A MULTI-CHANNEL BIOTELEMETRY SYSTEM FOR THE ACQUISITION AND PROCESSING OF RESPIRATORY SOUNDS

by

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ABSTRACT

Respiratory disorders can be diagnosed by analyzing respiratory sounds produced during breathing. Main tool for physicians to analyze respiratory sounds is stethoscope. Developing a system capable of acquiring and displaying respiratory sounds and performing real-time analysis and classification is a challenging goal for researchers.

This study presents a preliminary approach for the telemetry of respiratory sounds. Increasing the reliability and efficiency of the acquisition process of respiratory sounds is aimed. For this purpose, a system with two separate telemetry transmitters placed on the body of the patient and a remote receiver connected to a PC is developed. A radio frequency link is established between the transmitters and the receiver using frequency modulation.

Communication between the PC and receiver is supplied via serial port. To control data acquisition process, a user interface is developed. The receiver can be tuned to any of the transmitters with the help of this interface, which provides the user with the choices of listening, recording and displaying data. A microcontroller is responsible for tuning the receiver according to the commands issued by the computer.

The respiratory sounds are filtered by high pass and low pass filters having cut-off frequencies at 80 Hz and 2000 Hz, respectively. A sampling frequency of 5 kHz is selected. Data is digitized by an 8-bit analog-to-digital converter.

Performance of the system is tested by measuring its response to some pre-defined signals and by recording respiratory sounds from human subjects. Promising results are obtained revealing the feasibility of telemetering respiratory sounds.

Keywords: Respiratory sounds, telemetry, frequency modulation

SOLUNUM SESLERİNİN KAYDEDİLMESİ VE İŞLENMESİ İÇİN ÇOK KANALLI UZAKTAN ÖLÇME SİSTEMİ

ÖZET

Solunum yolu hastalıklarına, solunum sırasında ortaya çıkan seslerin incelenmesi yoluyla tanı koyulabilir. Doktorların solunum seslerini incelemekte kullandıkları temel araç steteskoptur. Solunum seslerini kaydedip gösterecek ve gerçek zamanda analiz ve sınıflandırma yapabilecek bir sistemin geliştirilmesi birçok araştırmacının üzerinde çalıştığı bir konudur.

Bu çalışma solunum seslerinin uzaktan ölçülmesi için bir ön yaklaşım sunmaktadır. Solunum seslerinin ölçülmesi işleminin güvenilirliğinin ve verimliliğinin arttırılması hedeflenmektedir. Bu amacı gerçekleştirmek için hastanın üzerine yerleştirilen iki vericiden ve uzaktaki bir bilgisayara bağlı bir alıcıdan oluşan bir sistem geliştirilmiştir. Alıcı ile verici arasında frekans modülasyonu ile bir radyo bağlantısı sağlanmıştır.

Alıcı ile bilgisayar arasındaki iletişim seri bağlantı üzerinden yapılmaktadır. Veri toplama işlemini yönetmek üzere bilgisayarda bir kullanıcı arayüzü oluşturulmuştur. Bu arayüzü kullanarak alıcının istenilen vericiye ayarlanması ve elde edilen seslerin dinlenmesi, ekranda gösterilmesi ve kaydedilmesi mümkündür. Alıcının, bilgisayardan iletilen komutlara göre ayarlanmasından bir mikrodenetleyici entegresi sorumludur.

Alıcıda, solunum sesleri, sırasıyla 80 Hz ve 2000 Hz köşe frekanslarına sahip yüksek ve alçak geçiren süzgeçlerden geçirilir. Örnekleme frekansı 5 kHz'dir. Veri, 8-bit'lik bir analog-sayısal çeviriciden geçirilmektedir.

Sistemin performansı, belirli sinyal şekillerine verdiği cevabın ölçülmesi ve bu sistem kullanılarak solunum seslerinin ölçülmesi yoluyla denenmiştir. Bu yöntemle solunum seslerinin uzaktan ölçülmesinin mümkün olduğunu ortaya koyan sonuçlar elde edilmiştir.

Anahtar kelimeler: Solunum sesleri, uzaktan ölçme, frekans modülasyonu

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1. INTRODUCTION

1.1 Objectives

Developing reliable and objective methods for the analysis of biological signals is one of the major goals of biomedical engineering. If one aspect of this problem is the application of feasible signal processing techniques for the evaluation of information contained in the data, another one is the accurate measurement of the signal.

Every measurement causes an alteration on the value of the signal to be accessed. Thus, in every measurement a prime importance is given to keep these alterations as small as possible. However, if the information source is a biological system, then things become more complicated. Source value will not only be influenced by the measurement, but from some other secondary factors as well. To state some of these secondary factors, environmental conditions, psychological situation of the subject, impediment of the subject by the measurement equipment and measuring under restraint conditions can be mentioned.

Biotelemetry comes into stage at this point. Biotelemetry is an effective method to reduce the influences of the measurement system on the source value and thus, to perform a more reliable measurement. Biotelemetry frees the subject from all cables and connections to data processing equipment. By using telemetric techniques it is possible to perform the measurements without disturbing the natural living conditions of the subject. This aspect is especially important in wildlife researches.

Although biotelemetry is a well-known technique for over a century, biotelemetry of respiratory sounds does not have a well-established basis. One important problem, when dealing with respiratory sounds, is the lack of standards in recording and analyzing respiratory sounds. This point is demonstrated in the work of Mussel [1]. Another difficulty with the telemetry of respiratory sounds is the need for recording respiratory airflow synchronously with respiratory sounds. Respiratory airflow measurements require big transducers and this requirement is difficult to coincide with the objectives of biotelemetry. A method to extract respiratory signal from electrocardiogram QRS complex is proposed by Dobrev [2].

1.2 Approach

This study is actually a part of and a contribution to a much wider project, that is, developing an "intelligent stethoscope." The need for such a device comes from the following arguments:

Physicians' primary tool for the diagnosis of respiratory sounds is stethoscope. However, auscultation of the chest via stethoscope also poses some questions. Criterion for evaluating the sounds heard by the aid of stethoscope differs from one physician to another. It depends on the experience of the physician and therefore, it is subjective. So, it is a challenging task to provide the physicians with a tool for objectively analyzing respiratory sounds.

The work presented here proposes a telemetry technique for the recording of respiratory sounds. It is shown that via a radio frequency (RF) link provided between the telemetry unit placed on the posterior chest of the subject and the information receiver in communication with an IBM-compatible personal computer (PC), it is possible to record respiratory data reliably.

The system has two separate telemetry transmitters and it is fully under physician's control to decide which transmitter to be accessed. Listening,as well as recording and displaying the received data are possible.

One contribution of this thesis is providing the physicians with a visual tool for the acquisition of respiratory sounds. System is completely portable and removes the need for cables. It provides electrical isolation of the patient from the recording device.

With a stethoscope only one person can listen to the respiratory sounds. However, with a system like the one presented here, it is possible for several people to listen to the data and display it on the computer's screen. This aspect is especially important for educational purposes.

1.3 Outline of the Thesis

Chapter 2 gives an overview about respiratory sounds and their importance for respiratory disorder diagnosis. The standards of respiratory sound recording are also mentioned in this chapter. In Chapter 3, a background for biotelemetry is presented. Applications of biotelemetry are discussed in detail. This chapter also presents the technical aspects of biotelemetry. The topics like, transmission media, transmission frequencies, encoding schemes are explained in comparison with other researchers' findings. Chapter 4 demontrates our approach to the problem of biotelemetry of respiratory sounds. Principles of our telemetry system and detailed schematics are presented in this chapter. Chapter 5 is devoted to results and discussion. Chapter 6 contains the conclusions drawn from this study. Recommendations for future work are also outlined. Appendices A and B contain the listings of the assembler program of the microcontroller and of the user interface program, respectively. Appendix C presents the printed circuit board drawings of the circuits. Appendix D presents the charts and tables that are used for designing the filters used in this study.

2. RESPIRATORY SOUNDS

2.1 Background

Diagnostic importance of respiratory sounds is known since 1826, the year which French physician Rene Laennec published his book "Traite de l'Auscultation Mediate". After Laennec, attention to this field grew quickly and nature of respiratory sounds became an intensive research topic.

A respiratory cycle consists of two phases: inspiration and expiration. During inspiration and expiration, air flows through the upper airway, the tracheobronchial tree and the lungs. This process produces an acoustical energy that is transmitted through various tissues to the chest wall where it can be listened. Although mechanisms for respiratory sound generation are not totally discovered, it is known that this flow is the stimulating source for the generation of respiratory sounds.

Respiratory sounds are classified into two major groups: Breath sounds and adventitious sounds. Breath sounds can divided into two classes: Normal breath sounds and bronchial breath sounds. Normal breath sounds can be heard at the mouth, over the trachea and on the chest wall. Normal breath sounds heard on the chest wall are also called vesicular breath sounds.

Normal breath sounds have a frequency distribution between 200 Hz and 600 Hz and can be heard throughout inspiration and at the beginning of expiration. Bronchial breath sounds have frequency components between 200 Hz and 2000 Hz and are audible at both inspiration and expiration [3-4].

Adventitious sounds can be briefly divided into two groups: Continuous adventitious sounds which are mainly wheezes and discontinuous adventitious sounds which are crackles. Wheezes have a sinusoidal waveform and thus a musical quality. They have a frequency range of 100 Hz to 2000 Hz [5]. Crackles are short, explosive, non-musical sounds and are classified according to pitch, duration, number and timing. Their frequency spectrum is between 200 Hz and 2000 Hz [6].

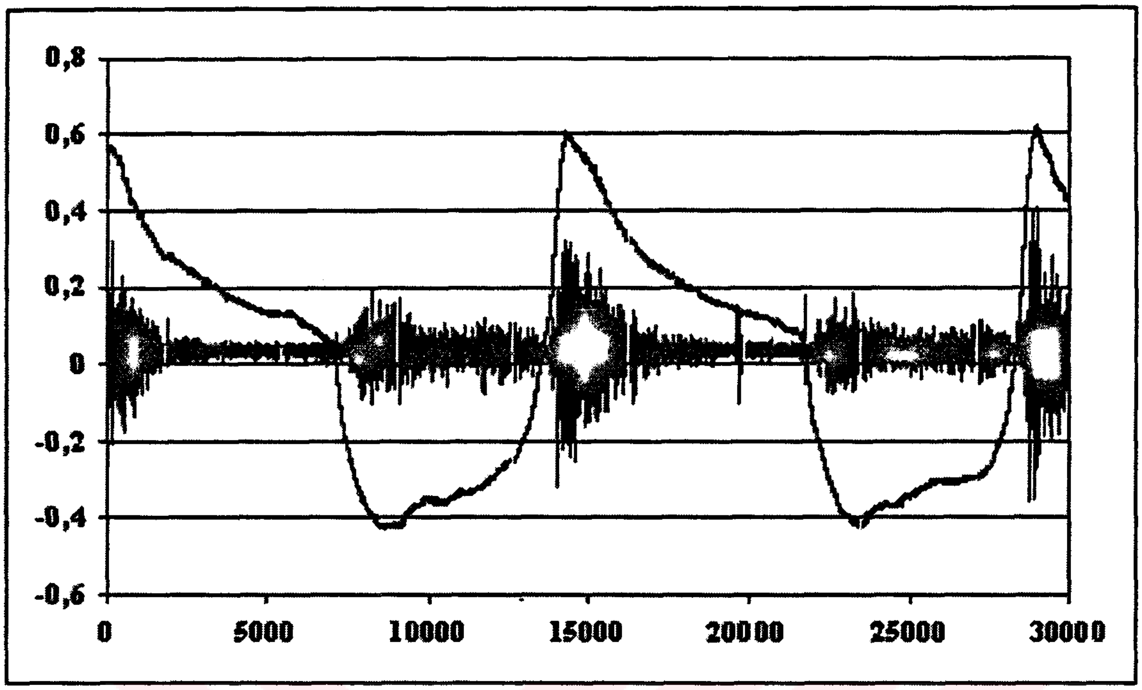


Figure 2.1 A representative respiratory sound waveform with flow signal.

