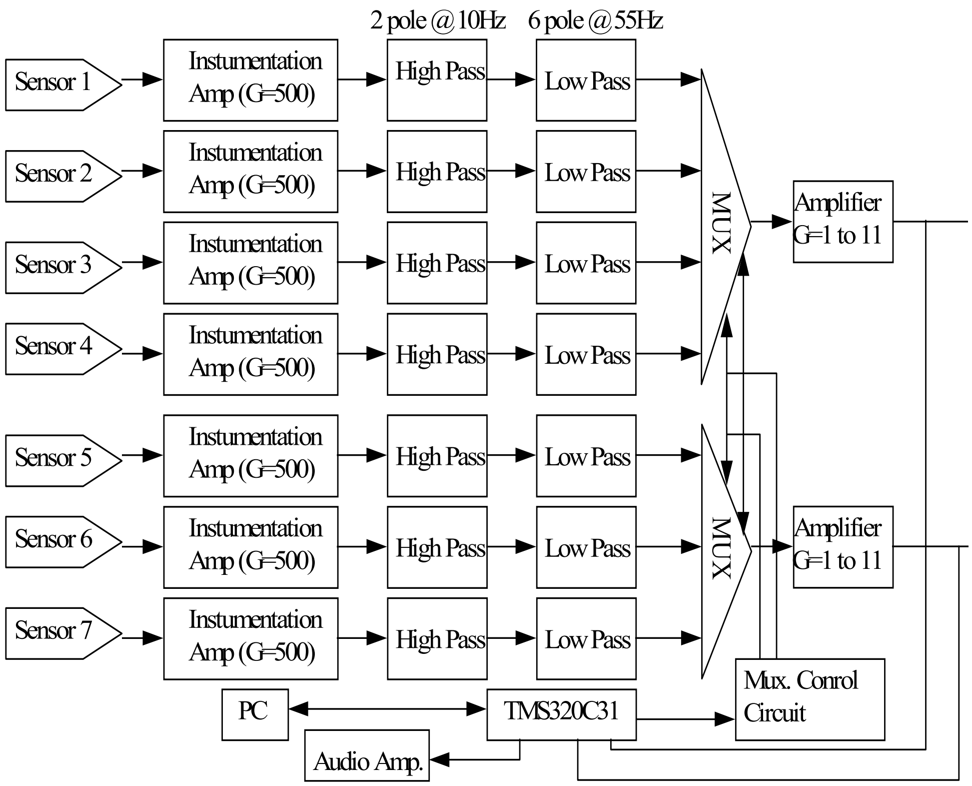

Figure 2-3 Front-End Electronics System

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The electronics system has fourteen low noise high gain instrumentation amplifiers (AD524). Each of the seven sensor elements has three wires that connect to the front-end electronic system. One wire is connected to the inner sensor, the other wire to the outer sensor, and the third wire is a common ground for the inner and outer sensor. Each amplifier is connected to a single sensor, either inner or outer, and has a gain of 500. The reason for using two sensors is to cancel motion artifacts. Because the phase of the motion signals is not the same for the two sensors, the signals of the two sensors are added after amplification, which reduces motion artifacts. Because the fetal signals are in phase for the two sensors, the fetal signal amplitude is increased.

After the amplification section, the seven signals are band passed filtered. The band pass filter is a four-pole high pass Butterworth filter with a cutoff frequency of 18 Hz, and a low pass Butterworth filter with a cutoff frequency of 58 Hz. The selected band pass cutoff frequencies were chosen to suppress acoustic noise and 60 Hz EMI, while allowing as much fetal energy to pass as possible.

The time-division multiplexed circuit was necessary to multiplex the seven channels to the two input A/D channels of the ELF board. The multiplexing circuit must be synchronized to the A/D on the Elf DSP subsystem to keep track of the seven channels of data. Therefore, one D/A output from the ELF board was used as a control signal for the multiplex circuit.

The two multiplexed signals are then amplified to match the dynamic range of the A/D on the ELF board by the final stage amplifier. The gain for the multiplexed signals is manually tuned with a dual 100 kilo ohm potentiometer.

The last main part of the front-end electronics is the audio amplifier circuit. The audio amplifier circuit supplies enough power for the acoustic playback signal to be played out of a speaker. The audio feedback is important to nurses using the FHM system to help them position the sensor belt based on the location of the strongest fetal heart beats. The acoustic signal obtained from the middle sensor is used for audio feedback.

2.3.3 Digital Signal Processing

This section describes the signal processing components of the FHM system at the end of phase 2 of the FHM project. Figure 2-4 below shows a block diagram of the signal processing strategy implemented at the end of phase 2. The signal processing components are as follows: sampling of the acoustic signal, digital band pass filtering, Teager energy operator, autocorrelation, and figure of merit.

In Chapter 3 the enhanced signal processing strategy is discussed. The sampling and digital filtering were not changed from phase 2 to phase 3. Thus, the enhanced signal processing presented in Chapter 3 is discussed assuming that the sampling and digital filtering has occurred as presented in this chapter.

<u>Sampling</u>

The two multiplexed signal outputs of the front-end electronic system are sampled by the A/D on the ELF board. The sampling is done at 8 kHz. The sampled signals are then demultiplexed into eight separate digital signals. By using the eighth signal as ground, each sensor number is determined by locating the ground signal. The ground signal is located by comparing each sensor's root-mean-square (rms) value and the

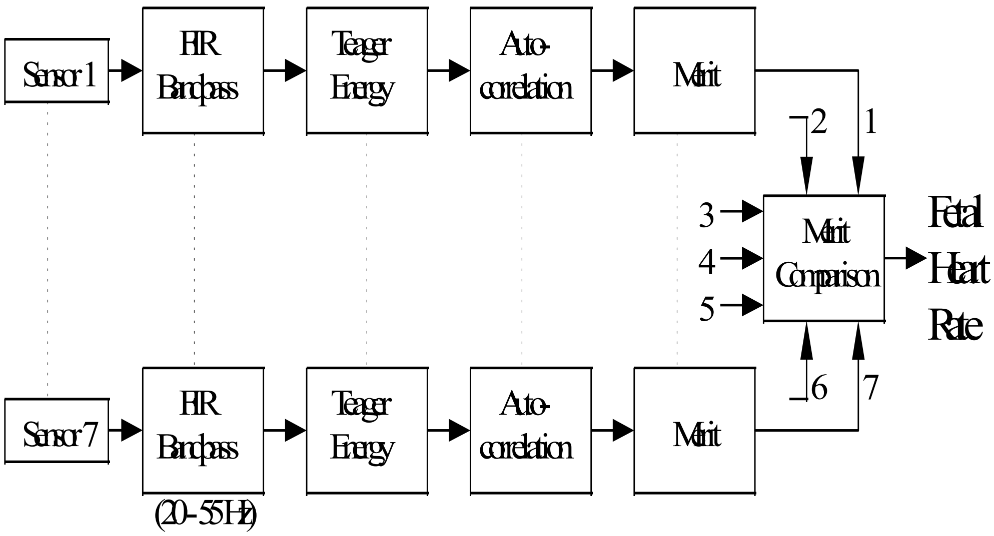


Figure 2-4 Previous Signal Processing Strategy

channel with the smallest rms value is the ground signal. Once the ground signal is located the order of the remaining seven channels is known. (Chuck—font in fig 2-4 is messed up)

Digital Filtering

After the sampling routine, the signals are filtered by a 124^{th} order equal ripple digital band pass finite impulse response (FIR) linear phase filter. The pass band of the filter is controlled by keyboard commands in the real-time FHM system. The digital filter increases the SNR of the fetal heartbeats by eliminating noise outside of the desired frequency range. After filtering, the acoustic signals were decimated by a factor of two, resulting in signals with an effective sampling frequency of 250 samples per second.

<u>Teager Energy Operator</u>

Following the filtering routine is the Teager energy operation. The Teager energy processing is part of the enhanced signal processing strategy discussed in Chapter 3. The discussion of the theory for the Teager energy operator is delayed until Chapter 3, when the enhanced signal processing strategy is discussed.

<u>Autocorrelation</u>

Autocorrelation calculations are performed on the eager energy signal. Discussion of use of autocorrelation is also done in Chapter 3, because autocorrelation is a part of the enhanced signal processing strategy.

<u>Figure of Merit</u>

A figure of merit is calculated for each heart rate corresponding to each peak in the autocorrelation signal. The figure of merit is used to determine the best heart rate from many heart rate candidates in each channel and the best heart rate from all seven channels. The higher the value of the figure of merit the more confidence there is in the corresponding heart rate. There are two primary factors that contribute to the figure of merit. The first factor is the size of the peak in the autocorrelation result. The second factor of the figure of merit is the deviation of the rate candidate from the average heart rate. The average heart rate is a weighted combination of previously detected heart rates:

$$\overline{Rate} = \frac{1}{N_R}\sum_{i=1}^{N_R} Rate(i) * Merit(i) \, , \tag{2-4}$$

where the weighting factor is the merit of each heart rate and N_R is the number of previous heart rates to average over. The merit calculation combines the two factors mentioned above into one equation:

$$Merit = \frac{R_a(k)}{R_a(0)}(1.0 - \overline{Merit} * \frac{\left|Rate - \overline{Rate}\right|}{\sigma_R}), \tag{2-5}$$

where σ_R is the rate deviation, $R_a(k)$ is the autocorrelation value, and $R_a(0)$ is the energy of the signal which normalizes the autocorrelation values between 0 and 1. The average merit and average heart rate were typically calculated over 2.5 seconds of past merits and heart rates. To determine the reliability of the final detected heart rate of all seven channels a nominal threshold was used. If the figure of merit for the final detected heart rate was above the nominal threshold, then the FHM system has "confidence" in the FHR. Conversely, if the figure of merit was below the threshold then the heart rate was considered unreliable, which is called a "drop-out".

2.3.4 PC-ELF Communication

Every half second a fetal heart rate is detected by code on the Elf board and sent to the PC for display. There must be communication between the Elf board and the PC since the ELF code computes the FHR and PC displays it. Two basic ways to implement this communication are polling and direct memory access (DMA). The DMA method of communication runs in parallel with the signal processing on the ELF board. The DMA transfer method is much faster for transferring blocks of data. However, polling is used for synchronization between the PC and the ELF. Polling occurs when the PC (or ELF) sends a command to the ELF (or PC) and waits for a response before continuing. The digital acoustic heart beat signal is passed from the ELF to the PC via DMA transfer. The digital acoustic heart beat signal is passed to the PC for displaying in an oscilloscope mode and saved to a file (*.wav) for post-analysis. The detected fetal heart rates and keyboard commands are transferred through polling techniques. The detected fetal heart rate is passed from the ELF to the PC every 0.5 seconds. The keyboard command register, shown in figure 2-5, is passed from the PC to the ELF every 0.5 seconds. The keyboard command register is used to change the signal processing options on the ELF board. One example is the digital filter could be changed from a band pass of 20-50 Hz to a band pass of 9-50 Hz. The structure of the keyboard command register is given in figure 2-5. The options in the keyboard command register are changed through keyboard input by the FHM user.

Adding Commands to Keyboard Command Register

Adding commands to the keyboard command register is important to allow more

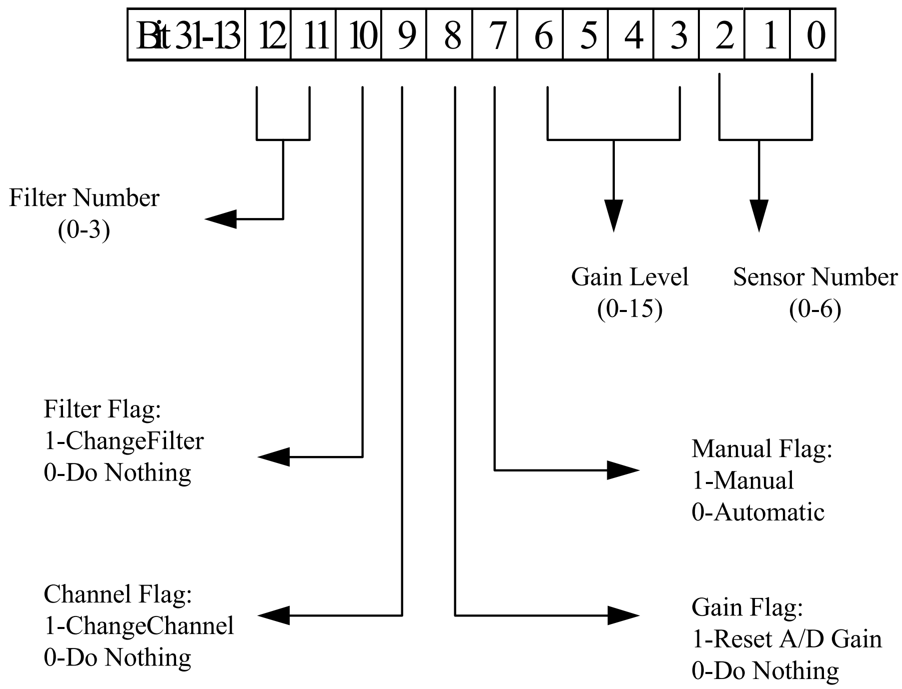


Figure 2-5 Keyboard Command Register

flexibility to the FHM system. The keyboard commands are the only way to change the signal processing on the Elf board during real-time operation. The keyboard commands are conveniently set up to change commands in a circular fashion over a range of pre-set values. For example, there are four filter options in the following order with there index value given in parenthesis: 16-50 Hz (0), 20-50 Hz (1), 25-50 Hz (2), and filter off(3). Each time the "S" key is pressed the filter index is incremented by one and the change filter flag (bit 10 of command register) is set to 1. The Elf code reads bits 11 and 12 to determine the index of the new filter setting then resets the change filter flag to 0. The new filter settings are used until the change filter flag becomes set to 1.

The first step in adding a keyboard command is choosing the mode for which the command will be available. Next, a key on the keyboard must be selected to represent the command. The program running on the PC side must be modified to check if this new key has been pressed under the correct menu option. If the key has been pressed, a flag bit for the new command should be set to 1. Code on the Elf side should be added to check if the new flag has been set. If the new flag has been set then action must be taken accordingly in the Elf code.

2.4 Literature Review

The fetal heart signals obtained through passive acoustic methods are extremely noisy, which greatly increases the difficulty of the signal processing task. Some of the noise sources are as follows: movement of mother, mother's heart beat, and environmental noise. Because of this noise problem, standard autocorrelation methods alone are not capable of determining the period of the fetal heart signal reliably. As discussed in Chapter 2 section 2.3.3, the Teager energy operator was combined with the autocorrelation method in previous work. However, since this previous method still made no attempt to specifically make use of a template corresponding to the fetal heart waveform, (i.e., no "signature" matching), the method was still quite susceptible to noise.