2.2 Respiratory Sound Recording

As Mussel [1] points out, there is a lack of standardization of equipment and protocol among investigators. The consequence is that results of different researchers are difficult to compare.

2.2.1 Sensors

Criteria for the selection of sensors for respiratory sound acquisition are a high dynamic range, a high signal-to-noise ratio and a flat frequency response throughout the spectrum of respiratory sounds. Sensors used for breath measurements may be divided into two groups: contact sensors and air-coupled sensors.

Contact sensors are coupled directly to the body surface. Accelerometers and piezoelectric materials are used as contact sensors. Relatively heavy mass of accelerometers dictates the need for a much firmer contact, which may distort the sound transmission characteristics [7].

Microphones cannot be used to pick up sounds from body surface because of the great mismatch between body surface vibration and air [5]. Microphones must be coupled to the body surface with an air chamber. Shrouds are employed for this task. Shrouds also increase the background noise immunity of the microphone. However, a badly designed shroud also introduces some problems such as, producing resonant peaks and disturbing the flatness of the frequency response.

The most widely used microphone for recording respiratory sounds is the electret condenser microphone [1]. They are preferred because they have a wide dynamic range, good sensitivity, flat frequency response and are light and easy to attach.

2.2.2 Microphone Amplifiers

There is a wide variety of microphone amplifiers that can be used for respiratory sound amplification ranging from instrumentation amplifiers to those within electronic stethoscopes. Amplifiers used for respiratory sound amplification must be low-noise and have a flat response in the frequency range of interest.

2.2.3 Filtering and Sampling

Different researchers focus on different frequency bands when analysing respiratory sounds. However, there is a general agreement that the frequency components of respiratory sounds are populated between 200 Hz and 600 Hz and extend up to 2000 Hz [3], [6]. At low frequencies, below 80 Hz, heart sounds dominate over respiratory sounds. Thus, filtering must also remove the sounds produced by the heart.

When the respiratory sound signal is to be digitized, sampling frequency has to be chosen according to Nyquist criterion which states that to prevent aliasing, sampling frequency must be at least twice the highest frequency component of the signal. Taking this into consideration, sampling frequency of respiratory sounds has to be no lower than 4000 Hz.

3. BIOTELEMETRY

3.1 Definition, History, Objectives

Telemetry can be defined as measuring at a distance. In the case of biotelemetry, subject of the measurement is a biological system. Biotelemetry is a method to transmit physiological signals to a remote information receiver.

History of biotelemetry can be dated as back as 19^{th} century [8]. Third edition of “Animal Mechanism” by E. J. Marey was published in 1883. Marey had used a kind of a biotelemetry system to investigate the mechanism of flying. In 1903, Einthoven transmitted electrocardiogram voltages over telephone wires about a mile. In 1921, Winters transmitted heart sounds over a marine radio link. Later innovations in biotelemetry were closely linked with the advances in electronic methods. Transmission of signals from within a subject was possible after 1950s.

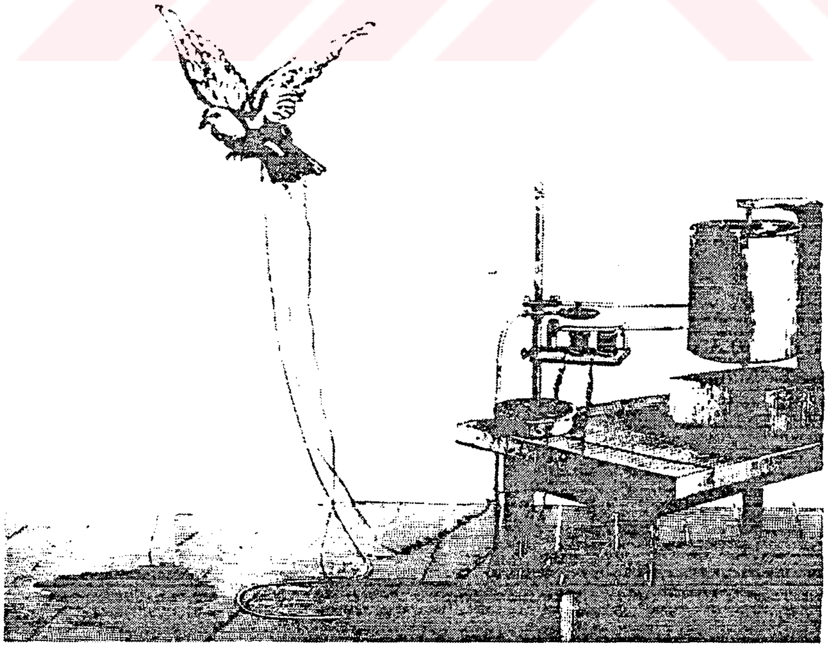


Figure 3.1 Marey monitored flying a century ago[8].

The purpose of biotelemetry is to monitor or study biological systems with minimal disturbance to their normal activity and to explore otherwise inaccessible parts of the body. Biotelemetry offers complete electrical patient isolation. With telemetry it is possible for portable emergency care units to communicate with hospital base stations to transfer the physiologic data of the patient.

Biotelemetry, generally, incorporates a wireless link between the information source and receiver. Frequencies used for telemetric transmission expand over almost the entire spectrum. Transmission distances vary from a centimeter to a few thousand kilometers. Subjects can be humans or animals ranging from bees to whales.

3.2 Applications of Biotelemetry

Biotelemetry is a powerful tool for scientists working in the field of wild-life research. By using telemetric techniques it becomes possible to monitor and record the physiological data of animals in their natural living conditions. Herzog et al. [9] used telemetry to record muscular forces and electromyogram (EMG) signals from cats. Mohseni et al. [10] proposed a biotelemetry equipment to record EMG signals in moths. A telemetry system was developed by Yonezawa [11] et al. to monitor Doppler audio signals in unrestrained animals. Patrick et al. [12] built a telemetry system to record the left-ventricular (LV) thickness and LV blood pressure in unrestrained animals and tested it successfully with baboons. Same physiologic variables were also investigated by Pitsillides et al. [13] and a telemetry system was used to record these variables from miniswine. Muscle potentials of a locust during free flight were transmitted by a telemetry unit by Kutsch et al. [14]. Core body temperature monitoring of Mongolian gerbils is another application of biotelemetry [15]. Wright et al. [16] showed that it is possible with biotelemetry to measure tail skin temperature of rats.

One major field where biotelemetry employed is monitoring the physiological data of human beings. A system for monitoring glucose rate was reported by Shults et al. [17]. Hof et al. [18] transmitted EMG signals from humans. Puers et al. [19] established a telemetric link to transfer data from implanted sensors for the detection of hip prosthesis loosening. Monitoring bradycardia and apnea by measuring heart rate and respiratory signal is another field where biotelemetry is engaged [2]. Taylor et al. [20] devised a wireless cardiotocograph to monitor the condition of the fetus.

Telemetric measurements may be both invasive and non-invasive. In invasive measurements care must be given not to damage the biological system and for the adaptation of the telemetric unit to the biological environment. Using an implantable biotelemetry system for functional electrical stimulation (FES) is a widely used technique [21-22].

If the physiological values are not required to be observed in real time, they may be stored in portable equipments. Miniature data-loggers are good examples of this kind of biotelemetry [23].

3.3 Technical Aspects of Biotelemetry

A biotelemetry system roughly consists of transducers to pick up data from the source, amplifiers to amplify the signals to a level adequate for transmitting and a generator for producing a carrier wave that is modulated by the physiologic signal.

Measurement can be carried over one channel or a multichannel system can be used. For multichannel operation, a multiplexing method, frequency-division or time-division, has to be used. Frequency-division multiplexing uses subcarriers with various frequencies that are frequency modulated by the measured signal. Subcarriers are linearly mixed and the resulting signal modulates the main carrier. Subcarrier frequencies must be chosen such that no overlapping occurs. In time-division multiplexing, the available time is shared between different biological signals and channels are sampled periodically. If Nyquist criterion is satisfied, no information is lost. Then sampled values are arranged side-by-side and transmitted.

Since transmitter is carried by the information source, it must be designed so as not to disturb and restrict it. Design of telemetric units must be guided with ergonomic principles. For instance, weight of the telemetry unit must be lower than the 2% of the total body weight of the subject [24].

Receiver section of the biotelemetry system consists of necessary circuits for receiving signals, signal conditioner, decoder, demultiplexer and a display and/or storage device. Block diagram of a generalized biotelemetry system is depicted in Figure 3.2.

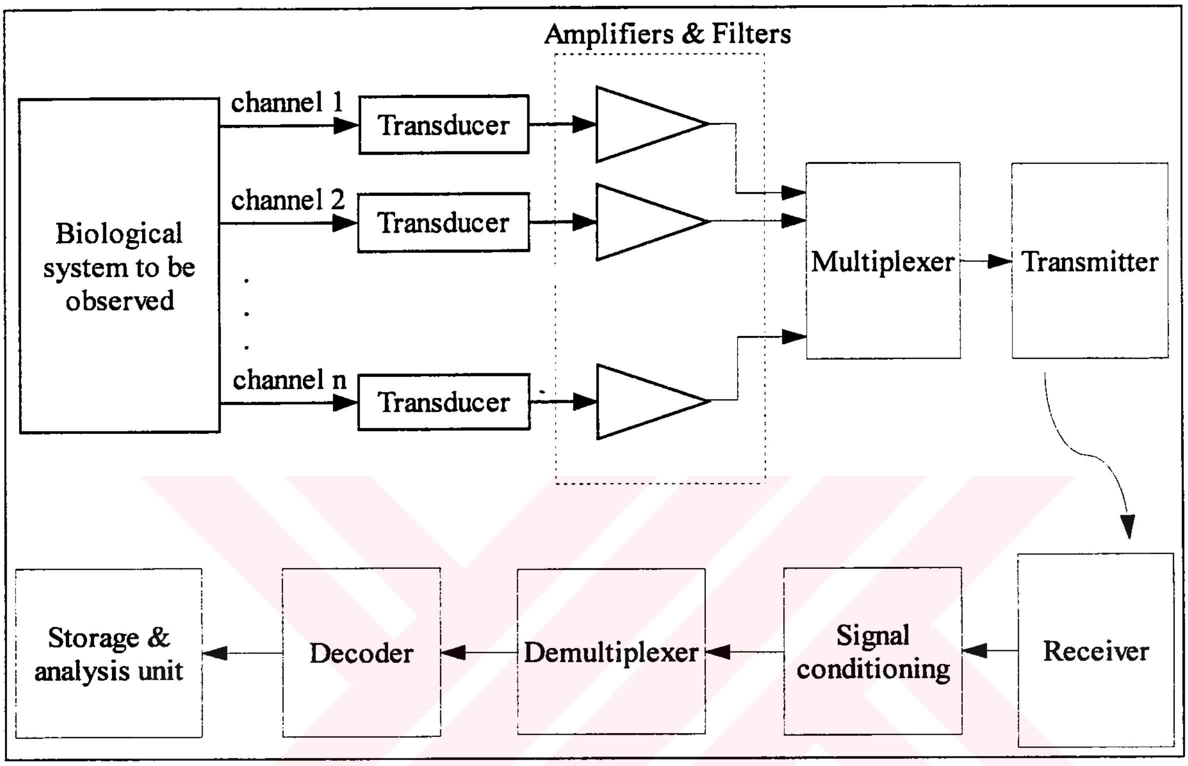


Figure 3.2 Block diagram of a generalized biotelemetry system.

3.3.1 Radiotelemetry

Radiotelemetry uses radio waves as the carrier. A carrier wave is produced by an oscillator and is modulated by the information signal.

There are no worldwide-accepted frequency bands allocated for biotelemetry. Many researchers use FM broadcasting band (88 MHz–108 MHz) to be able to use commercially available transmitters and receivers [10-13], [18]. Frequencies in the range of 140-190 MHz [14], 210-220 MHz [25], 418 MHz [20] are also used for biotelemetry.