Phase three, the current phase, of the FHM project began with a library search for signal processing techniques which attempted to make use of the wave shape of the fetal heart signal. The topics selected for investigation were matched filtering, quadratic energy detectors, and linear predictive analysis. The quadratic energy detector and linear predictive analysis are discussed below. Matched filtering, which was the only one of these three techniques which was found to be effective enough to warrant implementation in the real-time system, is discussed in Chapter 3. The other two techniques, although not judged to be good enough for implementation, are documented in this chapter to help prevent unwarranted duplication of previously attempted strategies in the future.

2.4.1 Quadratic Energy Detectors

Quadratic energy detectors are linked to quadratic time-frequency representations. The quadratic energy detector has resolution advantages in terms of simultaneous frequency selectivity and temporal resolution over linear detectors [6]. It is difficult to analyze systems with arbitrary nonlinearities; however, systems which have quadratic operators are manageable to analyze. The quadratic energy detectors incorporate frequency filtering with energy detection, which would seem to be an ideal approach for the filtering and energy detection in the acoustic FHM system. The formulation of the quadratic energy detector and results of using the quadratic energy detector for fetal heart rate detection are given below.

The formulation of the quadratic energy detector begins with the linear energy detector. The linear energy detector consists of a linear time-invariant (LTI) filter followed by a magnitude squared operation. Because of the LTI filter in the linear energy detector a trade-off between time and frequency resolution must exist.

The linear energy detector is described by the following equation:

$$E_L[n] = \left| \sum_k x[n-k] h_L[k] \right|^2 \tag{2-6}$$

where $E_L[n]$ is the energy of the signal and $h_L[k]$ is the impulse response of a linear filter. For a real signal equation 2-6 can be generalized as

$$E_G[n] = \sum_k \sum_l x[n-k-l] x[n-k+l] h_L[k+l] h_L[k-l], \tag{2-7}$$

where $h_L[k+l]\, h_L[k-l]$ is a separable kernel of the general class $h_G[k,l]$ [6]. One interesting case where $h_G[k,l]$ is not separable is when $h_G[k,l] = \delta[k]h[l]$ and $\delta[k]$ is the unit pulse function, which results in the quadratic energy detector [6]. The equation for the quadratic energy detector is given as follows:

$$E[n] = \sum_{m=0}^{M-1} x[n+m] x[n-m] h[m] \tag{2-8}$$

where $h[m]$ is an M-point set of quadratic filter coefficients. The Teager energy operator is derived from the quadratic energy operator by setting M equal to 2, set h(0) equal to 1, and set h(1) equal to -1 in equation 2-8.

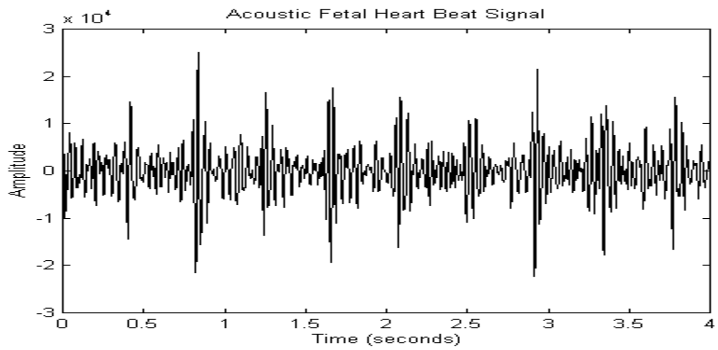
The quadratic energy detector was tested with some pre-recorded fetal signals. The idea was to process the fetal signals with the quadratic energy detector to enhance the fetal heart beats. The $h[m]$ "filter" was chosen to match the time waveform of an "ideal" fetal heart rate signal. The off-line testing was performed using MATLAB. The fetal signals were buffered into 4 second frames, like the one shown in panel a of figure 2-6. A 30 point quadratic energy detector was calculated over each frame (result in panel b of figure 2-6).

The 30 filter coefficients, chosen to match the time waveform of an ideal fetal heart beat signal, are shown in panel c of figure 2-6.

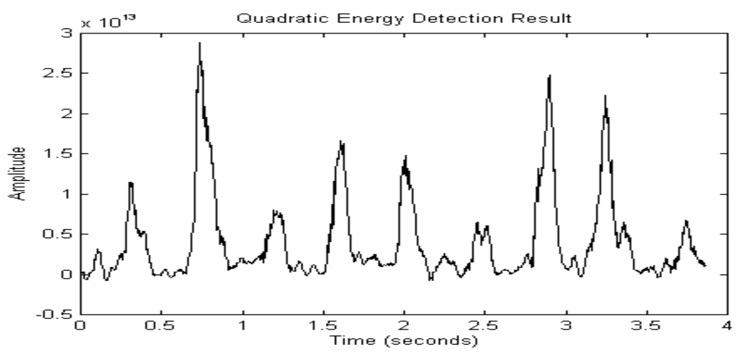
From the Matlab tests, the quadratic energy detector did not appear to be an improvement over the method of combining the Teager energy operator and autocorrelation as discussed previously. The quadratic energy detector was able to successfully detect the energy in the signal but was not able to increase the SNR any more than the previous signal processing method (in phase 2). In addition, the amount of time taken to compute the quadratic energy was found to be about a 100 times longer than the comparable calculation for the Teager energy (as per Matlab). There are more efficient quadratic energy detectors available; but, the general quadratic energy detector will always take more time than the Teager energy operator (a special case). Because of these considerations, the quadratic energy detector was not implemented for the real-time FHM system.

2.4.2 Linear Prediction

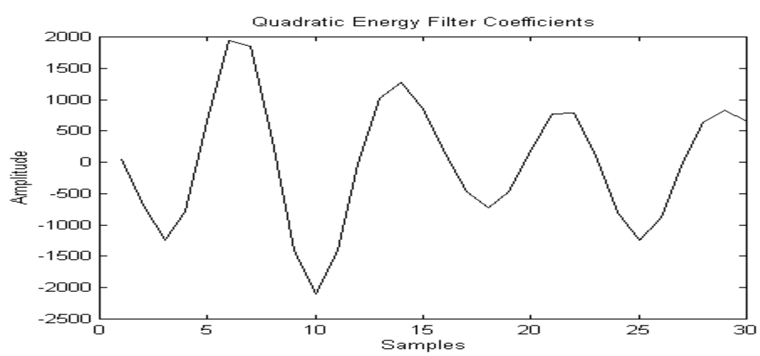
Linear prediction (LP) is commonly used in speech processing for modeling the vocal tract transfer function. Linear prediction can be used to aid in the determination of fundamental frequency of voiced sounds by using the inverse LP filter to remove the harmonic structure of the signal and only leaving periodic pulses. Alternatively, since the



Panel a



Panel b



Panel c

Figure 2-6 A 30 Point Quadratic Energy Detection on a Fetal Heart Signal

LP model is a good approximation to the spectral envelope, it forms a type of IIR matched filter. It was this latter approach that was investigated in this project.

Linear prediction analysis techniques were first reported in 1976. Linear predictive coding (LPC) is mathematically simple and straight forward to implement. The definition of LPC is as follows: a given signal sample at time *n* can be predicted, or approximated, by a linear combination of the past *p* samples of the signal [5]. Hence the name linear prediction. The following equation is used to define linear prediction mathematically:

$$\tilde{s}(n) \approx a_1 s(n-1) + a_2 s(n-2) + \ldots + a_p s(n-p), \qquad \text{(2-9)}$$

where $\tilde{s}(n)$ is the signal sample at time *n*, and a_i's are the linear prediction coefficients. To make the above equation an equality an excitation source needs to be taken into account. The following equation results when an excitation source is added to equation 2-9:

$$s(n) = \sum_{i=1}^{p} a_i s(n-i) + Gu(n), \qquad \text{(2-10)}$$

where u(n) is the excitation source and G is the gain factor. By taking the Z-transform of both sides of the above equation and rearranging the terms, the following transfer function results:

$$H(z) = \frac{S(z)}{GU(z)} = \frac{1}{1-\sum_{i=1}^{p} a_i z^{-i}} = \frac{1}{A(z)}. \qquad \text{(2-11)}$$

The system defined by 2-11 is an all-pole system, known as an autoregressive model.

Next, the method for determining the LP coefficients is summarized. The LP coefficients are calculated by minimizing the mean square error of equation 2-12. The error equation is given as follows:

$$e(n) = s(n) - \tilde{s}(n), \qquad (2\text{-}12)$$

Using the method of least squares to solve for the LP coefficients allows the signal spectrum to be matched with a model spectrum. The following equation is solved to determine the LP coefficients from a frame of the signal:

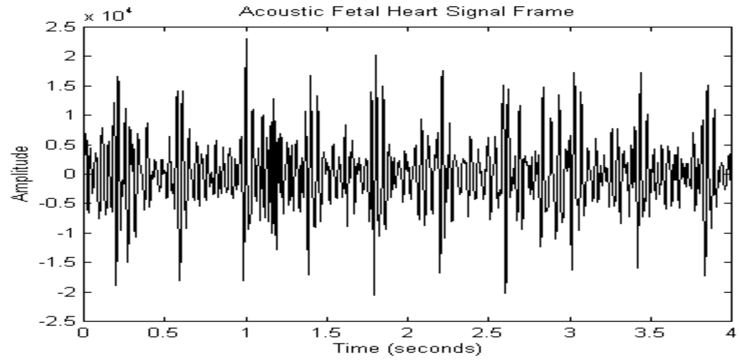
$$\begin{bmatrix} R(0) & R(1) & \cdots & \cdots & R(p-1) \\ R(1) & R(0) & \ddots & & \vdots \\ \vdots & \ddots & & \ddots & \vdots \\ \vdots & & \ddots & & R(1) \\ R(p-1) & \cdots & \cdots & R(1) & R(0) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ \vdots \\ a_p \end{bmatrix} = \begin{bmatrix} R(1) \\ R(2) \\ \vdots \\ \vdots \\ R(p) \end{bmatrix}, \qquad (2\text{-}13)$$

where R(i) represents the i^{th} term of the autocorrelation result and the a_i's represent the LP coefficients.

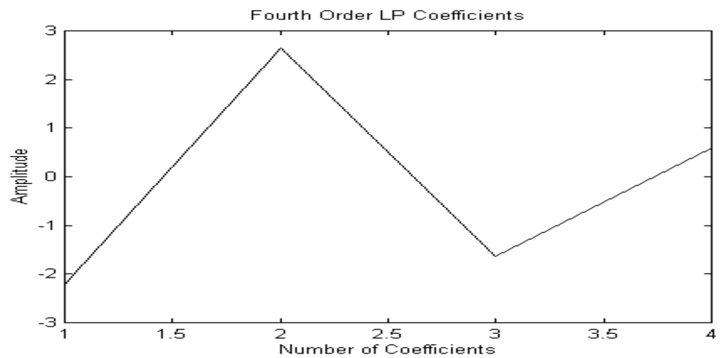
Experimental Test

As mentioned above, in this study LP coefficients were used as an IIR matched filter. That is, after calculation of the LP filter from "good" sections of the signal, Equation 2-10 was used to filter the signal with the intention of improving the signal-to-noise ratio. Equation 2-10 was implemented using Matlab to process pre-recorded fetal heart signals. Panel a of figure 2-7 shows a 4.0 second frame of an acoustic fetal heart beat signal. Panel b of figure 2-7 shows the LP coefficients for the frame with p=4. Panel c of figure 2-7 shows the result of filtering the frame in panel a using equation 2-10. Figure 2-8 shows the impulse response h(n) ($=Z^{-1}\{H(z)\}$) from equation 2-11, the magnitude spectrum of H(z), |H(z)|, and the magnitude spectrum for the fetal signal displayed in panel a of figure 2-7. Notice in panel b and panel c of figure 2-8, the spectrum of H(z) is an envelope of the signal spectrum. This means the h(n) coefficients match the frequency domain waveshape of the fetal heart signal.

Many test were performed with different LP coefficients. A LP order of 4 was considered the best because the spectral shape matched the general shape of the spectrum of the acoustic signal. One major problem with the LP analysis was that the computation of the LP coefficients was very time consuming, even for a fourth order linear predictor. The LP IIR filter was combined with autocorrelation and the Teager energy operator for off-line FHR detection in Matlab. Although, the LP IIR filter appeared somewhat promising, the computational difficulties mentioned above again made this a poor candidate for inclusion in the real-time implementation. However, as mentioned in the next chapter, a similar approach, but using a simpler FIR filter was implemented



Panel a



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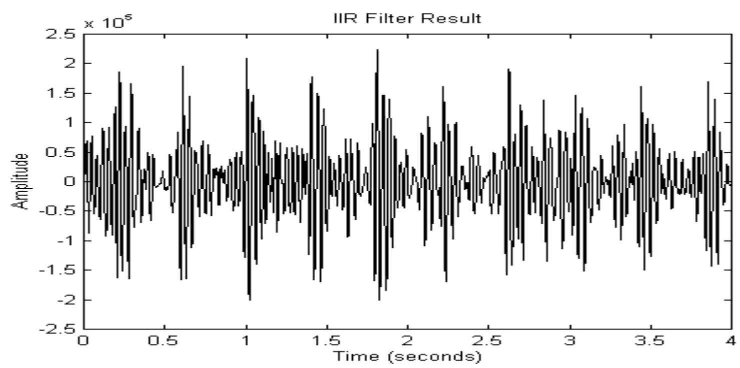
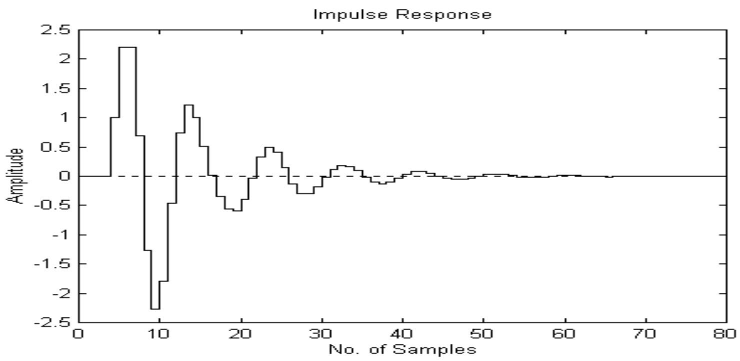
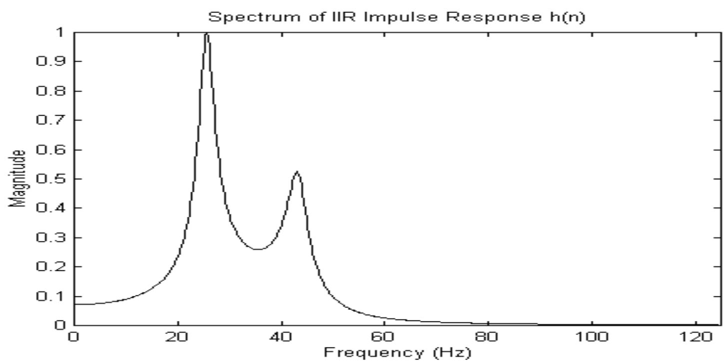