Modulation techniques used in radiotelemetry may be analog or digital. Amplitude modulation (AM) is the earliest modulation method for wireless communication. AM modulates the amplitude of the carrier. The information signal is inserted onto the carrier by nonlinear mixing of these two signals. Receiver demodulates the signal by envelope detection. Since amplitude of the received signal signal depends on many parameters, such as distance between transmitter and receiver or orientation of the antennas, determination of the absolute signal amplitudes is a difficult task and limits the usage of AM. AM signals are also adversely affected by sources of interference. Another limitation of AM is that a significant amount of power is in the carrier, which is not required to furnish the original signal. The bandwidth of an AM signal is twice that actually required for the reception of the intelligence being sent.

Frequency modulation (FM) was originally invented to overcome the drawbacks of AM, primarily that of excessive noise sensitivity. Since noise is normally produced by undesired amplitude variations in a signal, this is removed in frequency-modulated receivers by amplitude limiters.

FM accomplishes the modulation process by altering the carrier's frequency in step with the amplitude changes of the information signal. In the receiver, the frequency variations are changed back into amplitude variations.

Main benefits of FM over AM are superior noise immunity and higher transmitter effficiency. However, FM also has its drawbacks: It is more expensive to design and contruct FM transmitters and receivers and secondly, FM requires a better frequency stability.

In pulse-modulation techniques, only discrete samples representing the signal are used to modulate the carrier. These discrete samples are used to vary a parameter of a pulse waveform. Such parameters are the amplitude (pulse amplitude modulation, PAM), duration (pulse duration modulation, PDM), width (pulse width modulation, PWM) or position (pulse position modulation, PPM). An overview of these techniques can be found in Figure 3.3.

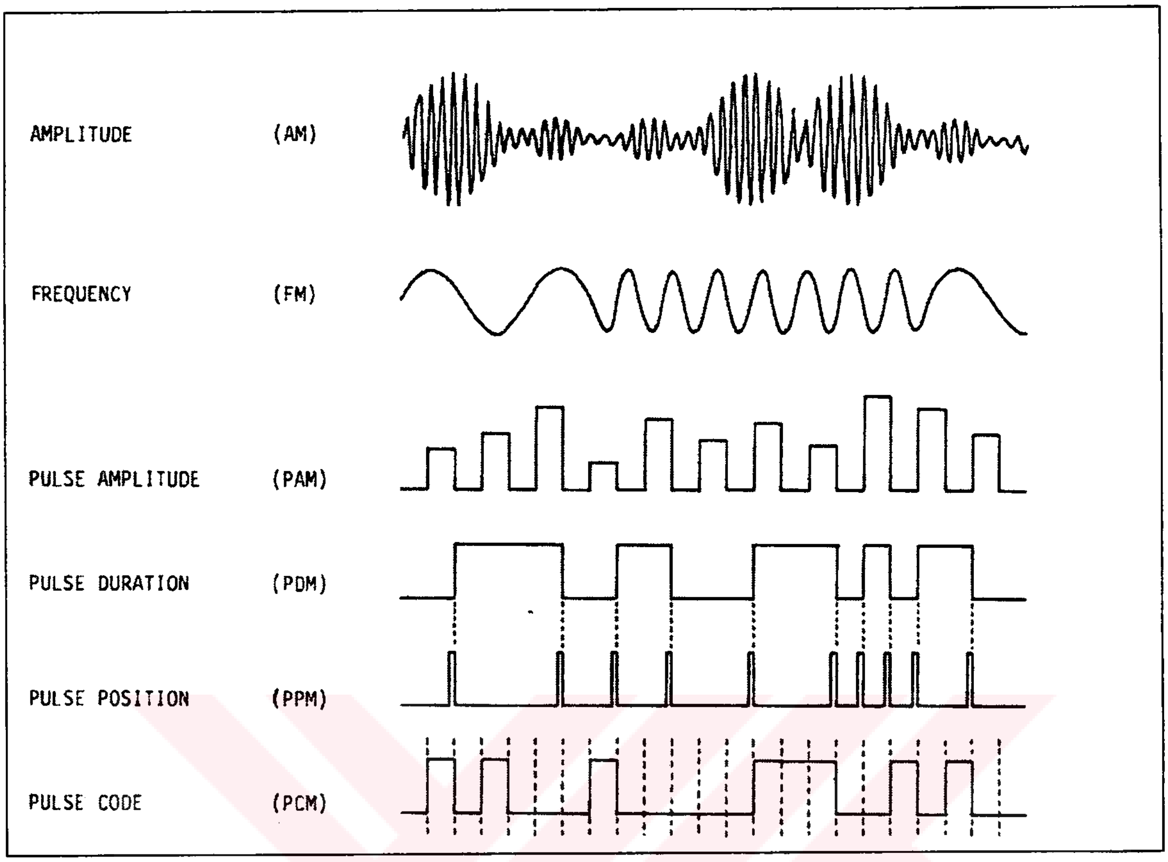


Figure 3.3 Modulation and coding techniques.

Digital modulation techniques offer higher data rates, higher reliability and noise immunity levels. Earlier digital modulation methods, like amplitude shift keying, frequency shift keying, had much in common with the older analog modulation methods. The difference is that these schemes have discrete states at discrete times. With the introduction of more sophisticated digital modulation methods, like quadrature amplitude modulation, quadrature phase shift keying advantages of digital modulation become to be widely exploited.

3.3.2 Infrared Telemetry

Using infrared (IR) light for telemetry has considerable advantages. IR can hardly penetrate thorough most materials and it is reflected by obstacles. So same frequency can be used in adjacent rooms in a hospital without any interference. However, IR telemetry also poses some problems such as multipath propagation of transmitted signals, which "confuses" the receiver, low efficiency of IR emitters and low performance of IR receiving semiconductors to detect signals with large dynamical ranges. To cite some of the researchers in the field of IR telemetry, Hof [18], Lankovic [26], Park [27] can be stated.

3.3.3 Ultrasonic Telemetry

Ultrasonic telemetry is used especially for underwater measurements. Radio waves are attenuated very rapidly in seawater. IR is only suitable for clear water and at short distances. So, although ultrasound has also some drawbacks such as very slow propagation speed, it is the only choice for most of the underwater measurements [28-30].

3.3.4 Power Sources

Batteries are the most commonly used power source for biotelemetric applications. Especially in implanted systems, lifetime of the biotelemetry equipment is very important. With the introduction of higher capacity batteries it became possible to conduct the measurements for a long time with small batteries.

An alternative for supplying power to an implanted system is coupling it to a radio frequency source from ouside the body. This can be done by inductively coupling a primary coil to an implanted secondary coil [31-32]. Power limits should not exceed the accepted safe limit of 10 mw/cm^2 of tissue area [33].

3.3.5 Integrated Circuit Telemetry Systems

Custom integrated circuits (IC) designed specially for biotelemetric purposes are offered by some researchers. Fernald et al. [34] developed an implantable digital telemetry IC that is equiped with the capability to adapt antenna variations. Liu et al. [35] presented a neuro-stimulus chip with telemetry unit to be a part of an implantable device to replace the functionality of defective photoreceptors. An IC, presented by Kawahito et al. [36], is designed for noninvasive systems and uses IR telemetry.

4. A TELEMETRY SYSTEM FOR RESPIRATORY SOUNDS

4.1 Design Considerations

The telemetry system presented in this thesis is a two-channel system. Respiratory sounds acquired by telemetry modules placed on the body are transmitted to the receiver by a radio link. Transmitting telemetry modules are placed on a belt that is worn by the patient. Microphones are outside of the case of the transmitter and attached to the body by adhesive tapes. Transmitters use different frequencies for transmission: One of them transmits at 109 MHz and the other at 109.6 MHz. Receiver is capable of tuning itself to any of the transmitters. Tuning is accomplished by a microcontroller according to the commands delivered by a computer.

User of the system can, at a time, listen to or record the respiratory signals transmitted from one channel, only. Telemetry of the respiratory flow signal was not taken into consideration during this thesis work.

4.2 Transmitter Unit

Transmitter unit consists of a microphone to pick up sounds, an amplifier and a high-frequency oscillator. The unit is powered by a 12 volt alkaline battery. 8 volts for the transmitter and 5 volts for the microphone are produced by voltage regulators. Transmitter draws a current of 12 milliampers.

4.2.1 Microphone

The respiratory sounds are picked up by an air-coupled microphone. The microphone is an omnidirectional electret conderser type. It has a flat frequency response between 30 Hz and 3000 Hz which makes it suitable for respiratory sound pick up. Frequency response of the microphone supplied by the manufacturer is presented in Figure 4.1.

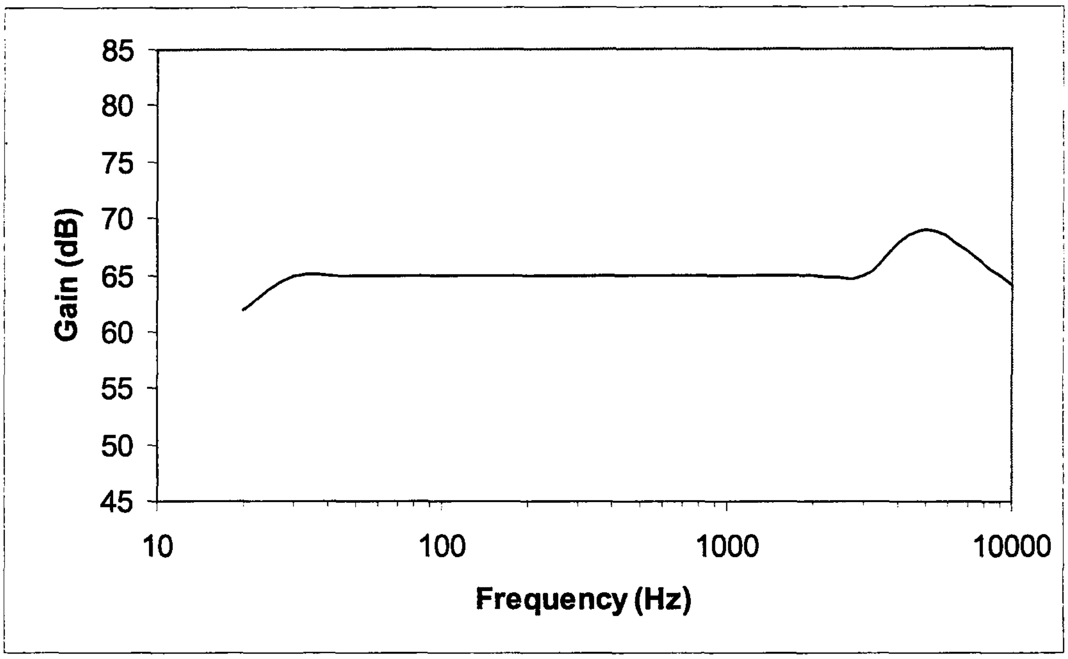


Figure 4.1 Frequency response of the electret microphone [37].

Microphones are placed in conical shaped shrouds to achieve the air-coupling between the body of the subject and microphones. This method also improves the noise-immunity of the microphones.

4.2.2 Amplifier

The electrical signal produced by the microphone is amplified by a low noise amplifier. Amplifier is built around two general purpose transistors. Frequency response of the amplifier is measured between 20Hz and 100000 Hz; results are presented in Figure 4.2. The schematic layout of the amplifier is given in Figure 4.3.

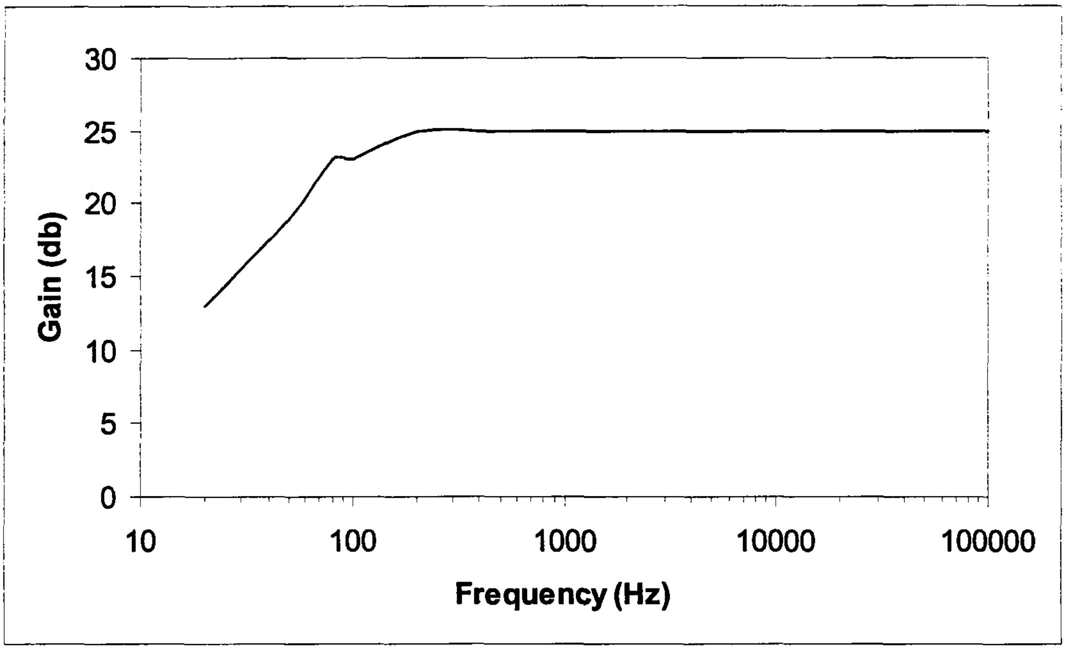


Figure 4.2 Frequency respose of the amplifier.

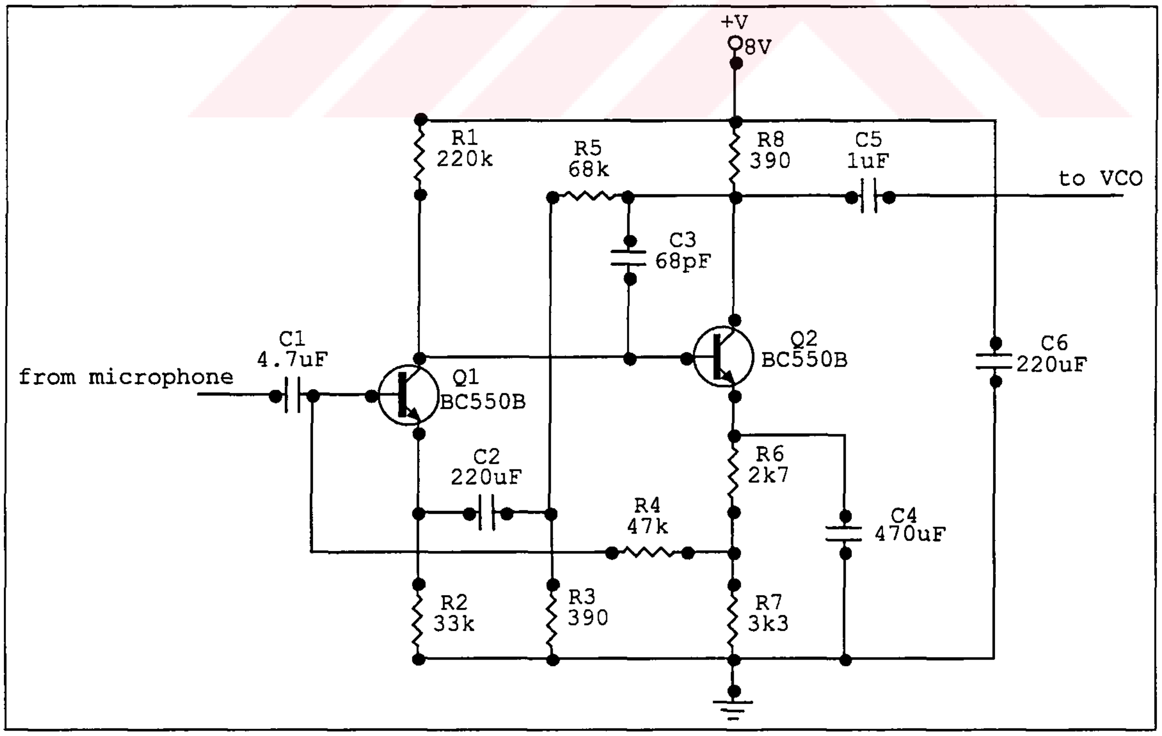


Figure 4.3 Schematic layout of the amplifier.

4.2.3 High Frequency Oscillator

Modulation technique used for transmission is frequency modulation. To accomplish this task, a voltage controlled oscillator (VCO) which is built around a JFET transistor is employed. Oscillator is actually a modified version of Colpitts oscillator. Oscillator works on the basic resonance principle and the resonance frequency is determined by an inductor etched on the printed circuit board in parallel with a set of capacitors. A variable capacitor (C4) is used to fine-tune the oscillator frequency. A tuning diode (D1) is responsible for the modulation of VCO signal. Signal coming from the amplifier is applied to this diode whose capacitance value changes according to the reverse voltage applied. Changes in the capacitance of this diode causes deviations in the oscillating frequency of the circuit and thus, frequency modulation is achieved. VCO is shown in Figure 4.4 in detail.

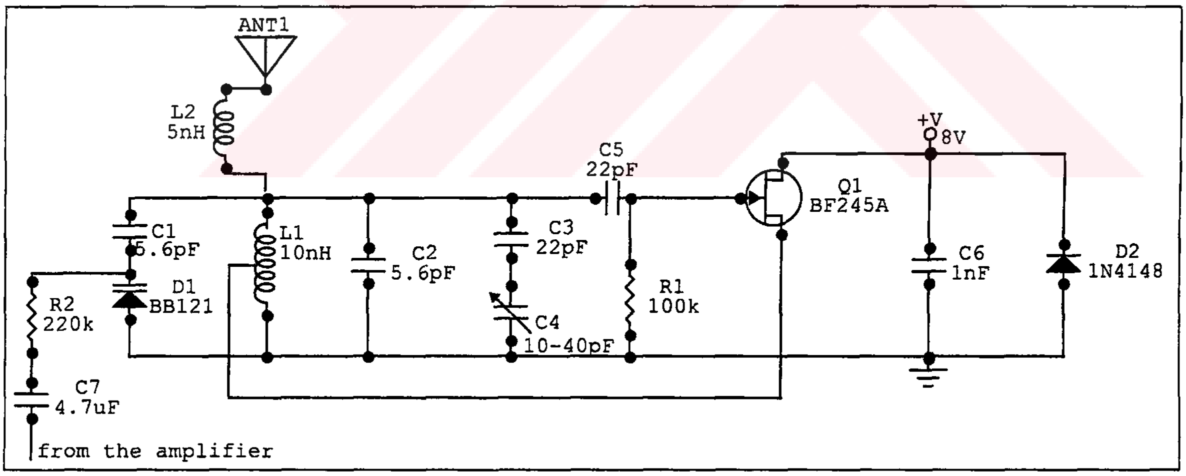


Figure 4.4 Schematic layout of the high-frequency oscillator.

VCO's oscillating frequency covers a range of 98-112 MHz. No external antennas are used for delivering the output power. Inductor etched on the printed circuit board also acts as the antenna. Voltage versus frequency characteristics of the VCO is given in Figure 4.5.

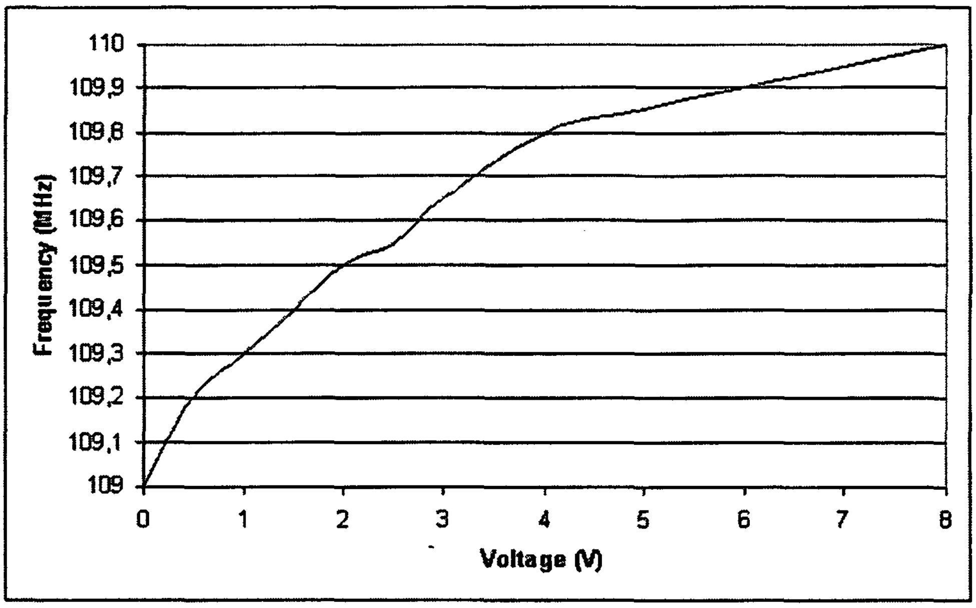


Figure 4.5 Change in the frequency of the VCO with the applied voltage.

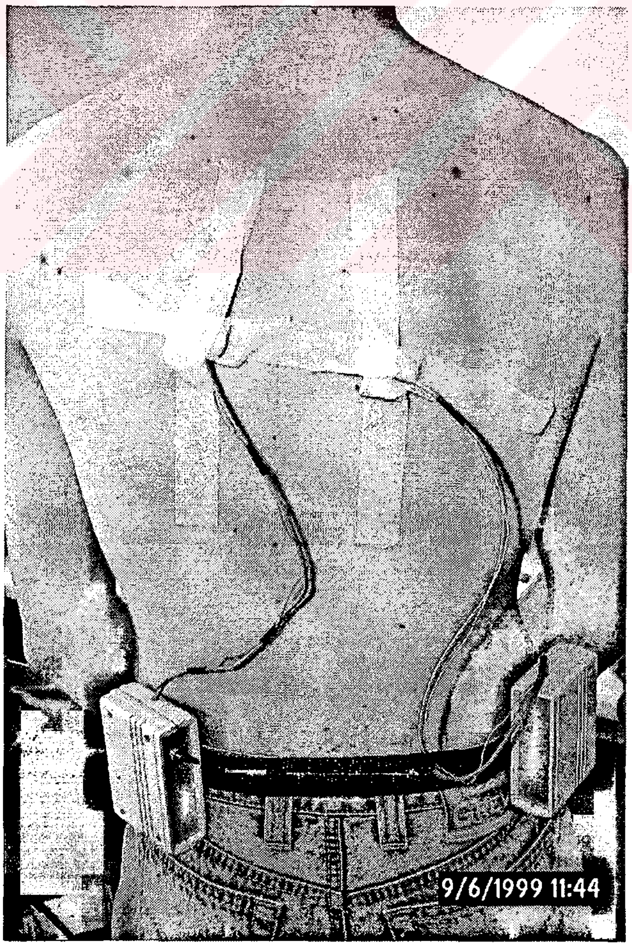


Figure 4.6 Transmitters are placed on a belt that is worn by the patient. Microphones are attached by adhesive tapes.