Panel c

Figure 2-7 IIR Filter Result



Panel a



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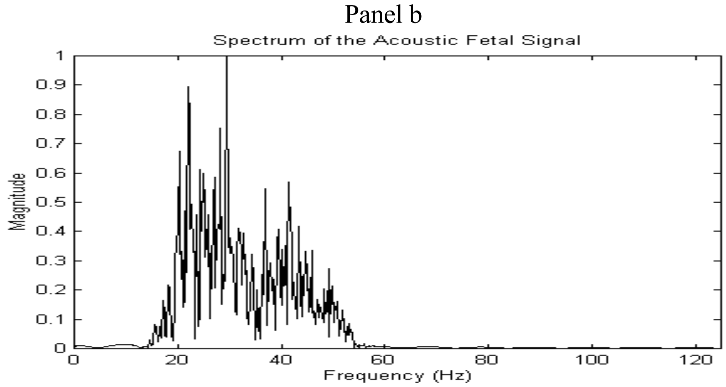


Panel c

Figure 2-8 IIR Filter Impulse Response h(n) and H(z)

Chapter 3

ENHANCED SIGNAL PROCESSING STRATEGY

3.1 Introduction

This chapter discusses the enhanced real-time signal processing strategy implemented for the final real-time acoustic FHM system. As mentioned in the previous chapter, matched filtering was considered to be the most feasible preprocessing step to improve noise immunity. In addition, based on several Matlab simulations, it was observed that the periodic component of the fetal signal appeared to be emphasized if the Teager energy and autocorrelation operations were reversed. Note that because of the nonlinear operation, these two operations are not commutative, and are also difficult to analyze using standard linear system theory tools. Thus two similar versions of an algorithm were implemented in the acoustic FHM system as shown below in figure 3-1, and investigated using empirical methods. In figure 3-1, the x[k] are the samples of the acoustic fetal heart signal, and y[k] are the samples from which the fetal heart rate is computed.

The organization of this chapter is as follows. Section 3.2 discusses theory for the Teager energy operator, autocorrelation, and matched filter, the main components of the enhanced signal processing strategy in the FHM. Section 3.3 gives the details for

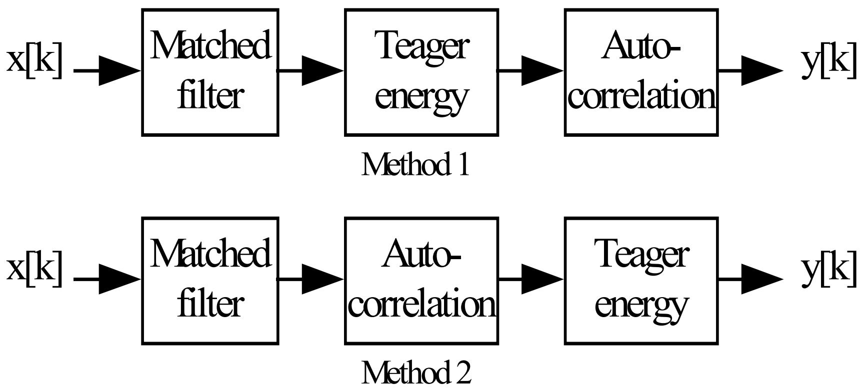


Figure 3-1 Flow diagram for Signal Processing Implemented in Real-time

implementing the two algorithms shown in figure 3-1 and illustrates results obtained with each method.

3.2 Theoretical Background

The theoretical background for the enhanced signal processing strategy is given in this section. The topics discussed are matched filtering, the Teager energy operator, and autocorrelation. Reviewing the concepts for these techniques helps to motivate and explain the overall enhanced signal processing strategy which combines these three methods.

3.2.1 Matched filtering

Matched filtering is a technique commonly used to detect recurring time signals corrupted by noise. The underlying assumption in matched filtering is that the time signal has a known wave shape. Matched filtering then maximizes the SNR at the output by enhancing this known signal while suppressing the noise. The matched filter is typically represented as a finite-impulse response (FIR) filter. The equation for a FIR filter of order N is given below.

$$y(n) = \sum_{k=0}^{N-1} h(k) * x(n-k) \tag{3-1}$$

In equation 1, the h(k)'s are the matched filter coefficients which ideally correspond to a time-reversed version of the wave shape of the input signal. The x(k)'s are the samples from the fetal heart signal and the y(k)'s are the enhanced fetal heart signal (i.e., the output of the filter).

There are two difficulties with using a matched filter in the FHM. The first (and most fundamental) problem is that the actual wave shape of the fetal heart beat signal is not known. Secondly, all calculations for the FHR detection algorithm, including equation 3-1 must be performed in real-time, thus preventing the use of a high order filter.

Because the actual wave shape of the fetal heart signal is not known, estimation of the wave shape of the fetal heart signal is necessary. This estimation problem was solved using frequency domain techniques. In particular, a distinctive magnitude frequency wave shape is apparent for “good” sections of the fetal heart signal. This pattern is shown in panel b of figure 3-3. As is well known from Fourier and signal processing theory, the envelope of this pattern represents the transform of the basic waveshape, whereas the fine details are related to the periodic nature of the signal. Therefore a good estimate of the time domain waveshape corresponding to the fetal heart tone can be obtained from the low-ordered terms in an inverse FFT of this magnitude spectrum.

Based on the discussion of the previous paragraph and real-time limitations, the following algorithm was developed for computing the matched filter coefficients in the real time system.. First, for each “good” frame of data (as determined by the figure of merit previously mentioned), the magnitude spectrum is computed using a 1024-point fast Fourier transform (FFT) of the fetal signal. The actual matched filter is comprised of the low-order 49 points of a 1024-point inverse FFT of this magnitude spectrum. Since the wave shape of the fetal heart signal would not be expected to change very rapidly, the matched filter coefficients are not computed every 0.5 seconds. Instead, for good sections of the fetal heart signal, the spectrum for each frequency sample is averaged over time with a 1-pole IIR filter (with a coefficient of .85). The filter coefficients obtained from the inverse FFT of this time-averaged spectrum are also only updated in good sections of the fetal heart signal to eliminate unnecessary calculations, and also to prevent high noise regions of the signal from corrupting the filter estimate. The matched filtering of the fetal signal is accomplished with the most recent set of filter coefficients. In effect, the matched filter response is slowly adapted to the fetal signal over a period of several seconds. This estimation process for computing the matched filter coefficients, h(k), is illustrated in figure 3-2.

To illustrate the process of estimating the matched filter coefficients, figure 3-3 shows the result after each step of the algorithm shown in figure 3-2. In panel a of figure 3-3, a "good" frame of the fetal heart signal is shown. Panel b shows the average magnitude spectrum of the fetal signal as the solid line. The matched filter coefficients are displayed in panel c. Panel d shows the inverse fourier transform result. The spectrum of h(k), which is shown as the dashed line in panel b, is a good match to the envelope of the spectrum of the fetal heart signal. Thus the matched filter coefficients, h(k), represent the approximate fetal heart beat pulse shape. Note this matching is only approximate, because of the estimation process and the lack of use of phase information. Pilot experiments with off-line pre-recorded data indicated that the difficult phase estimation step did not result in much improvement. Therefore the implemented matched filter was designed only to match in terms of the magnitude spectrum.

The second constraint for using a matched filter in the FHM system is the real-time consideration. Equation 3-1 is the matched filter equation implemented in the FHM system. The frame length in the fetal heart rate monitoring system is typically 4.0 seconds

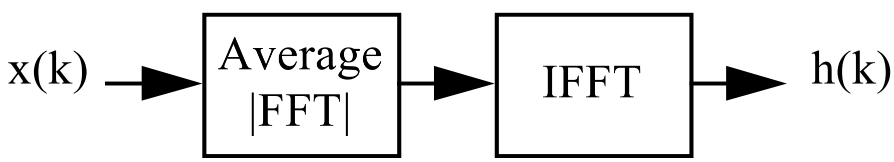
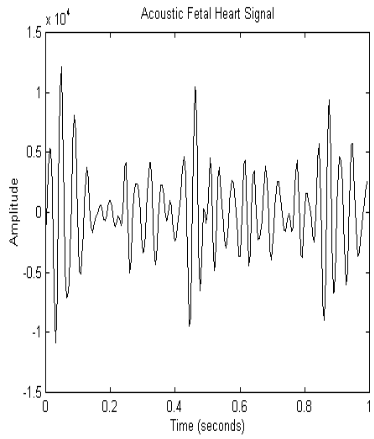
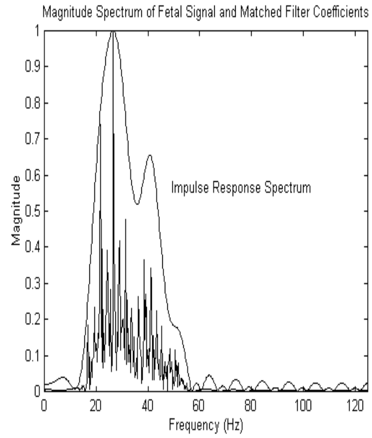


Figure 3-2 Estimation of Matched Filter Coefficients



Panel a



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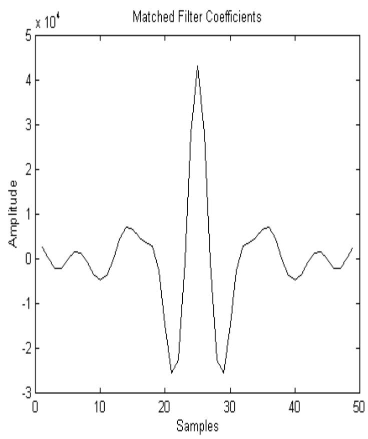

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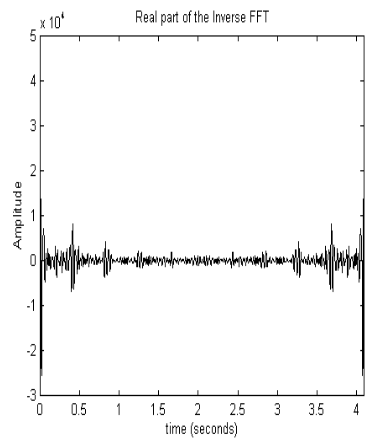


Panel d

Figure 3-3 Matched Filtering Results

with a sampling frequency of 250 Hz. This implies there are 1000 points of the input signal (N=1000) used for matched filtering of each frame. The matched filtering is also done for all seven channels of data. A filter order of 49 was chosen as a compromise between accuracy and these real-time considerations. By reducing the filter order, the calculation time for the matched filter is reduced.

3.2.2 Teager Energy Operator

In order to make the best estimate of fetal heart rate, it is important to identify or emphasize the individual fetal heart beats. The fetal heart beats are seen as areas of local high energy in the fetal heart signal (see figure 2-1). A non-linear operator designed to enhance areas of local high energy is the Teager energy operator proposed by James F. Kaiser [3]. The following equation is used to describe the Teager energy operator:

$$E(n) = s^2(n) - s(n-1) * s(n+1) \;, \tag{3-2}$$

where E(n) represents a measure of the Teager energy at time n, s(n), s(n+1), and s(n-1) are the values of the signal being processed at time n, n+1, and n-1 respectively. When s(n) is greater than s(n-1) and s(n+1) the Teager energy operator will give a large output relative to the signals s(n-1) and s(n+1). A problem with using the Teager energy operator is that noise bursts are enhanced along with the fetal heart tones. However, by combining the Teager energy with matched filtering, as just described, and with autocorrelation calculations, as described in the next section, the fetal heart beats can be enhanced and the noise reduced.

3.2.3 Autocorrelation

In order to determine the period of noisy semi-periodic signals, autocorrelation techniques are commonly used. Autocorrelation emphasizes the periodic components in the fetal heart signal while reducing the non-periodic components. This method works provided that the period of the input signal is approximately stationary over the period of the calculation. A frame length of 4.0 seconds is typical for the FHM system and is short enough that the period of the signal is generally stationary. The autocorrelation is computed as follows:

$$R_a(k) = \sum_{n=0}^{N-k-1} E(n) * E(n+k), \tag{3-3}$$

where E(n) is the signal to be processed and R(k) is the autocorrelation result. In equation 3-3, N is the frame length and k is the time shift. The autocorrelation depends on time differences only, and not time itself. For typical fetal heart tones the longest expected period is 1.5 seconds which corresponds to 90 BPM. For slowly varying fetal heart rates a long autocorrelation window is desired for optimal tracking of the fetal heart rates. On the other hand, rapidly varying fetal heart rates should be computed with a short autocorrelation length. In this work, although a real-time adjustable frame length (increasing the frame length for slow varying heart rates and decreasing the frame length for accelerations and decelerations in the heart rate) was investigated with Matlab, for the final implementation a fixed frame length of 4.0 seconds was used. For periodic signals, $R_a(k)$ is maximum if k is equal to a multiple of the period. If the fetal signals were the only periodic source, autocorrelation alone could be used to determine the fetal heart rates. However, periodic noise does corrupt the fetal heart signal leading to peaks in the autocorrelation result that due not correspond to the FHR. The fetal heart rates are calculated from peaks in the autocorrelation as follows:

$$FHR = \frac{Fs * 60}{k} BPM, \tag{3-4}$$

where Fs is the sampling frequency and k is the lag index of the autocorrelation peak. The number 60 in equation 3-4 is used to convert seconds to minutes. Additional processing, using the figure of merit as described in Chapter 2 was used to separate FHR peaks from spurious peaks.

3.3 Comparison of Method 1 and Method 2

This section explains two similar methods tested in the real-time FHM system. The flow diagram for each method is shown in figure 3-1. Both method 1 and method 2 begin with a matched filter. The matched filter is used to increase the SNR, which is important for detecting the period of the fetal signals using autocorrelation techniques. Method 1 uses the Teager energy operator followed by autocorrelation. The rationale for method 1 is that the Teager energy operator would further enhance the fetal heart beats and that the autocorrelation method would be used to determine the FHR, as for any periodic source. For Method 2 , the overall autocorrelation signal, which increases the SNR by suppressing the non-periodic noise in the fetal heart signal, is used prior to the Teager energy calculations. The Teager energy operator is used after the autocorrelation to further enhance peaks and slightly smooth the autocorrelation result. The final step is the same peak picking procedure as was used for method 1. Each method is discussed and illustrated in more detail below.