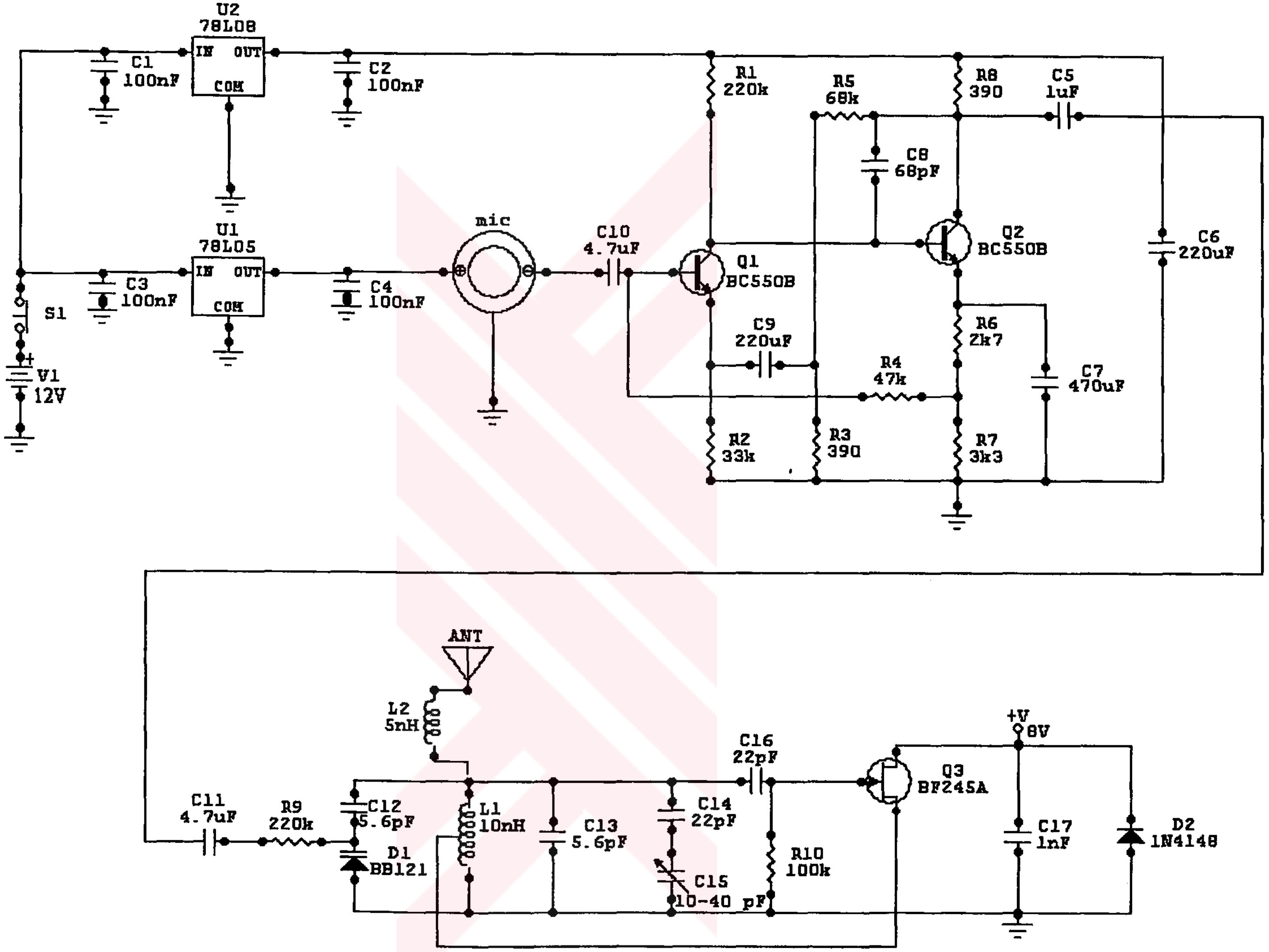


Figure 4.7 Complete schematic layout of the transmitter.

4.3 Data Management Unit

This subsection of the system is responsible for the following tasks:

(A) capturing the signals transmitted by the module placed on the body of the subject;

(B) communicating with the PC to set the receiver to the appropriate channel and if record command is received from the PC, digitizing the analog signal and sending the digitized data to PC via serial port.

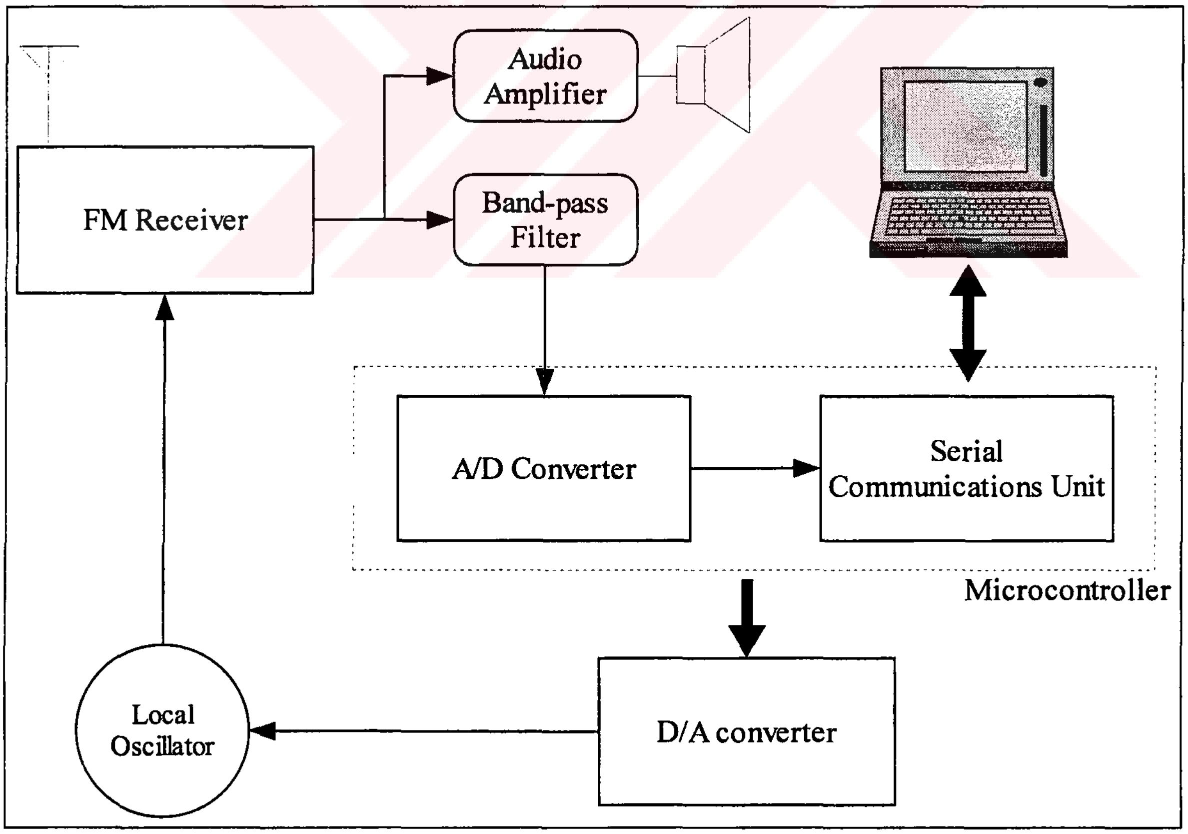


Figure 4.8 Block diagram of the data management unit.

4.3.1 FM Receiver

Heart of the receiver is an FM receiver integrated circuit (IC), TDA 7000. This IC is a direct conversion receiver. It has a frequency-locked loop system with an intermediate frequency (IF) of 70 kHz. The TDA7000 has the following functions: RF input stage, mixer, local oscillator, IF amplifier/limiter, phase demodulator, mute detector, mute switch. Some specifications of the TDA7000 are depicted in Table 4.1.

Table 4.1
Specifications of TDA7000 [38]

Parameter	Min.	Typ.	Max.	Unit
Supply voltage	2.7	4.5	10	V
Supply current at 4.5V supply		8		mA
Output current		60		μA
A.F. output voltage at $R_L = 22k\Omega$		75		μV
Sensitivity				
muting disabled		1.5		μV
for –3 dB muting		6		μV
for S/N = 26 dB		5.5		μV
Signal-to-noise ratio		60		dB
Variation of oscillator frequency Supply voltage		60		kHz/V
Selectivity		45		dB
A.F.C. range		±300		kHz
Load resistance At 4.5 V supply		22		kΩ

Block diagram of the FM receiver which is mostly included in the TDA 7000 IC is shown in Figure 4.9.

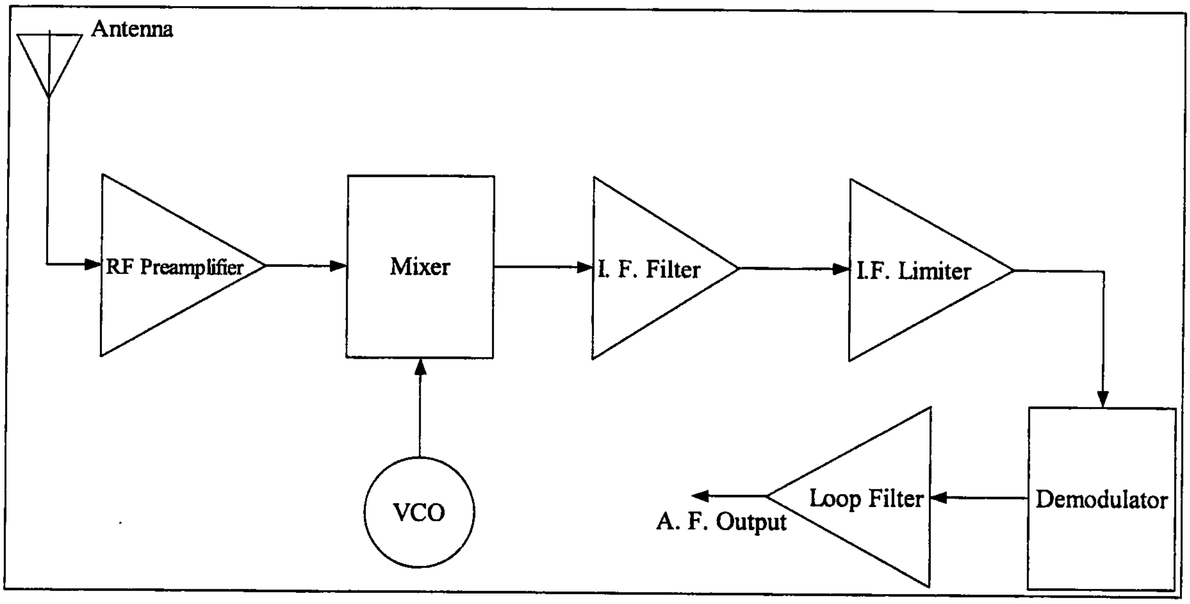


Figure 4.9 Block diagram of the FM receiver.

The unit is powered by four 9 volts rechargable batteries. An external antenna is not provided with the system. The cables of the headphone or speaker also serve as the antenna for the system.

Before mixing with the signal of the VCO which is the local oscillator of the receiver, signals are amplified with an RF preamplifier. At the mixer an intermediate frequency of 70 kHz is produced. After filtering this signal will be demodulated and signal will be recovered.

Output power from the receiver IC is not adequte for listening. So, an audio amplifier IC, LM 386, is used to enhance the signal to an audiable level. Power output of the amplifier is 0.5 watt. A speaker is connected to the output of the amplifier for listening the received sounds.

4.3.2 Filters

Frequency range of respiratory sounds is between 40 Hz and 2000 Hz. However, between 0 and 80 Hz, sounds produced by the heart dominates. So a bandpass filter with a low cut-off frequency of 80 Hz and a high cut-off frequency of 2000 Hz is used for filtering the received data.

Filters can be built solely from resistors, inductors, and capacitors which are passive components. Filters may also incorporate amplifiers in which case they are called active filters. A quad operational amplifier (LF347) is used for building the filters used in this study.

The behavior of a filter is characterized by its transfer function H(s), where s is the complex variable ($s = \sigma + jw$ with w as the angular frequency). All practical transfer functions turn out to be rational functions of s:

$$H(s) = \frac{N(s)}{D(s)} \tag{4.1}$$

N(s) and D(s) are polynomials of s with real coefficients and the order of N(s) never exceeds that of D(s). The order of D(s) is called the order of the filter. The zeros of N(s) and D(s) are called, respectively, the zeros and poles of H(s). Once H(s) is known, the circuit's response $V_o(t)$ to an input $V_i(t)$ can be determined as,

$$V_o(t) = L^{-1}\left[H(s)V_i(s)\right] \tag{4.2}$$

where $V_i(s)$ denotes the Laplace transform of $V_i(t)$ and L^{-1} denotes the inverse Laplace transform.

The cascade approach is the simplest and most popular method to build filters higher than second order. This approach generates the desired transfer function as the product of second and possibly first-order functions. Since the output impedance of the individual sections is low, interstage loading may be neglected.

Among the variety of possible responses, some have been found to be consistently satisfactory, and their coefficients have been determined and tabulated [39]. These include the Butterworth, Chebyshev, Elliptic and Bessel responses.

Butterworth filters maximize the flatness of the magnitude response within the passband. The general expression for this response is,

$$|H| = \frac{1}{\sqrt{\left[1+(f/f_c)^{2n}\right]}} \tag{4.3}$$

where n is the order of the filter and f_c is the cut-off frequency.

Chebyshev filters maximize the transition band cut-off rate at the price of introducing passband ripples. Elliptic filters, also called Cauer filters, accept ripples in both the passband and the stopband in order to achieve an even sharper characteristic in the transition band. Bessel filters maximize the passband time delay just as Butterworth filters maximize the passband magnitude. The result is a nearly linear phase characteristic within the passband.

The design procedure of a high pass filter starts with designing the low pass counterpart and ends up with conversion back to high pass. A low pass filter is converted into a normalized high pass filter by replacing each resistor by a capacitor of 1/R farads and each capacitor by a resistor of 1/C ohms.

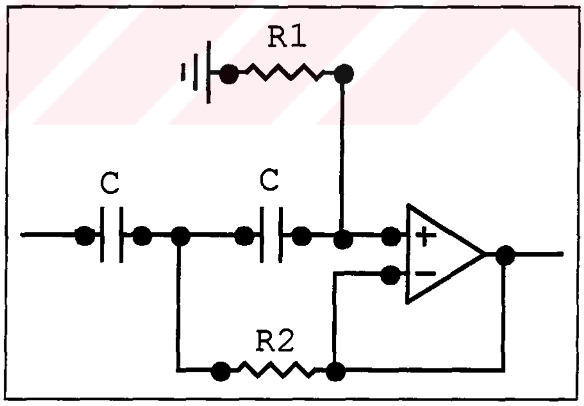


Figure 4.10 Section structure of the Butterworth high-pass filter.

Cut-off frequency of the Butterworth high pass filter used in this study is 80 Hz. Order of the filter is 4. It has unity gain and capacitors of 10nF are used. Minimum attenuation at the stopband frequency is selected as 30dB. The filter is built by designing second order sections and cascading them to get the 4th order response. Curves demonstrating the attenuation characteristics of Butterworth filters can be found in Appendix D. From Figure D.1 it can be seen that the steepness factor, f_s/f_c must be 2.5, where f_s denotes the beginning of the stopband. Thus, the beginning of the stopband is calculated as 32 Hz. The normalized values of capacitors are obtained from Table D.1 as,

$$C_1 = 1.0820\ \text{F} \qquad C_2 = 0.9241\ \text{F}$$
$$C_3 = 2.6130\ \text{F} \qquad C_4 = 0.3825\ \text{F}.$$

Values of the resistors are 1 Ω. To convert to high pass, each resistor is converted by a capacitor of (1/R) F and each capacitor by a resistor of (1/C) Ω. So,

$$R_1 = 0.9242\ \Omega \qquad R_2 = 1.0820\ \Omega$$
$$R_3 = 0.3827\ \Omega \qquad R_4 = 2.6143\ \Omega$$

Impedance scaling function, Z, is defined by the equation,

$$Z = \frac{C}{2\pi f_c \times C_{std}} \tag{4.4}$$

where C is 1 F and C_{std} is 10 F. From Eq. (4.4), Z is calculated as 1980. Denormalized values of the resistors can be calculated by multiplying the resistor values by Z. So,

$$R_1 = 183.9\ \text{k}\Omega \qquad R_2 = 215.3\ \text{k}\Omega$$
$$R_3 = 76.1\ \text{k}\Omega \qquad R_4 = 520.1\ \text{k}\Omega$$

By calculating the resistor values, the design procedure of the high pass filter ends; the resultant schematics is depicted in Figure 4.11.

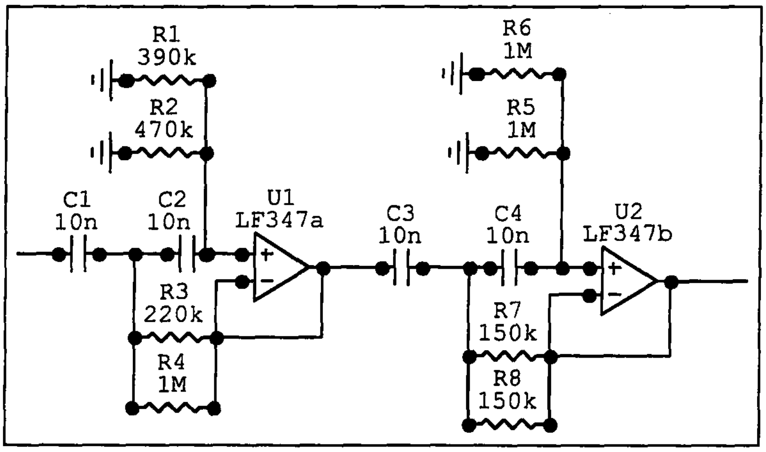


Figure 4.11 4th order Butterworth high pass filter with 80 Hz cut-off frequency.

Low pass part of the filter block is designed as a Bessel filter. Its cut-off frequency is 2000 Hz and order 4. Minimum attenuation at stopband is decided to be 20 dB. The standart capacitor values are 10 nF. The steepness factor, from Figure D.2 is calculated as 2.5. So, the beginning of the stopband is at 5000 Hz. 4th order response is obtained by building second order sections and cascading them. One section of a Bessel filter is show in Figure 4.12.

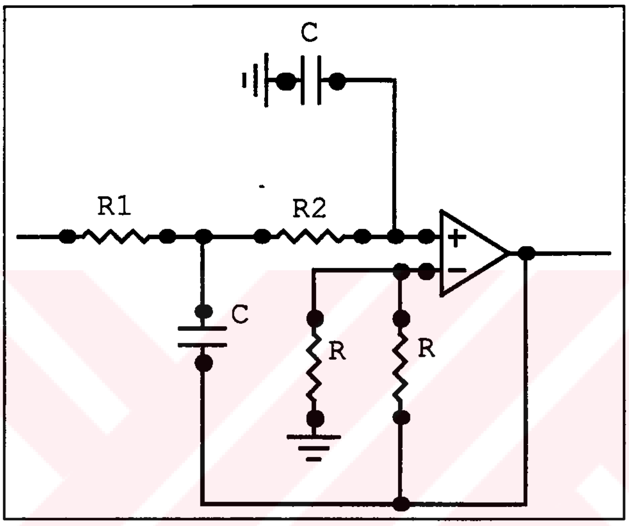


Figure 4.12 Section structure of a Bessel low-pass filter.

In Figure 4.12, values of R_1 and R_2 can be calculated as follows:

$$R_1 = \frac{1}{4\pi f_c \alpha C} \quad \text{and} \quad R_2 = \frac{\alpha}{\pi f_c C\left(\alpha^2 + \beta^2\right)} \tag{4.5}$$

where α is the real part and β is the imaginary part of the pole of filter. From Table D.2, pole locations of the filter are obtained as,

$\alpha_1 = 1.3596$ $\beta_1 = 0.4071$

$\alpha_2 = 0.9877$ $\beta_2 = 1.2476$

By using Eq. (4.5) resistor values can be calculated as, 1st section: $R_1 = 2928\ \Omega$ $R_2 = 10748\ \Omega$

2nd section: $R_1 = 4030\ \Omega$ $R_2 = 6211\ \Omega$

Final schematic diagram of the low pass filter is presented in Figure 4.13 and Figure 4.14 exhibits the total response of the band pass filter.

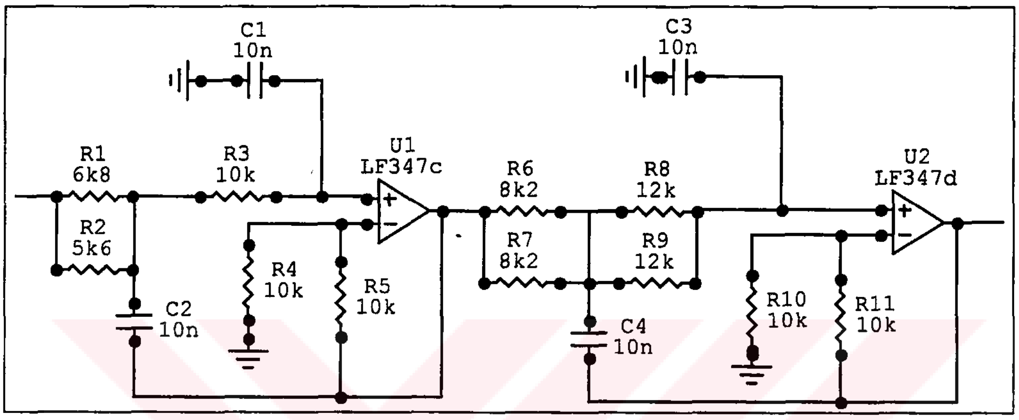


Figure 4.13 4th order Bessel low pass filter with 2000 Hz cut-off frequency.

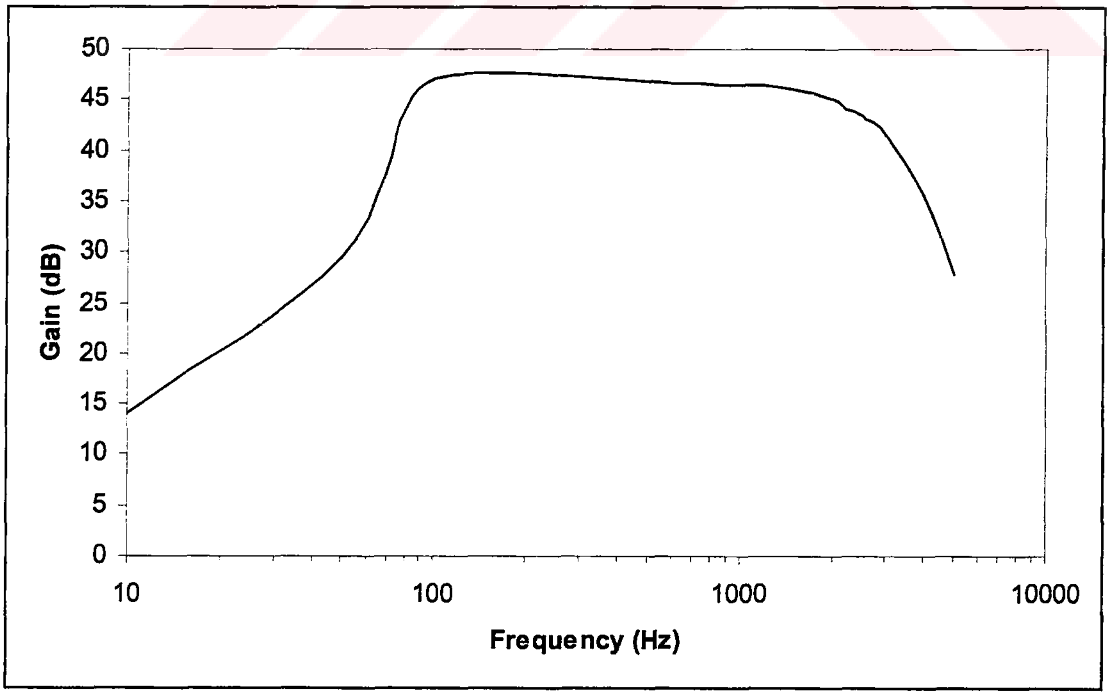


Figure 4.14 Frequency response of the band pass filter.