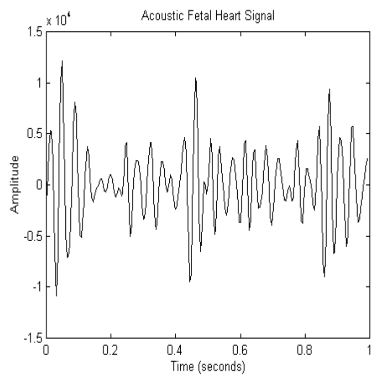
3.3.1 Method 1

Typical results obtained using the first method described in the top of figure 3-1 are illustrated in this section. A 4.0 second frame of the fetal signal is shown in panel a of figure 3-4. The frame of data is then matched filtered to increase the SNR. The matched filter result is given in panel b and the filter coefficients are shown in panel c. The matched filtered signal is then processed by the Teager energy operator and shown in panel d. The peaks in panel d line up with the fetal heart beats shown in panel a. Notice that the peaks are enhanced and the noise is reduced in panel d. Next the autocorrelation is computed and the fetal heart rate determined. The fetal heart rate is determined using the figure of merit discussed in section 2.3.3. The autocorrelation output is illustrated in panel e of figure 3-5. From the autocorrelation result it is clear the largest peak occurs at a lag index of 100. Using equation 3-4 with a sampling frequency of 250 samples per second, the fetal heart rate is 150 BPM.

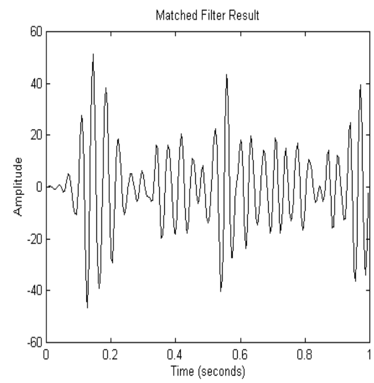
3.3.2 Method 2

The same patient file was used for method 2 as in method 1. The results from the method 2 algorithm is shown in figure 3-5. The same matched filter coefficients and matched filter results were obtained. Therefore panels a, b, and c of figure 3-5 are the identical for method 2. For this method, the autocorrelation is computed after the matched filtering. Notice the x-axis is still labeled in units of lag indexes and the fetal heart rate is calculated from the lag index of the “best” peak. The “best” peak is determined from the figure of merit for that peak. The “best” peak occurs at a lag index of 100. Using equation 3-4 with a sampling frequency of 250 Hz, the fetal heart rate is calculated as 150 BPM.

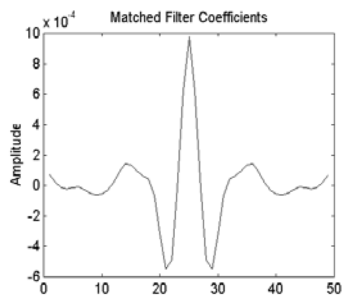
Both methods worked well in the two experiments described above. In both cases the fetal signal extracted was a good record of the fetal heartbeat. Both methods produced the correct fetal heart rate of 150 BPM (the baseline fetal heart rate from the



Panel a



Panel b



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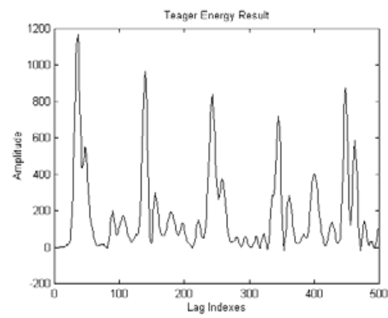

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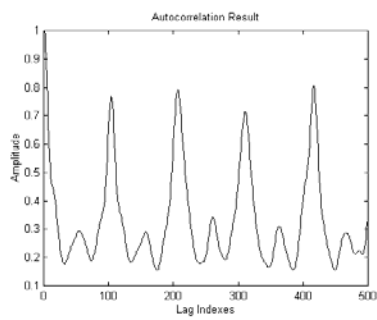
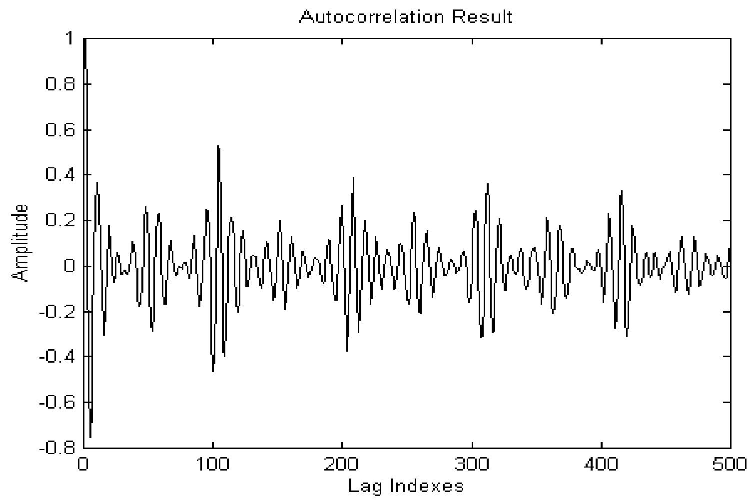
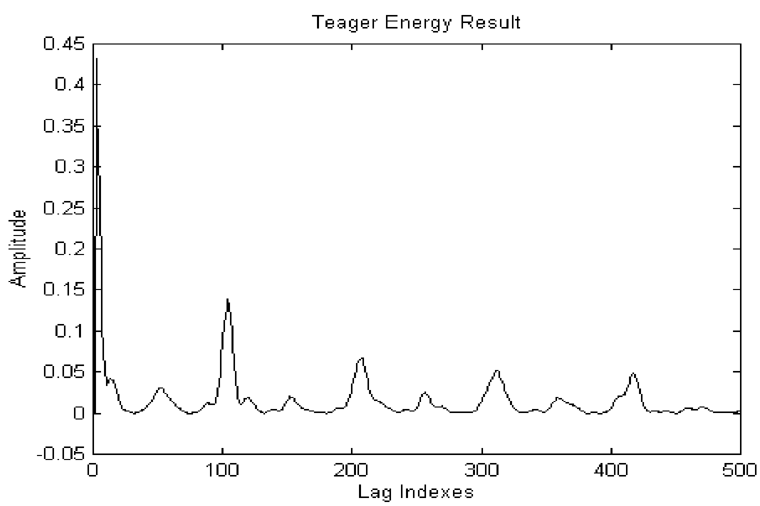


Panel e

Figure 3-4 Method 1 Results



Panel a



Panel b

Figure 3-5 Method 2 results

ultrasound recording). In order to have a better comparison both methods were implemented in real-time on 18 minutes of fetal data. A fetal heart rate trace was produced for each method and the ultrasound record of the same patient is shown. Notice both method 1, illustrated in figure 3-6, and method 2, illustrated in figure 3-7, have the same baseline which agrees with the ultrasound recording obtained from the same patient only 30 minutes prior the acoustic fetal heart beat recording. The ultrasound chart is shown in figure 3-8.

3.4 Conclusion

Based on a detailed comparison of prerecorded fetal data, method 1 appeared to be more reliable than method 2. It was not evident from looking at good frames of data which method was superior. Both methods worked well for the good frames of data. The relatively flat sections in the fetal heart trace shown in figures 3-6 and 3-7 are considered to be the good sections of the fetal heart signal. A typical fetal heart trace contains sections of accelerations and decelerations in the fetal heart rate (see figure 3-8). The algorithm for method 2 did not track the fetal heart rate during the accelerations in the fetal heart rate as well as the procedure of method 1.

The superiority of method 1 was apparently related to the normalizing effect of using autocorrelation as the last step of the process, thus easing the problem of setting a threshold for peak picking, as required in this procedure. Because of the importance of the accelerations and decelerations of the fetal heart rate method 1 was chosen as the better of the two algorithms discussed in this report, and has been implemented in the most recent version of the real-time FHM system (as of December 1995).

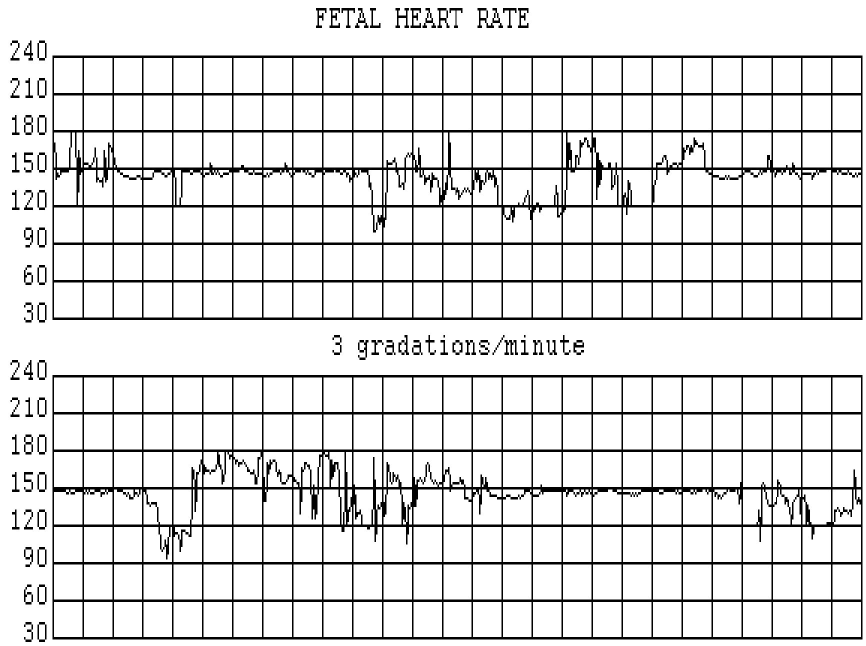


Figure 3-6 FHR Trace using Method 1

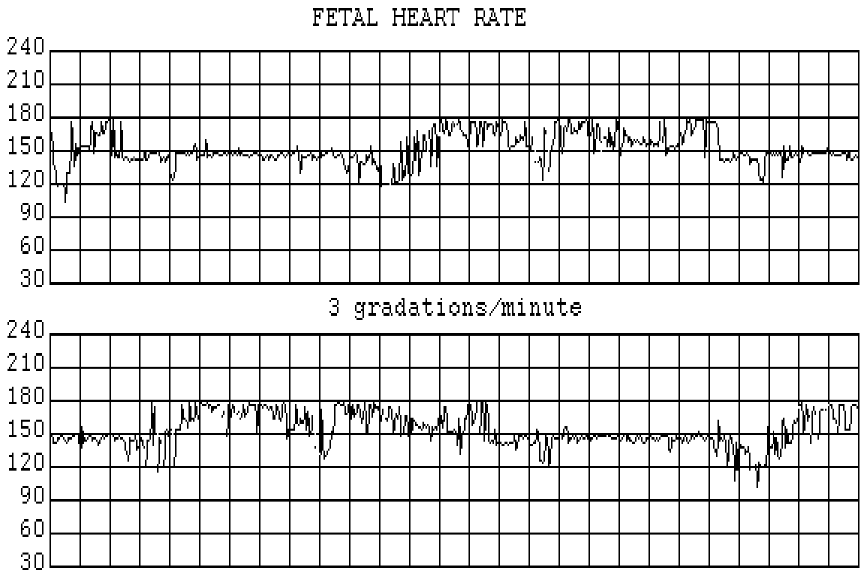


Figure 3-7 FHR Trace using Method 2

Figure 3-8 Ultrasound Fetal Heart Rate Chart

C h a p t e r   4

FHM REAL-TIME REFINEMENTS

4.1 Introduction

To improve the value of the FHM system, many refinements were made. As discussed in the last chapter, the major focus of this work was to develop signal processing for improved accuracy of FHR calculations. The improvements discussed in this chapter, some at the requests of the nurses and doctors using the FHM system, also improve the usefulness of the FHM system. The key refinements discussed in this chapter are audio feedback enhancements, fetal heart rate range selection, and a real-time fast-fourier transform (FFT) option.

4.2 Audio Feedback Enhancement

Per request from the medical community, an audio output option was made for the FHM system. The main purpose of this option was to provide a convenient monitoring method for users of the system to aid in positioning the FHM sensor belt on the mother's abdomen and to insure that a reasonable signal was being acquired by the sensors.. In order to maximize the likelihood that the belt would be positioned so that the center sensor would be positioned over the strongest fetal signal, the center sensor was used for the audio feedback signal. If the fetal heart signal were originally centered on the belt, movements of the fetus, which are very common, would still be likely to result in fetal signals which could be monitored by the outer acoustic sensors. Chapter 2 , section 2.2.1, gives some additional explanation of the arrangements of the sensors to allow for movements of the fetus.

The fetal heart signal from the middle sensor (labeled as sensor 1) , is processed and then output via the Elf digital to analog converter to the front-end electronics box. The signal is then amplified with an integrated circuit audio amplifier circuit and connected to a speaker. As mentioned before, after filtering, the data had an effective sampling frequency of 250 Hz. However, the minimum sampling frequency for the ELF D/A is 8000 Hz. Therefore, a digital zero order hold (ZOH) of 32 points was implemented in software on the ELF board to give the data an effective sampling rate of 8000 Hz.. After the ZOH, a low pass digital filter was used to smooth the discontinuities created by the ZOH. However, since most of the energy of the fetal signal is below 50 Hz, this signal is still be below the audible range for most people.

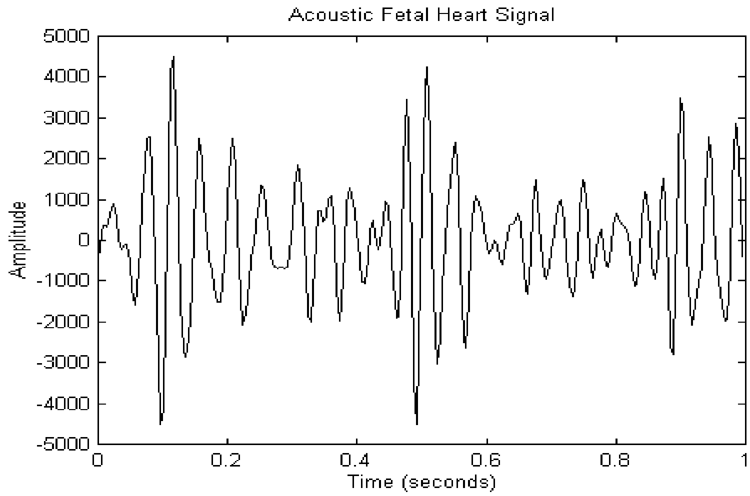
Therefore, frequency modulation was used to translate the frequency of the fetal heart tones to a higher frequency. By increasing the frequency of the fetal heart tones, the fetal heart beats became more audible. Frequency modulation translates the frequency of a signal to a higher frequency by multiplying the signal by a sine wave at the modulation frequency. Using pre-recorded fetal heart signals, the modulation frequency was determined experimentally by listening to the audio output for different frequencies. Experimentally, it was determined that a modulation frequency of 200 Hz resulted in the most “pleasant sounding “ heart beat sound.