4.3.3 Channel Selection

Channel selection is done via changing the frequency of the local oscillator of the receiver. The tuning diode (D1) in parallel with the oscillator coil is reverse biased to set the oscillator frequency to the desired value. Internal capacitance of the tuning diode changes according to the reverse voltage applied. Reverse voltage on the tuning diode is controlled by a digital-to-analog (D/A) converter which is also controlled by the microcontroller, MC68HC705B16.

4.3.4 Microcontroller

MC68HC705B16 microcomputer (MCU) is a member of Motorola's MC68HC05 family of 8-bit single chip microcomputers. It contains an on-chip oscillator, CPU, RAM, EPROM, EEPROM, analog-to-digital (A/D) converter, pulse-length modulated outputs, I/O, serial communications interface, programmable timer system and watchdog.

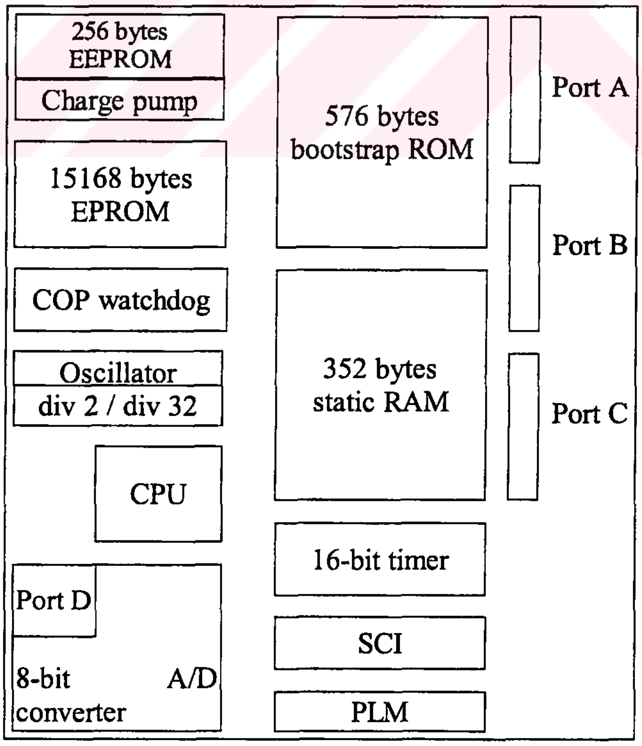


Figure 4.15 Block diagram of MC68HC705B16 microcontroller.

MCU communicates with the PC via serial port. It gets the information on which channel is to be listened. According to this information it drives the inputs of the 8-bit D/A converter DAC 0800 to high or low voltage and D/A converter produces a voltage output depending on its inputs with the help of an operational amplifier. This voltage is applied to the tuning diode which is a part of the local oscillator of the receiver.

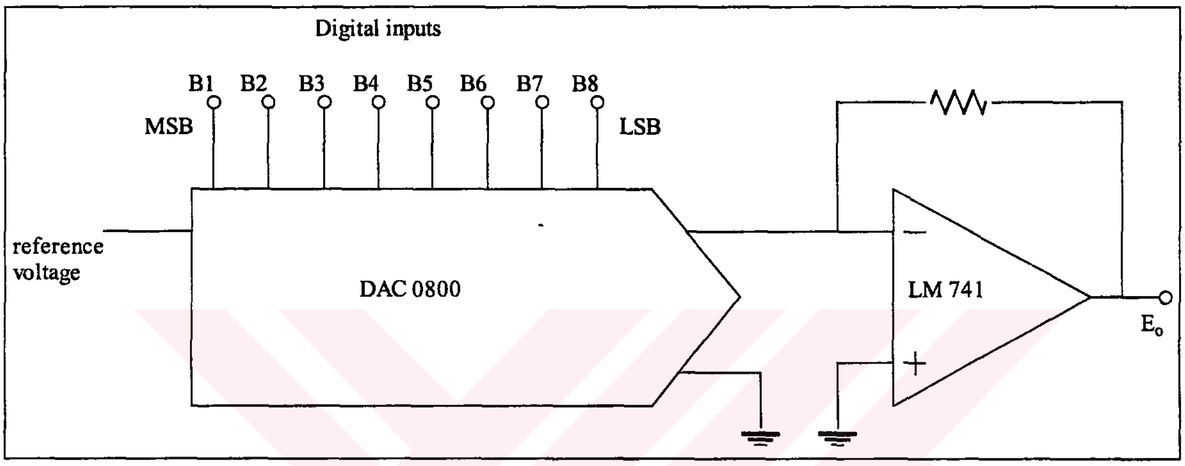


Figure 4.16 Simplified schematic layout of D/A converter.

4.3.5 Serial Communications Interface

Two important advantages of using serial data transmission rather than parallel can be stated as follows:

(A) Serial port transmits a "1" as –25 to –3 volts and a "0" as 3 to 25 volts, whereas parallel port transmits a "0" as 0 volt and a "1" as 5 volts. Therefore serial port can have a maximum swing of 50 volts compared to the parallel port with a maximum swing of 5 volts. So cable loss is not a problem for serial cables as they are for parallel ones.

(B) Serial communication does not require as many cables as parallel transmission.

In serial communication data is "framed". That is, a data word is framed between start and stop bits. Transmission begins with a start signal which is logic 0. Then data bits are sent beginning from the least significant one. After eighth bit is transmitted stop bits are transmitted to signal the end of transmission. Number of stop bits can be one or two. If necessary, a parity bit can also be included in the frame. Diagram below shows an RS-232 waveform with 8N1 format which is also used in our system. 8N1 signifies 8 data bits, no parity and 1 stop bit.

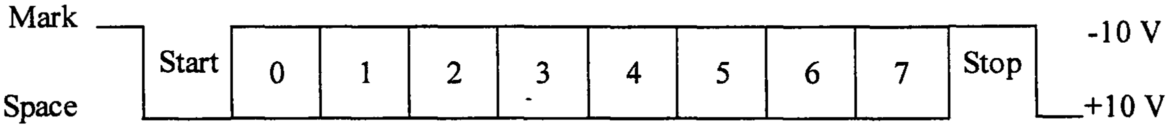


Figure 4.17 RS-232 waveform shape with 8N1 format.

Our system provides a full-duplex asynchronous serial communications with non-return-to-zero format and baud rates upto 125 kHz. In our case, baud rate is 115200 Hz. A level converter is used to transfer RS-232 voltage levels back into 0 and 5 volts and vice versa.

4.3.6 Analog to Digital Converter

After amplification and filtering, signal is applied to one of the eight analog inputs of the MCU. If requested by the PC, MCU will then convert this signal to digital and send the digitized data to PC via serial port.

The (A/D) converter consists of a single 8-bit successive approximation converter. The A/D converter has eight analog inputs to be digitized which can be selected by the MCU.

The 8 bit A/D converter has a total error of ±1 LSB which includes ±1/2 LSB of quantization error. High and low voltages for reference are supplied to MCU by the respective pins. An input voltage greater than or equal to high reference converts to $FF and an input voltage equal to low reference converts to $00.

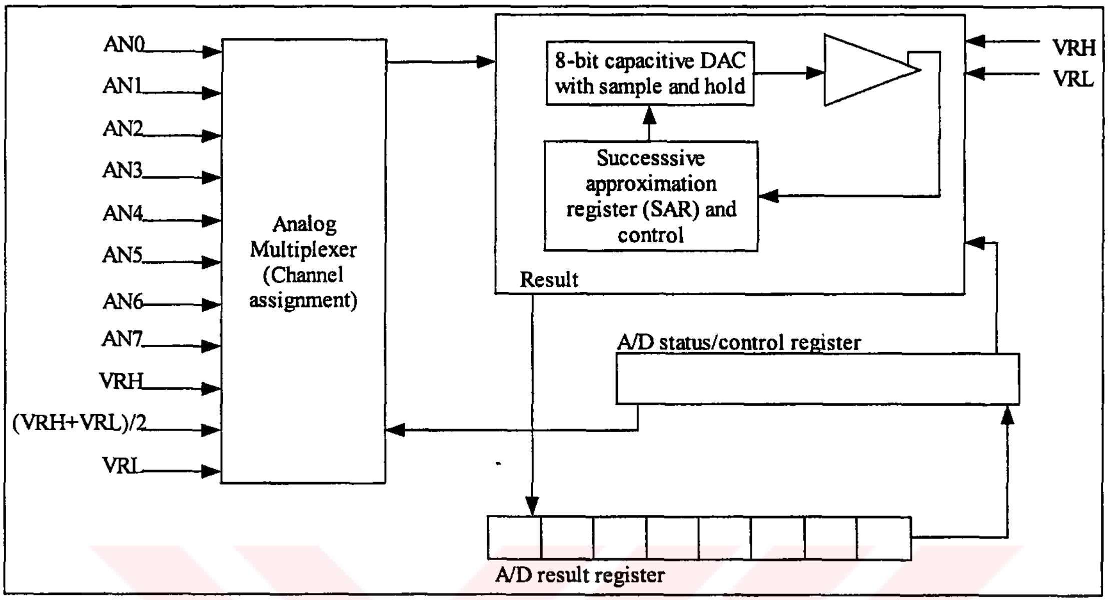


Figure 4.18 Block diagram of the A/D converter.

Figure 4.19 Data management unit is connected to the PC via serial port. Sounds can be listened by a headphone or speaker.

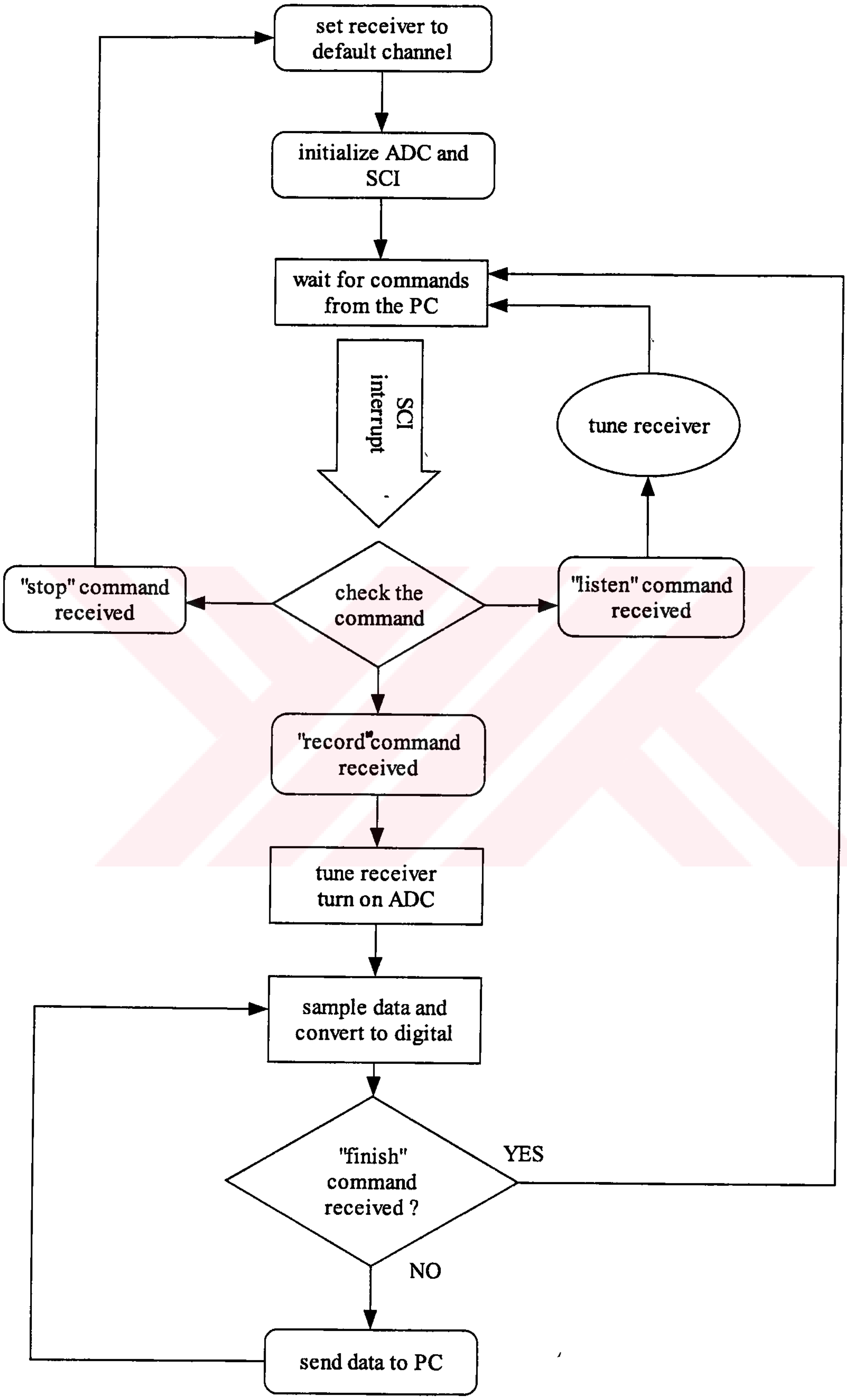


Figure 4.20 Flow chart of the microcontroller program.