In figure 4-1, an illustration of the acoustic fetal heart signal (panel a) is given as well as its frequency spectrum (panel b).. The result of the frequency modulation of the acoustic fetal heart signal is given in panel a of figure 4-2. The spectrum of the frequency modulated result is given in figure 4-2, panel b. The energy of the frequency-modulated signal is around 200 Hz, which produces a more audible fetal heart beat sound.

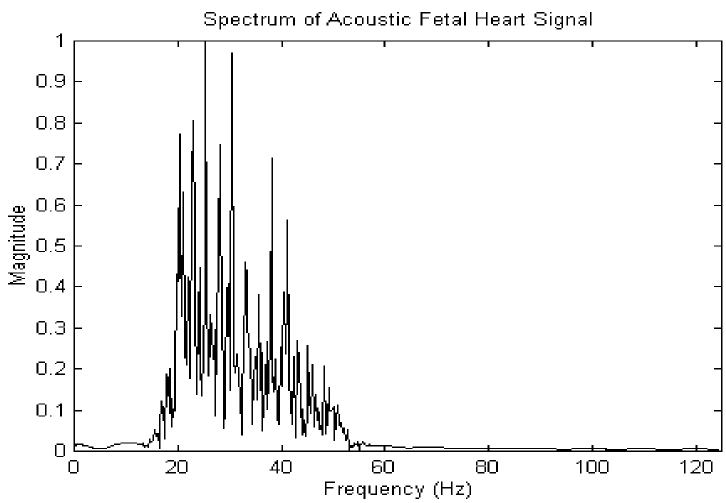
Although this method was found to work well for sections of good signals, and also for adults on whom the belt was tested, it was not found to be as useful in clinical tests, as described in the next chapter. This was thought to be a direct result of the poor quality signal generally obtained. However, it is anticipated that this option will be more useful after the initial signal quality is improved.

4.3 Fetal Heart Rate Range Selection

Due to real-time constraints, it was necessary to restrict the range (maximum and minimum BPM), over which the FHR was computed. Limiting the FHR range reduced the number of points in the autocorrelation buffer. The previous FHM software only allowed one FHR range during each test. This range was set by editing the FHM parameter file. For analysis and testing purposes, a real-time adjustable FHR range was important. During analysis, an adjustable FHR range was convenient to test the fetal heart rate detection algorithm over the full range, 30-240 BPM, without exiting the FHM software. For some high risk patients , fetal rates could drop below 90 BPM and rise above 180 BPM. The enhanced FHM program allows the user to change the FHR range in real-time by pressing the appropriate key on the keyboard.

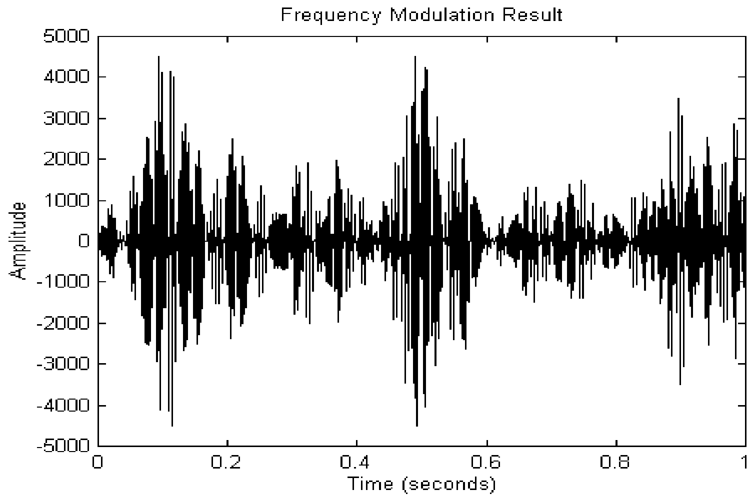


Panel a



Panel b

Figure 4-1 Acoustic Fetal Signal Before Frequency Modulation



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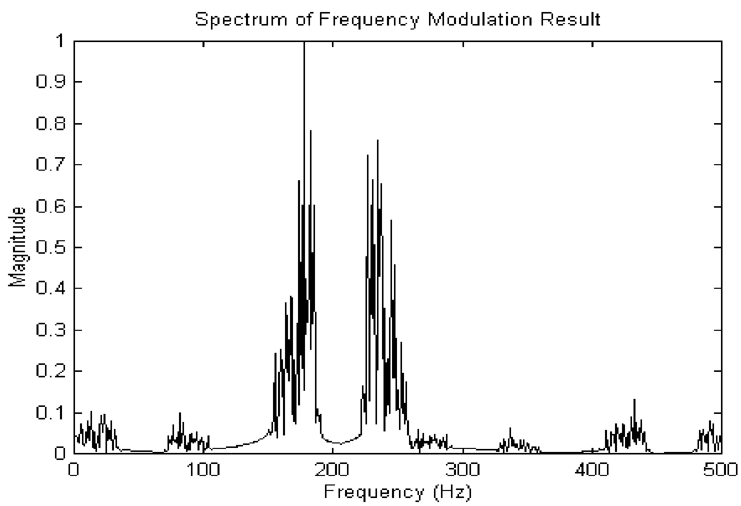


Panel b

Figure 4-2 Frequency Modulation Results

Using the automatic mode of the FHM software, there are four possible ranges. The default FHR range is the "normal" range (90-180 BPM). The other ranges are the "high" range (120-240 BPM), "low" range (50-90 BPM), and automatic range. In the automatic mode of the "Acoustic Unit Only" option in the FHM software, when the "r" or "R" (Range) key is pressed a message is sent to the Elf DSP subsystem telling the DSP subsystem to change the heart rate range. There are four different ranges to choose from, which are labeled 0 to 3 in the DSP subsystem. The default range is 0 (normal), each time the "r" or "R" key is pressed the next range is selected and highlighted. The four ranges are indexed in a circular fashion. The FHM user's guide, acoustic unit only option, in appendix A gives further details for selecting the FHR range.

A 32-bit command register is used for passing keyboard commands from the PC to the Elf DSP subsystem, which is shown below in figure 4-3. Zongyao Zhou's master's thesis, "Fetal Heart Rate Detection with a Passive Acoustic Sensor," Old Dominion University, May 1995, page 93, contains further information on the keyboard command register. Bits 0 to 12 in the command register were defined and explained in the description of phase 2 of the FHM project [1] (section 2.3.4). Bit number 13 is a flag sent to alert the Elf DSP system that the FHR range has been changed. Bits 14 and 15 of the command register hold the label, a value from 0 to 3, for the selected range. Once the Elf DSP system receives the new range label, the FHR_max and FHR_min are used to compute lag_min and lag_max. The FHR_max and FHR_min are the maximum and

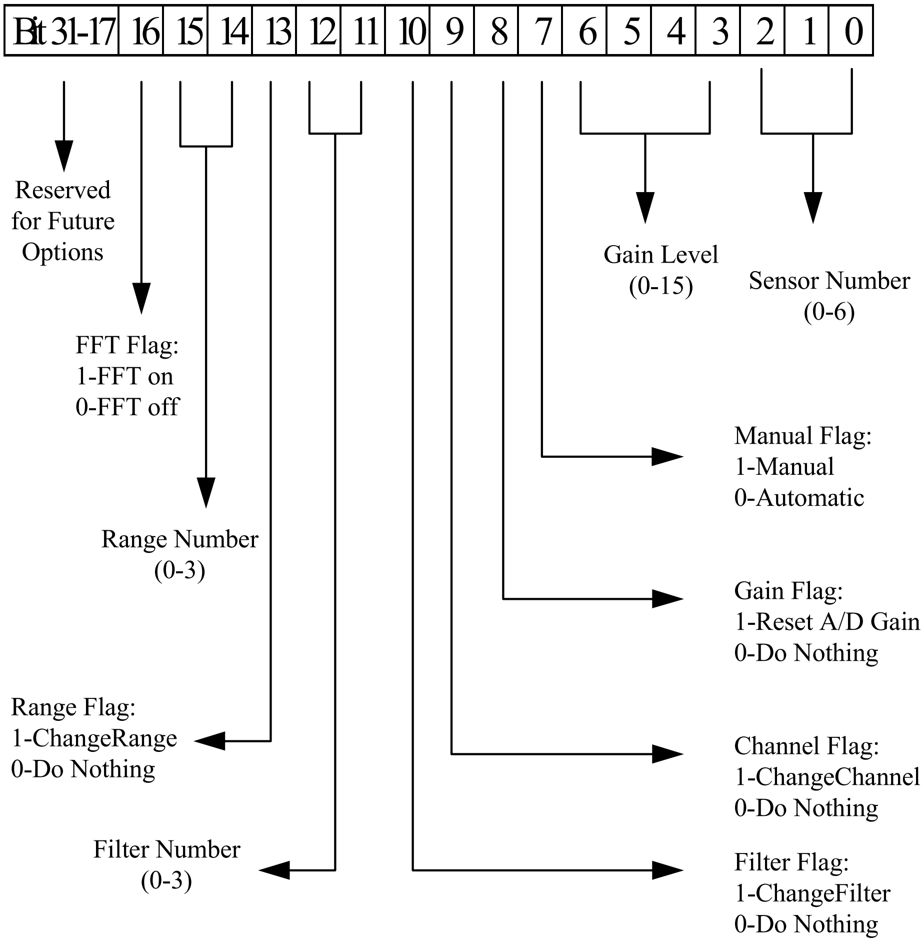


Figure 4-3 New Command Register

minimum fetal heart rates for the current FHR range. The values of lag_min and lag_max determine which range of autocorrelation points are used to compute the FHR.

Due to real-time constraints, the entire fetal heart rate range of interest, 30-240 BPM, could not be used to detect the FHR. As mentioned in section 3.2.3, the peaks in the autocorrelation buffer are used to determine the fetal heart rate. A "lag_max" and "lag_min" are associated with the minimum and maximum heart rates for the selected range as follows:

$$lag\_\max = \frac{Fs * 60}{FHR\_\min} \qquad lag\_\min = \frac{Fs * 60}{FHR\_\max} \tag{4-1}$$

where Fs is the sample rate (250 Hz), 60 is used to convert seconds to minutes, and FHR_min and FHR_max are the minimum and maximum fetal heart rates in the range. A heart rate range of 90-180 BPM would have a lag_min of 83 and a lag_max of 167. Limiting the heart rate range reduces the difference between lag_max and lag_min allows fewer autocorrelation points to be computed. Table 4.1 below gives some fetal heart rate ranges with corresponding lag indexes, the number of autocorrelation points computed, and the time taken to compute the autocorrelation points, where Fs = 250 samples per second.

Comment:

FHR_min (BPM)	FHR_max (BPM)	lag_max	lag_min	Autocorrelation length	Time (ms)
15	15000	1000	1	1000	33,300
30	240	500	62	439	6,366
90	180	167	83	85	238
50	90	300	167	134	592
120	240	125	75	50	83

Table 4.1 Autocorrelation Computation Time

As shown in table 4.1, by limiting the fetal heart rate range a large amount of time is saved because there are fewer autocorrelation points computed. The equation for computing the autocorrelation buffer is as follows:

$$auto\_cor[k] = \sum_{i=lag\_\min}^{i=lag\_\max} \Pr oc\_buf[i] * \Pr oc\_buf[i+k] \qquad (4\text{-}2)$$

where Proc_buf[i] is the processed fetal heart signal after the band-pass filter, matched filter, and Teager energy operator (in Method 1, section 3.3.1). The length of the Proc_buf[i] is 4.0 seconds. At the sampling rate of 250 Hz there are 1000 samples of data in Proc_buf[i]. For every point computed in the autocorrelation buffer, there are lag_max minus lag_min multiplies and accumulates and there are lag_max minus lag_min points in the autocorrelation buffer. With the ELF DSP subsystem used for this work (TMS320C31 based) one multiply and accumulate could be done in one clock cycle. One clock cycle took 33 micro-seconds for the processor used in this work. Therefore, the time taken to compute the autocorrelation is given by the following equation:

$$auto\_time = (lag\_\max - lag\_\min)^2 * 33 \times 10^{-6} \tag{4-3}$$

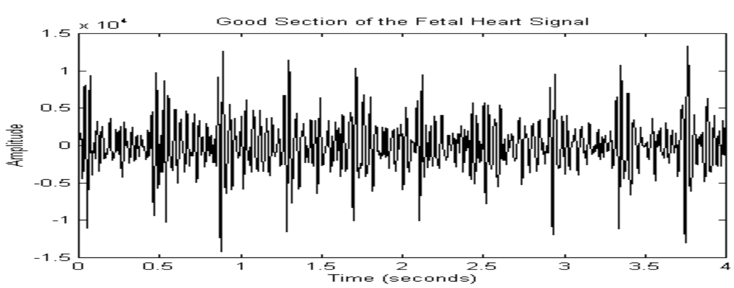
where auto_time is the time taken to compute the autocorrelation points of length lag_max minus lag_min. The values under the time column in table 4-1 above were calculated with equation 4-3. The importance of limiting the FHR range to save time is evident from table 4-1. If the range over which the fetal heart rates could be computed were not limited, the FHM system would not have worked in real-time.

Since the range (90-180 BPM) is the most common fetal heart rate range, it was chosen as the default range. A high and low range were included for special cases of fetuses with very low or very high heart rates. Also, an automatic range was implemented to allow tracking of heart rates with out manually changing the heart rate range. The automatic range is useful if the fetal heart rate is expected to exceed the bounds of a fixed limit range. For the automatic range, the lag_min and lag_max are adjusted in real-time based on the average heart rate. In order that the average heart rate be at the center of the range, the FHR_max and FHR_min are calculated as plus or minus 30 BPM from the average heart rate. Because the automatic range depends on the average heart rate as computed over a 10 second interval , the FHM system should be tracking the heart rate for at least 10 seconds before switching the fetal heart rate range to the automatic mode.

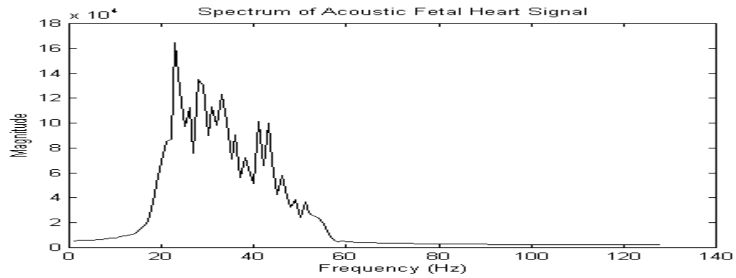
4.4 Real-time FFT Option

A real-time fast-fourier transform, FFT, was also added to the FHM system to allow analysis of the frequency domain characteristics of the fetal heart beats during real-time fetal monitoring. The general shape of the FFT signal, shown below in figure 4-4 panel b, was known from off-line frequency domain analysis. However, changes in the shape of the FFT signal were not correlated with the tracking of the fetal heart rate. Therefore, the real-time FFT was needed to visualize changes in the FFT signal shape during “good” and “bad” sections of the fetal heart rate trace. When the FHM system is tracking the fetal heart rate with a high level of confidence (merit), that section is known as a “good” section. When the FHM system is not tracking the fetal heart rate or is tracking with a low merit the section is considered a “bad” section. Panel a of figure 4-5 illustrates one frame of a “good” section of the fetal heart signal. Panel b of figure 4-5 shows a plot of a 256 point magnitude FFT computed with the signal in panel a. Panel c in figure 4-5 shows one frame of a “bad” section of the fetal heart signal and its corresponding magnitude FFT in panel d.

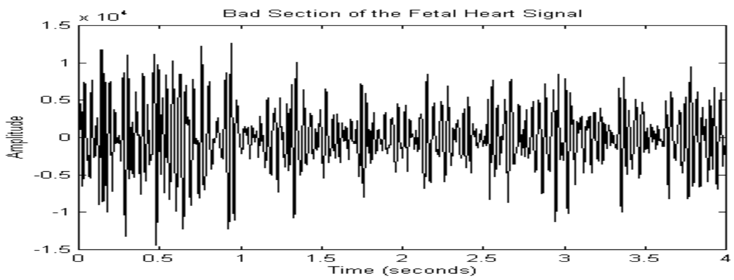
A 256 point real-time FFT was used to calculate the magnitude spectrum of the fetal heart signal. Two factors aided in determining the number of points for the FFT. The factors are time considerations and detail in the FFT. For real-time calculation and display time is the major factor. The FHM system must be able to calculate and display the FFT in a short amount of time. A heart rate is computed every .5 seconds for all seven channels of data, which consist of the calculations discussed in Chapter 3. The more points in the FFT the more time is needed to calculate and display FFT. On the other hand, for more points in the FFT, the more detail can be seen in the FFT. A 125 point frame was sent to the PC to update the graphics display of the fetal heart signal. A 256



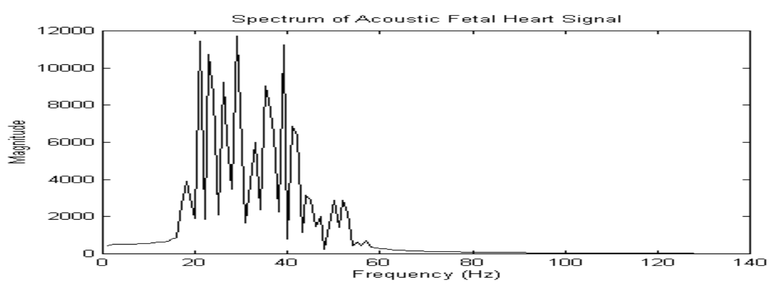
Panel a



Panel b



Panel c



Panel d

Figure 4-4 "Good" and "Bad" Sections of the Fetal Heart Signal

point FFT requires only 129 points to see all information in the symmetric FFT signal. Therefore, a 256 point FFT was computed and the first 125 points of the 129 points in the FFT were substituted in place of the .5 second buffer of the acoustic fetal heart signal. Thus from the PC code point of view, the only required changes was a re-labeling of the x-axis in order to display the FFT magnitude spectrum. A 1024 point FFT was not possible due to real-time constraints and display constraints. Because the FFT was used to see the general peaks of the fetal heart spectrum and not necessarily the detailed peaks, the 256 point FFT contained as much detail as needed. Figure 4-4 below shows the FFT signal for a good frame of the acoustic fetal heart signal with FFT's computed with 1024, 512, and 256 points. Figure 4-4 below gives an idea on how much more detail is available with a higher resolution FFT. If more detailed real-time spectral analysis were needed, the 256 point FFT implemented in the real time system could be increased to 512 points. Implementation of the FFT on the ELF DSP subsystem was done with the SPOX DSP operating system.

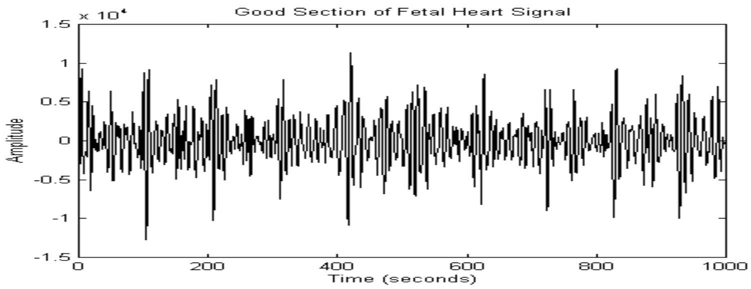
SPOX offers a standard set of high-level objects and functions for DSP applications. Direct memory access, DMA, was used to transfer data from the ELF DSP subsystem to the PC. DMA uses a data exchange register as an output port to the PC. The DMA is efficient for exchanging blocks of data because it operates in parallel with the signal processing on the ELF. The PC handles the control and displaying of the block of data. In the Oscilloscope Mode under the Acoustic Unit Only option in the FHM software, a real-time 256 point FFT is available by pressing the "F" or "f" key, which sets a fft_flag variable in the PC code. Once the fft_flag is set, bit 16 in the command register, shown in figure 4-1, is set. Every .5 seconds the command register is read by the ELF program. If bit 16 is set the ELF program computes a 256 point FFT and passes the first 125 points to the PC via DMA for display. The PC modifies the labels on the x-axis to show a frequency range from 0 to 125 Hz and the FFT vector received from the DMA buffer is displayed.

Since there are some special considerations in using SPOX, the SPOX implementation of an FFT is discussed. All SPOX vectors must be initialized with a call to

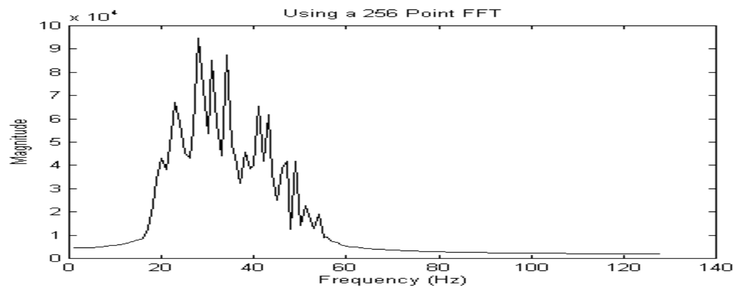
SV_Vector. After the sampling and buffering by the ELF DSP subsystem, a .5 second block of data was used for processing with an effective sampling rate of 250 Hz [1]. The digital fetal heart signal was band pass filtered using SPOX filter routines. The .5 second block of the fetal heart signal (125 points) was copied to a time vector and zero padded 256 points, the required length by SPOX for computing a 256 point FFT. A SPOX FFT function was used to calculate the 256 point FFT efficiently using 3/4 of a sine wave for a lookup table. The magnitude of the result was computed and the magnitude FFT was reduced by a scale factor of 0.1. Finally, the first 125 points in the resulting magnitude FFT were sent to the DMA buffer.

4.5 Conclusion

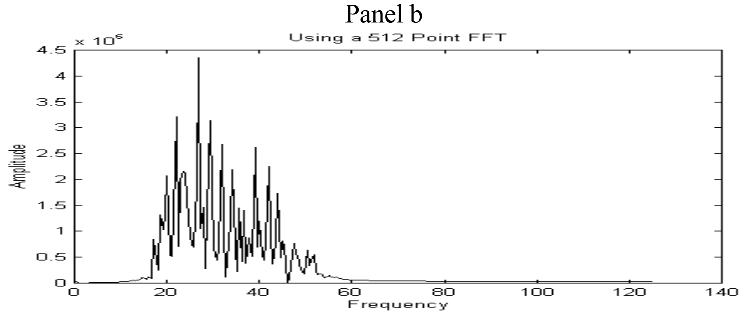
The above FHM refinements were the major refinements in the FHM system. Other refinements were made to the FHM system that helped to improve the usefulness of the FHM system. One of these was changing the FHR trace such that fetal heart rates for which the system did not have a high level of confidence were not drawn on the FHR



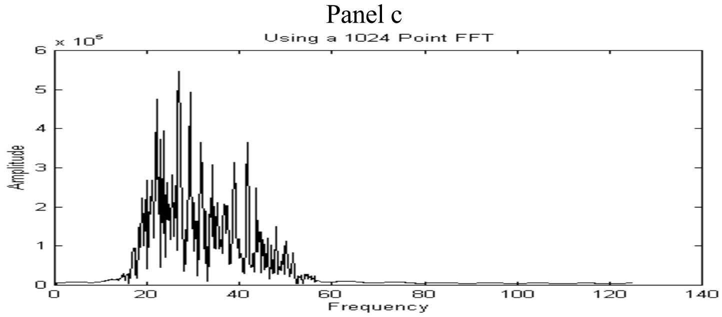
Panel a



Panel b



Panel c



Panel d

Figure 4-5 A 256, 512, and 1024 Point FFT

(Chuck—panel a in Figure 4-5 is still not labeled correctly)trace (i.e., drop outs in the FHR trace). The User's Guide was updated with new modifications to the FHM system and steps for setting up communications between the acoustic FHM and the ECG Corometrics 116 unit. A data base was created with all parts and prices for front-end electronics device. Each of the major refinements mentioned in Chapter 4 play an important role in the FHM system. The FFT is important for real-time analysis tool. For example, because of the FFT analysis, the matched filter preprocessing was investigated. The fetal heart rate range selection allows for real-time modification of the fetal heart rate range with out loss of data due to stopping the FHM program. The audio feedback option makes it possible to place the FHR acoustic sensor belt in the best location on the mother's abdomen.

Chapter 5

EXPERIMENTAL VERIFICATION

5.1 Introduction (Chuck—notice chapter title change)

Experimental testing was necessary to verify the reliability of the FHM system. Three types of experimental analysis were used for the FHM, which are as follows: balloon testing, play back of pre-recorded fetal heart beat signals, and clinical testing. Each of the experimental analysis methods played an important role in improving the FHM system. The roles that each experimental test plays are discussed in the section describing the experimental test. Comparison tests were done for the previous FHM system (phase 2), ultrasound tests, and the enhanced FHM system (method 1 discussed in Chapter 3). The next three sections explain the three types of experimental analysis used for the FHM system. Section 5.5 compares the fetal heart rate detection of the enhanced FHM system with the previous FHM system (phase 2) and the ultrasound results.

5.2 Balloon Testing

Balloon testing was performed at NASA using a beach ball filled with water to simulate a fetal heart beat passing through amniotic fluid to the wall of the mother's abdomen. The balloon had a loud speaker on its outside surface. The loud speaker was driven by a function generator to produce acoustic signals at a known frequency. The acoustic sensor belt was also attached to the outside surface of the balloon.

The balloon test was important to test the hardware and software for the FHM system before the FHM system was taken to the hospital for clinical tests. Also, the balloon experiments were important to test the reliability of the FHM system after major refinements. The balloon tests were a way of calibrating the FHM system with a known signal. Calibration was done by comparing the simulated heart rate to the heart rate computed and displayed by the FHM system.

5.3 Play Back of Pre-recorded Fetal Heart Beat Signals

The FHM software was tested by playing back pre-recorded fetal heart beat signals into the Elf DSP subsystem. The acoustic FHM system saves the fetal heart beat signals in a “wav” format (i.e., *.wav). The signals must then be converted to a “sig” (i.e., *.sig) format. The “sig” format is the raw acoustic data with out a header. A PC with a TMS320C25 based DSP platform generated an analog fetal heart beat signal from pre-recorded clinical testing data in the “sig” format using a digital to analog converter. The analog signal produced from the TMS320C25 DSP system was connected directly to the ELF DSP subsystem, bypassing the front-end electronics box. The FHR charts used to compare the acoustic FHR charts to the ultrasound FHR charts (section 5.4.2) were produced by playing back pre-recorded fetal heart signals.

Software verification using pre-recorded fetal heart signals were very useful. Instead of trips to the EVMS hospital to test each new algorithm or enhanced real-time feature, the test could be done at ODU. Also, the availability of patients for clinical testing was limited.

5.4 Clinical Testing

After verifying that the FHM system worked well on the balloon and pre-recorded signals, clinical tests were performed. Clinical test were needed to test the FHM system in a real-world environment and compare ODU's FHM system to ultrasound fetal monitoring systems. The clinical tests were conducted in conjunction with Eastern Virginia Medical School (EVMS) Department of Fetal Maternal Medicine at Norfolk General Hospital. The patients monitored by ODU's FHM system were high risk mothers in for weekly ultrasound non stress tests.

5.4.1 FHM Settings

The patients in for ultrasound non stress tests were asked if they were willing to participate in the non-invasive acoustical FHM tests. If the patients agreed to participate in ODU's FHM tests, the patients were placed on the acoustical FHM system upon completing their ultrasound fetal monitoring. Simultaneous testing was not possible because the ultrasound and acoustic FHM sensor belts required the same spot on the mother's abdomen. The patient was then placed on ODU's acoustical FHM for 18-20 minutes.

The first step in testing the patient with ODU's FHM system was positioning the acoustic sensor belt. The nurse placed the acoustic sensor belt on the patient's abdomen. The location of the sensor belt was determined by the nurse feeling the mother's abdomen for the location of the fetus. The audio feedback of the fetal heart beat signals was still too noisy for the nurses to rely on it for positioning of the acoustic sensor belt. Once the belt was positioned correctly, the nurse choose the Acoustic Unit Only option from the main menu in the FHM software. Once the patients initials were entered by the nurse, the fetal heart rate chart appeared. The default fetal heart rate range of 90-180 BPM was selected. The default digital band pass filter had a pass band of 20-50 Hz (i.e., experimentally found to be the best). The system automatically began determining the fetal heart rates and recorded the fetal heart signal upon entering the Acoustic Unit Only option.

5.4.2 Comparison of Ultrasound and Acoustic Monitoring

Once the ultrasound fetal monitoring was done, the nurse printed the fetal heart rate trace from the ultrasound test. The fetal heart rate trace from the acoustic FHM was displayed on the computer screen and saved to the hard disk of the computer for post analysis and comparison with the ultrasound fetal heart rate trace. Two of the patients which agreed to the acoustic FHM test are used in this thesis to compare the ultrasound FHR trace, the acoustic FHR trace using signal processing algorithm resulting from phase two, and the acoustic FHR trace using the enhanced signal processing algorithm. The three methods compared are shown below in figure 5-1.

Figures 5-2 through 5-10 show the fetal heart rate charts from the ultrasound and acoustic FHM systems. There are two FHR charts for each method shown in figure 5-1. The methods are in the following order: ultrasound, previous (phase 2) FHM system, and enhanced FHM system. The patients files used for the tests are pt5_1021.wav and jcc0424.wav.

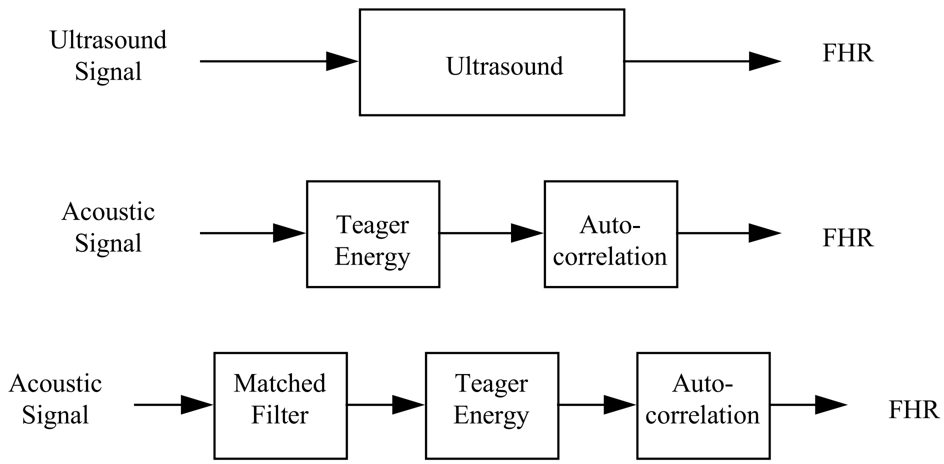


Figure 5-1 Methods for the Comparison Test

Figure 5-2 Ultrasound Test for Patient Pt5_1021 (10 gradations per minute)

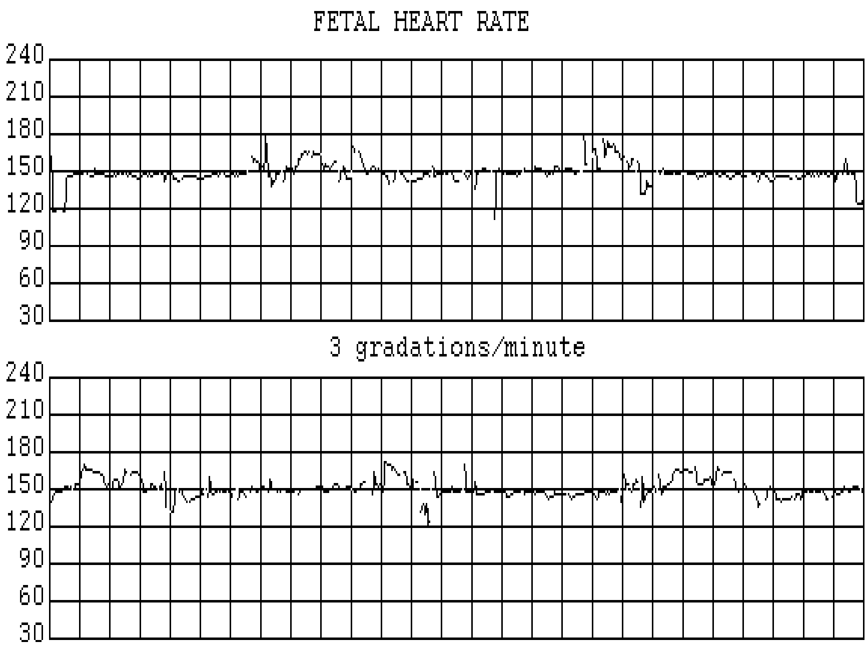


Figure 5-3 Acoustic FHM Test for Patient Pt5_1021 Using Phase 2 Algorithm

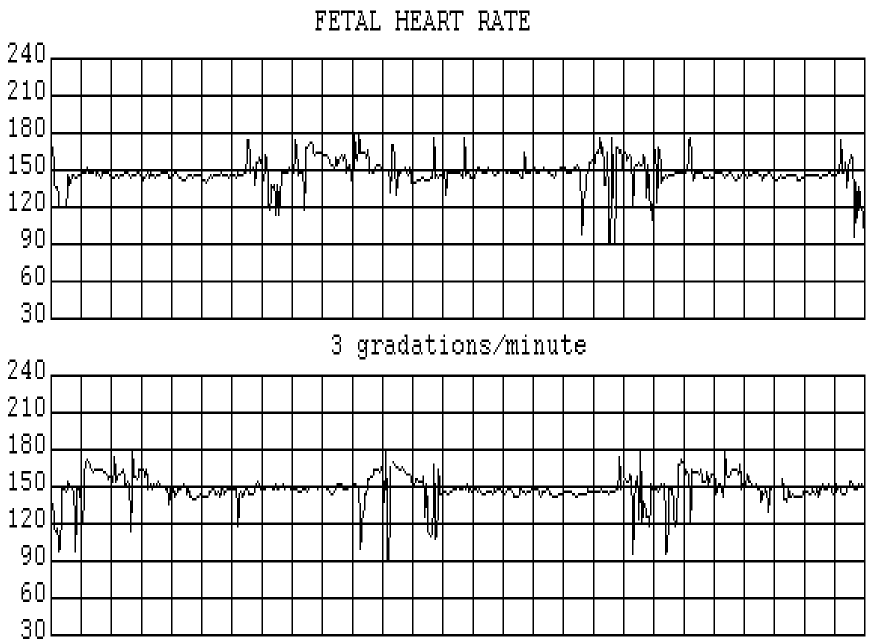


Figure 5-4 Acoustic FHM Test for Patient Pt5_1021 Using Enhanced Algorithm

Figure 5-5 Ultrasound Test for Patient JCC0424 (10 gradations per minute)

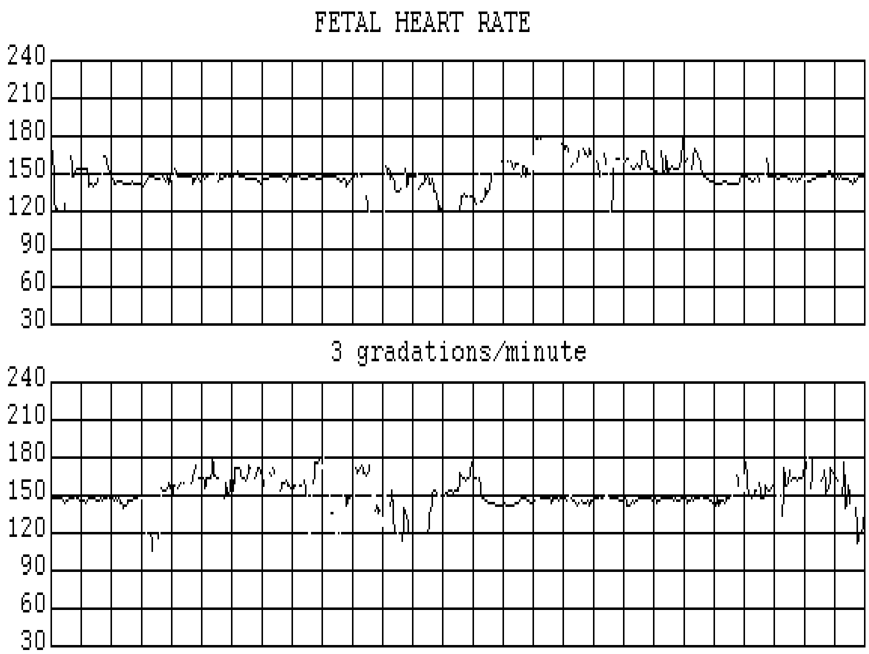


Figure 5-6 Acoustic FHM Test for Patient JCC0424 Using Phase 2 Algorithm

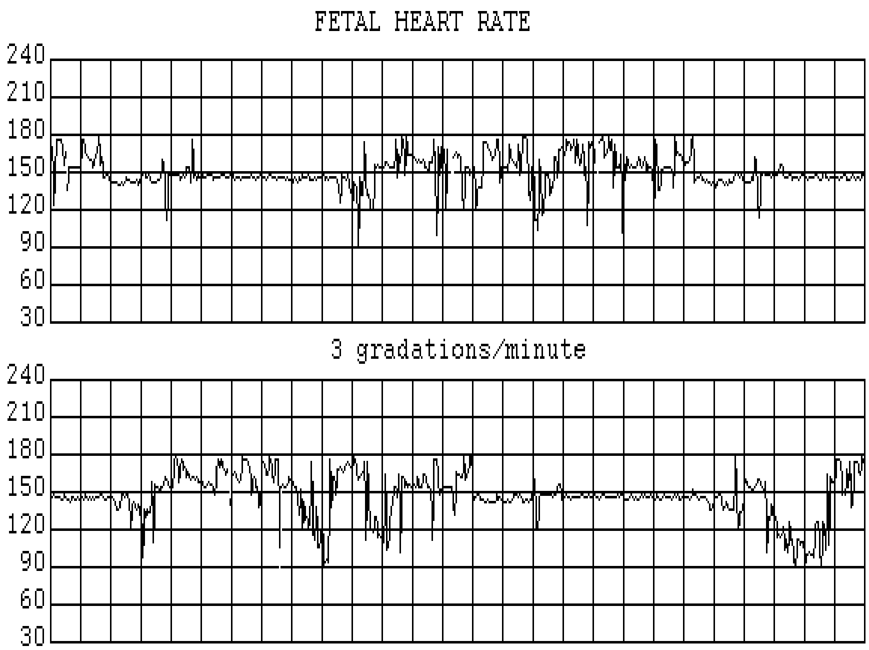


Figure 5-7 Acoustic FHM Test for Patient JCC0424 Using Enhanced Algorithm

C h a p t e r 6

CONCLUSION

6.1 Summary of Results

The FHR charts from the enhanced acoustic FHM system compares well with the ultrasound FHR charts (see figure 5-2 through 5-7). The baseline in the ultrasound FHR chart and the acoustic FHM FHR charts are the same for patient jcc0424 and pt5_1021. This implies there is a good correlation between the acoustic FHM results and the ultrasound results. The preferred testing is simultaneous testing of the acoustic system with an established “gold standard” monitor. The method for simultaneous testing of the current system is to use a Corometrics 116 Unit with a scalp electrode attached to the scalp of the fetus and to place the acoustic FHM sensor belt on the outside of the mother’s abdomen. Software has been written and laboratory verified for such testing. Attempts for simultaneous clinical testing are being made by ODU. However, scalp electrode ECG monitoring is rarely used today. Scalp electrode ECG monitoring is most typically used for “emergency” deliveries, which does not allow EVMS to give ODU advance notice about the monitoring.

The acoustic FHM is a valuable tool for the medical community as well as pregnant women. The acoustic FHM will allow for long term at-home fetal monitoring which will produce more fetal heart rate data. By collecting more fetal heart rate data, better fetal diagnostics can be obtained. Fetal diagnostic is defined as characterizing the health of the fetus based on the fetal heart rate. Better fetal diagnostics allows doctors to take appropriate actions when necessary, which leads to a larger number healthy babies being born. Also, pregnant women will be able to perform monitoring in the convenience of their home and upload the fetal data via modem to the doctors and nurses. At home monitoring will save time for doctors and nurses. The at home fetal monitor will save patients from paying for the doctor visits that are for fetal monitoring.

The portable FHM signal processing strategy has been enhanced and shown to work better than the previous FHM signal processing strategy. Refinements to the FHM system have been made per request from the medical community which improve the usefulness of the FHM system. The FHM system is one step closer to becoming a commercial medical system.

6.2 Future Research Efforts

The FHM requires future research and development before commercialization. The most critical part of the FHM, other than the signal processing issues discussed in this paper, relates to the acoustic sensors. By increasing the SNR of the fetal signals obtained from the acoustic sensors, the FHM will become much more reliable and comparable to the performance of invasive methods such as ultrasound and scalp electrodes.

The FHM system could be a stand-alone system, not needing to run on a PC computer. The stand-alone system could incorporate the functionality of the PC (displaying and saving the FHR data), the front-end electronics, and the DSP subsystem. A stand-alone system would be easier to carry and set up. The stand-alone FHM system would be less expensive to produce, therefore, reducing the cost of the system.

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Chuck—There are one or two key references on fhm signal processing which should be included. They are even referenced in Pretlow's thesis. This reference lsiting can be very valuable.)

APPENDIX

Acoustic Fetal Heart Rate Monitor User's Guide

The acoustic fetal heart rate monitor is a research project sponsored by NASA which will lead to a valuable medical instrument. Hardware of the monitor includes an IBM compatible PC, a TMS320C31 based ELF DSP platform, a front-end electronics box and an acoustic sensor belt.

After connecting all the hardware correctly, as shown in Figure A-1, turn on the power, and start the monitor by typing the following commands under a DOS prompt :

*c:\>***cd fhm\pc**
*c:\fhm\pc>***fhm**

A command menu is then displayed on the PC screen. There are six primary options listed on the menu. They are:

C -- Corometrics Unit Only

A -- Acoustic Unit Only

B -- Both Units

O -- One Channel Oscilloscope

S -- Seven Channel Oscilloscope

Q-- Quit

Each option is selected by pressing the keyboard letter listed in front of the option. For example, to select "Acoustic Unit Only" option, press "A" with the keyboard. To quit

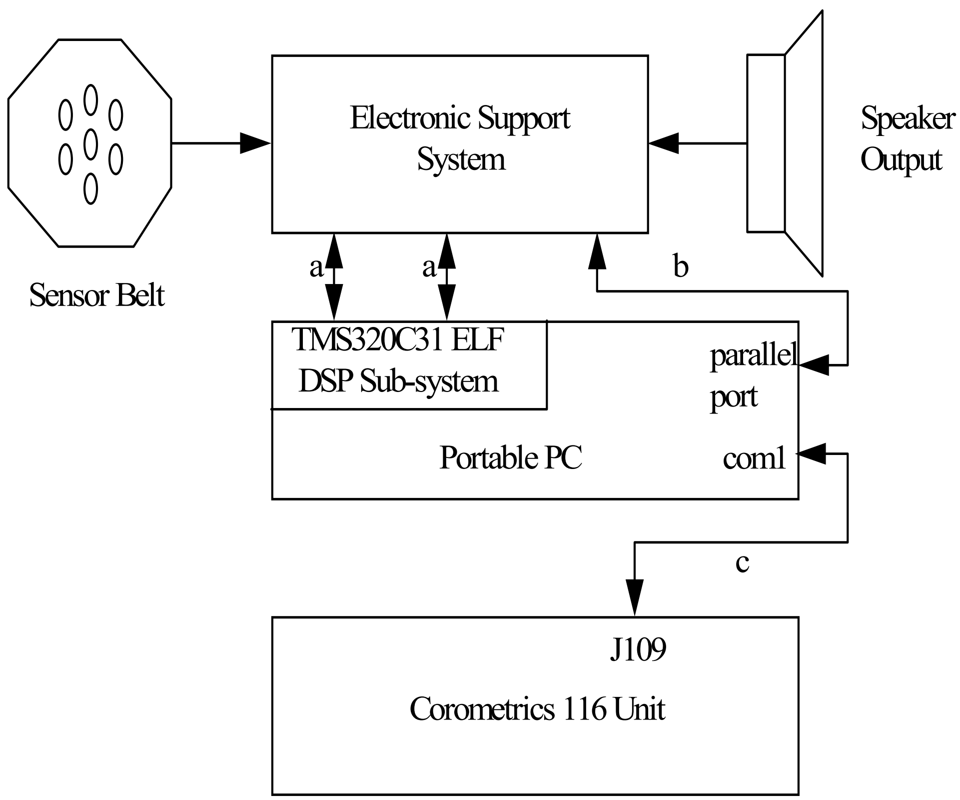

Figure A-1 Overview of Acoustic FHM System

the monitoring, press "Q". Note that this will work with both upper and lower case. We next briefly describe each of these options. A keyboard command tree is given in figure A-2. Each possible keyboard command is listed in the tree and the capitalized letter is the letter pressed on the keyboard.

A.1 Corometrics Unit Only

This option is used when fetal heart monitoring is only based on the Corometrics 116 unit. The PC serial port (COM1) has to be connected to either J109 or J110 of the Corometrics unit. The serial communication speed of the Corometrics unit has to be set at 2400 baud.

The only information acquired by the PC is the fetal heart rate information. After pressing "C" at the command menu, a strip chart type recording is drawn on the PC screen. The rate chart has a range from 30 beats per minute (BPM) to 240 BPM, and has two strips, each depicting up to 9 minutes of rate information. The rate information is also displayed as a numerical value in the middle of the bottom screen every second. If a recording is longer than 18 minutes, the tracing is redrawn on the oldest part of the chart.

In addition, there are three of four common suboptions for the rate chart.

Save

Pause

Quit

To select one of them, simply press the capital letter, which is the first letter of the desired option. For example, "S" is for the "Save" option. The "Save" option is used to begin saving the rate information to a file. The "Pause" option here is to stop saving the rate information to the file. The "Quit" option quits the current option and returns the user to the command menu mentioned above.

A.2 Acoustic Unit Only

The "Acoustic Unit Only" option is the primary mode used with the monitor. This option has two operating modes and two graphic modes. The two graphic modes are the rate chart mode and one-channel oscilloscope mode. The two operating modes are automatic mode and manual mode. In the automatic mode, which is the default operating mode, the monitor scans all seven acoustic sensors and selects the best detected result. In addition, the monitor automatically sets the optimal A/D gain level. In the manual mode, the user can set the monitor at the desired AD gain level, and monitor the desired sensor. In this option, both a rate chart is presented (as described for the "Corometrics Unit Only" option), and also a one-channel oscilloscope is available to view acoustic fetal heart tones of the selected sensor. Note that in the automatic mode sensor two (middle sensor) is saved to the file, displayed in the oscilloscope mode, and output to the audio. In the manual mode the selected channel is saved to the file, displayed in the oscilloscope mode, and output to the speaker.

On entering the "Acoustic Unit Only" option, patient's initial has to be given to generate the proper file name for the NST record. The automatic operating mode is the default operating mode of the system. However, the operating mode can be changed later (as described in the "One Channel Oscilloscope" section). If the operating mode is manual, the scanned sensor has to be selected from one to seven, and the A/D gain level

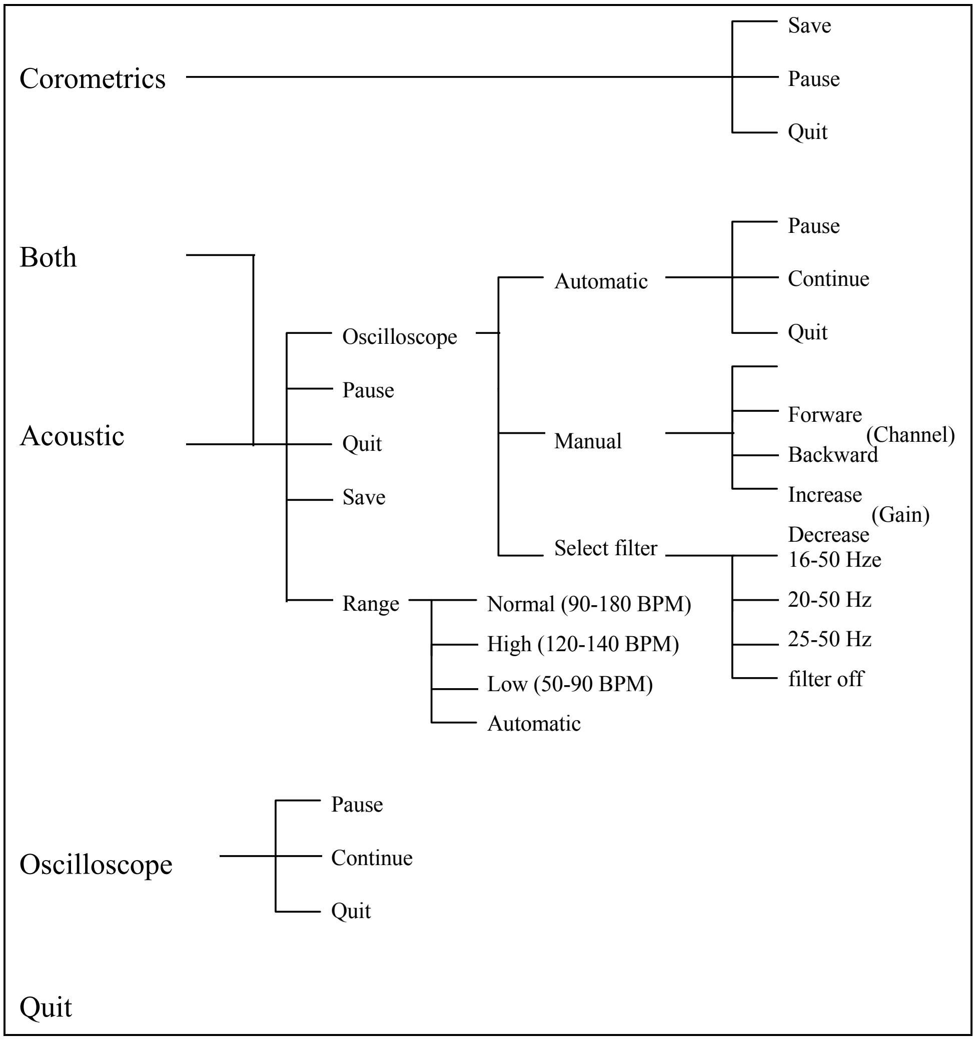

Figure A-2 Keyboard Command Tree

has to be chosen from sixteen levels. The first zero level is ±2.80 volts, and there is a 1.5 dB attenuation between two consecutive level. The final fifteenth level is ±0.21 volts. Typically choose sensor 2 (center sensor) and gain level 8. If the system is in the automatic operating mode, the default starting scanned sensor is the first sensor, and the default starting gain level is the zero level(±2.80 volts).

After all settings are made, the rate chart is the same as the one mentioned in the "Corometrics Unit Only" option. Note that there are five options available, as indicated by five words typed at the bottom of the display:

Save

Pause

Oscil

Quit

Range

Each option is invoked by typing the first letter of the corresponding word. Save, Pause, and Quit have the same functions as mentioned for the Corometrics unit, with the exception that the Save option caused two files to be saved. The Range key is given so that the user can define the heart rate range over which the heart rate should be detected. The Range that is being used is highlighted and by pressing the “R” key the ranges can be toggled. Also, the “Automatic Range” will track the heart rate over a global range (50-240) once the computer has been tracking the heart rate confidently for about 2 seconds. That is, one of the three ranges should be selected and appear to be tracking good before switching to the “Automatic Range”. Note that the default condition is for the Save mode to be entered automatically. This will be described more below. In addition, there is an additional

Oscilloscope option (Oscil) which can be used to view acoustic data, and also to modify the recording conditions. To switch to the one-channel oscilloscope, press "O" on the keyboard. As for the rate chart mode, there are several suboptions available in the one-channel oscilloscope mode, including changing the operating mode (Manual versus Automatic). These options are presented in detail in the following "One Channel Oscilloscope" section.

A.3 One Channel Oscilloscope

The "One Channel Oscilloscope" is used to view acoustic fetal heart tones of the selected sensor under the selected A/D gain level. Since this option is used to view the acoustic fetal heart tones, this option is available when fetal heart monitoring is based on the acoustic unit. That is, when either the "Acoustic Unit Only" option or the "Both Units" option is selected. However, this option is also available at the command menu. This option has two operating modes and two viewing modes. The two operating modes are the same as mentioned in the "Acoustic Unit Only" section. The two viewing modes are the static viewing mode and the dynamic viewing mode. The static viewing mode "freezes" two seconds of the acoustic fetal heart signal (by hitting the "P" key). The dynamic viewing mode continuously displays two seconds of acoustic fetal heart signal , with a "flow-mode" update every half second. Note that new information enters from the right and flows to the left.

The "One Channel Oscilloscope" option has three suboptions, including changing the operating mode, changing the pass band of a digital filter, changing the viewing mode and quitting. If this option is chosen from the main command menu, the operating mode

("M" or "A") has to be first chosen (as described in "Acoustic Unit Only" section). The default viewing mode is the dynamic mode.

There are several options available from the oscilloscope display, as listed below. (However, due to screen size limitations only prompts are listed for Pause, Continue, and Quit on the viewing screen.). The options are

"P" -- Pause , that is freeze the display;

"C" -- Continue, switch back to the dynamic mode;

"Q" -- quit this option and switch back to either the command menu or the rate chart mode;

"M" -- switch to the manual operating mode;

"A" -- switch to the automatic operating mode;

"S" -- change the pass band of the digital filter.

Note there are five filter options available:

1 9-50 Hz

2 16-50Hz

3 20-50Hz

4 25-50 Hz

5 filter off

Typically (and also the default) is 20-50 Hz. Each filter is an FIR linear phase 124th order digital filter.

If "M" is pressed to invoke the manual mode, there is another active option keyboard list:

"F" -- increase the channel number;

"B" -- decrease the channel number;

"I" -- increase the A/D gain level;

"D" -- decrease the A/D gain level.

These options can be used to view in more detail the operation of the various sensors.

A.4 Both Units

In this option, the monitor combines all the suboptions from the "Acoustic Unit Only" and the "Corometrics Unit Only". The rate chart here simultaneously displays both fetal heart rates from the acoustic unit and the Corometrics unit. The fetal heart rates from the acoustic unit are displayed in the top strip, and those from the Corometrics unit are in the bottom strip. Each strip is 9 minutes long. If the recording is longer than 9 minutes, the tracing is redrawn on the oldest part of the chart. The numerical heart rate is the one from the acoustic unit.

A.5 Seven Channel Oscilloscope Mode

This option creates a "flow-mode" oscilloscope display of all seven sensor signals. The gain level is automatically adjusted. The bottom trace is an average of all seven sensor signals. Thus channel seven is not explicitly shown. The only options available are Pause, (to freeze the display), Continue (to return to the dynamic flow-mode), and Quit, to return to the main menu.

A.6 **Notes on file saving**

In the Acoustic Unit only, or the Both units option, as mentioned above, file saving options are available. These are very important for record keeping to evaluate and improve the monitor. Whenever file saving is invoked with the acoustic unit in use, two files will be saved. The user will enter only the patients' initial with three or four letters. A file name is automatically generated by combining patients' initials and the NST date (i.e., The record of C.A. Norton's NST on 11/12 will have a name "CAN1112" with a proper extension). The extension is also automatically generated, as mentioned below to differentiate the two files.

**. rat*

This is an ASCII file which contains a table of computed heart rates, time information, status (0 is for reliable decisions, 1 for unreliable), and selected sensor number. If both units are used (Corometrics plus acoustic unit), then two heart rates are listed (acoustic unit is Rate1 and Corometrics is Rate2.)

**.wav*

This is a binary file containing samples of the acoustic heart beat signal from the selected sensor. The sampling rate is 250 Hz. This file also has a header used for later processing. These files will be saved in the *C:\FHM\PC* directory. The files must each be uniquely named to prevent overwriting of old files. The files can be copied to floppies and removed from the hard disk to prevent overfilling the capacity of the disk.

A.7 **Notes on Print Rate Charts**

For the current version of the software, there is no direct approach to print the fetal heart chart. A PCX file, containing the fetal heart rate chart image, has to be first obtained, and a graphic editor, such as Microsoft Power Point or a word processor, is needed to print the fetal heart chart on the Laser printer.

To get the PCX file, take the following steps:

c:>cd \fhm\show

c:\fhm\show>pcxgrab /I

c:\fhm\show> display

The testing date and the patient's initial are requested by the program. A heart rate chart is then displayed on the screen. However, the color scheme in this display is not very good for hard copy on a black and white laser printer. Therefore, a second heart rate chart, identical except for the trace color, is displayed after the "Esc" key is pressed. To grab the current display into a PCX file, press the keys "Alt" and "G" simultaneously. Two consecutive beeps will be heard to indicate that the current display is grabbed to a file with a name "grab_xx.pcx." Once the PCX file is created, we can print the display using Microsoft Power Point. (This could also be done using Word Perfect 6.0 or Hijack software.) Here we only give basic directions if using Power Point.

On entering MS Power Point, use a mouse to click the "Insert" and choose "Picture." Once the PCX file is inserted into the Presentation, highlight the image box by pointing the mouse to the image and clicking the mouse. Eight small black buttons are shown around the image box. Drag these buttons to resize the image. To print the image, choose "Print" from the "File" menu.