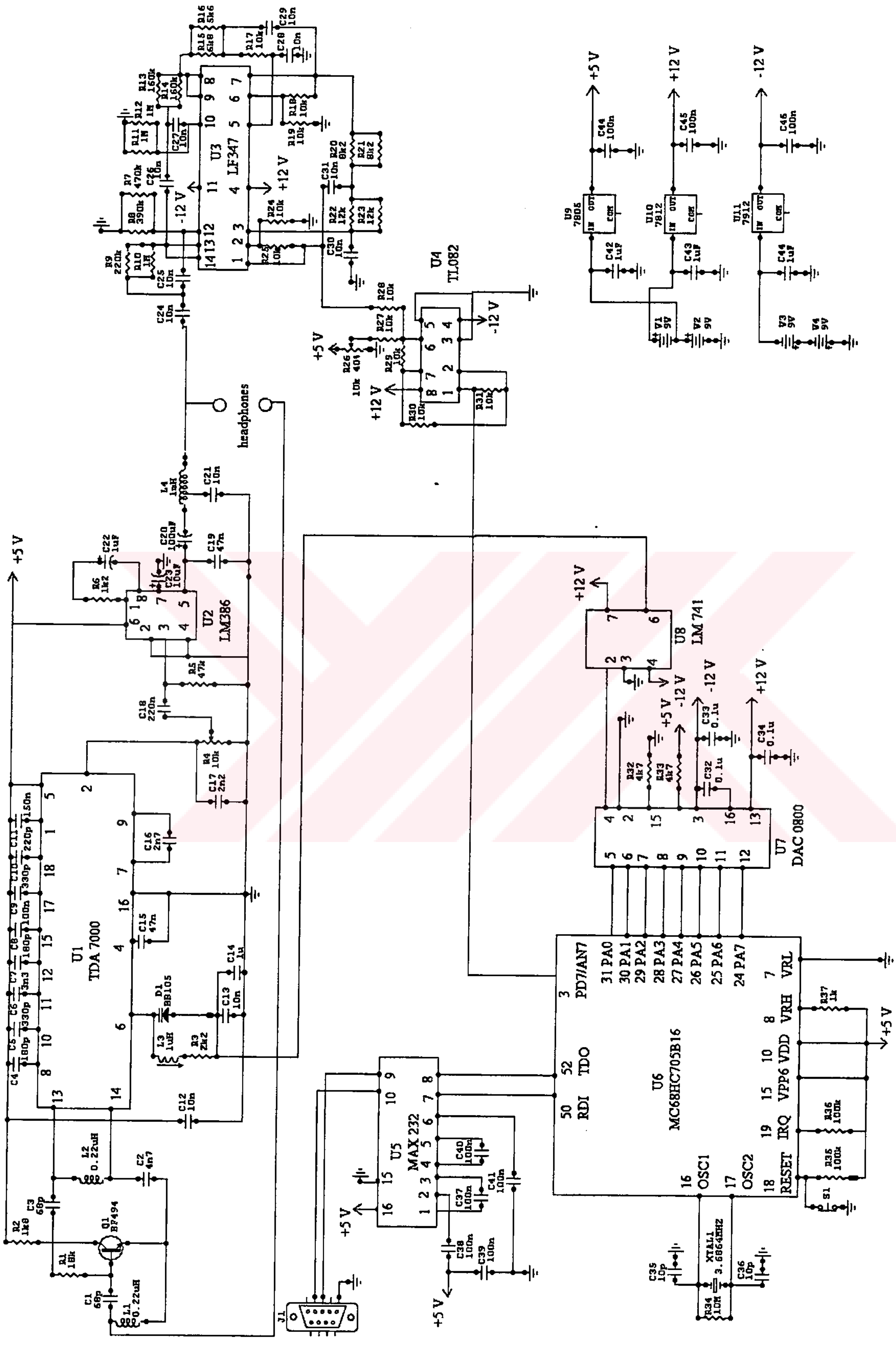


Figure 4.21 Complete schematic layout of the data management unit

4.4 User Interface

A friendly user interface is developed to control the data acquisition process. The user interface is developed on Delphi platform which is an object-oriented, visual programming language. The main screen of the interface is shown in Figure 4.17. With the help of the interface user can,

(A) select which microphone he/she wants to listen;

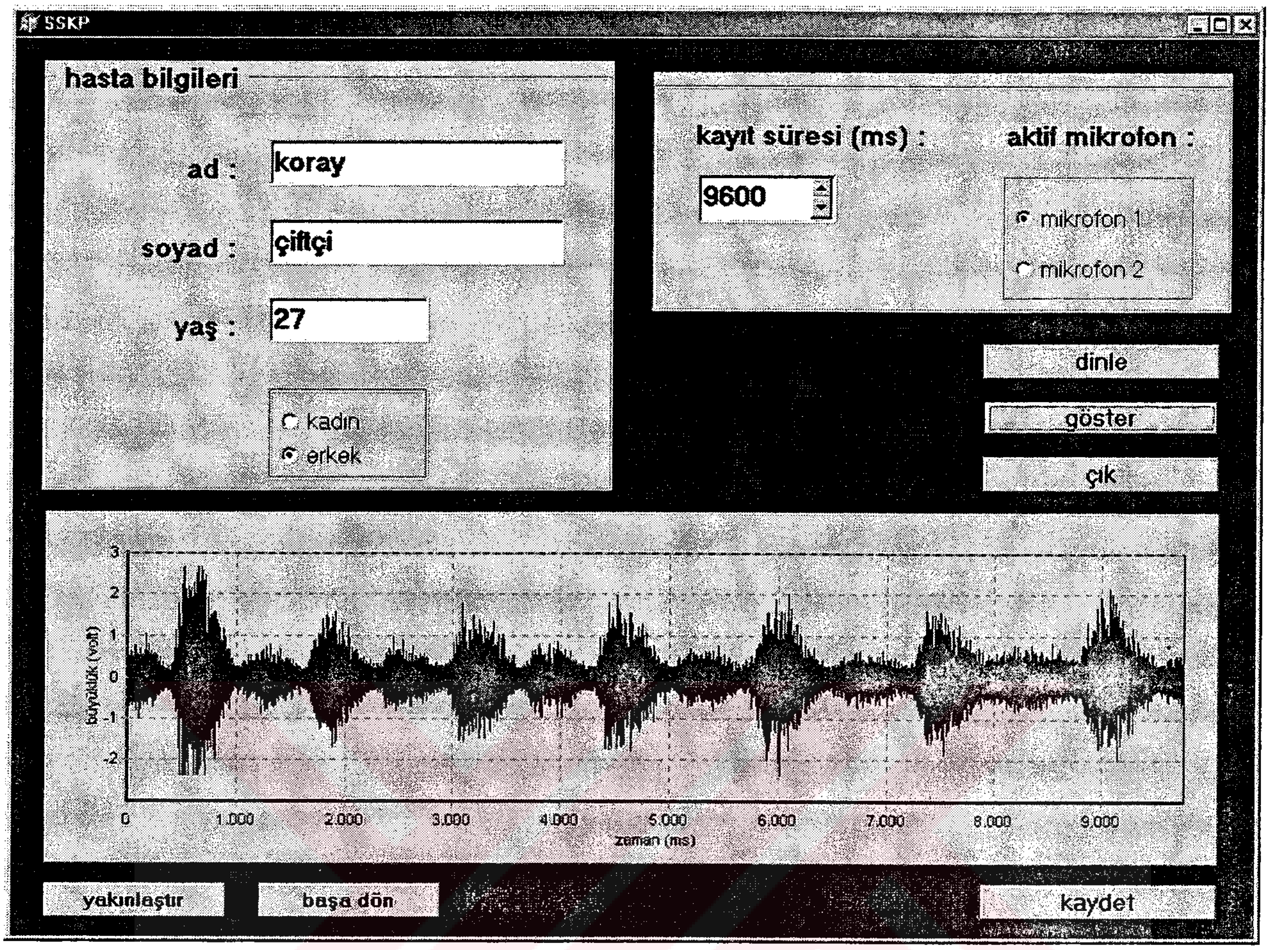
(B) specify a time period during which acquired respiratory sound data is displayed on the screen;

(C) save this respiratory sound data to a specified folder together with the personal data of the subject.

Two microphones are available for listening. Default microphone is the first microphone. When the user interface program starts, it first searches the serial port whether receiver of the telemetry unit is placed or not. If program does not receive a "I'm here" signal from the receiver then it gives an error message and program closes. If connection is established the user interface sends the requests of the user to the microcontroller on the receiver. Request may be "listen" or "record". When "record" button is pressed, for the recording to start, personal data of the patient must also be entered. When "listen" button is pressed it is not necessary to submit the personal data.

If user selects the "listen" button then the number of the microhone is sent to the microconttoller and listening starts.

If user selects the "record" button, then in addition to the number of the microphone, "digitize data" command is sent to the microcontroller. When the time period specified by the user ends computer sends "stop" command to the microcontroller and recorded data is displayed on the screen. Data chart can be zoomed and if wanted, recorded values may be saved into a file specified by the user together with the personal data of the patient.



ad : koray

soyad : çiftçi

yaş : 27

○ kadın
● erkek

kayıt süresi (ms) : 9600

aktif mikrofon :
● mikrofon 1
○ mikrofon 2

Figure 4.22 User interface window.

4.5 Notes on High Frequency Circuit Design

4.5.1 Noise Sources

Noise is of crucial concern in a high frequency circuit design. Noise cannot be eliminated totally. However, the magnitude and impact of the noise can be reduced. There are two primary classifications of noise: circuit generated and externally generated. Noise manufactured within circuits is called thermal noise (also referred to as Johnson or white noise). Thermal noise is created by a component's electrons randomly moving around under the influence of thermal energy. Shot noise, because of its characteristics, can also be considered as another type of thermal noise, but is caused by the haphazard movement of electrons across any semiconductor junction.

External noise is mainly caused by artificial sources of electromagnetic interference. Natural sources, such as the atmospheric lightning, can also be a noise source. External noise also includes space noise and cosmic noise, induced by stars radiating interfering signals in all directions.

Power of the noise, in watts, generated inside the circuit can be calculated by the formula given in (4.1).

$$P_N = KTB \tag{4.6}$$

where P_N is noise power, W

K is Boltzmann's constant, 1.38×10^{-23}

T is circuit temperature, K

B is circuit bandwidth, Hz

From the above formula, it can be deduced that, two contributors to noise in a circuit are the temperature and bandwidth of the circuit, the lower the temperature and the lower the bandwidth, the lower the noise contribution. The carrier frequency of the signal has no effect on the production of the noise.

4.5.2 Electromagnetic Interference

Sources of electromagnetic interference (EMI) includes microprocessors, transmitters, transient power components, alternating current sources and lightning. Attenuating EMI to the lowest levels possible is a major requirement for wireless design. Small RF levels flowing within the circuit can destroy the proper operation.

To reduce EMI, components must be properly placed on the printed circuit board (PCB). Analog, digital and noisy circuits must be separated to limit coupling between the subsystems. Analog and digital lines must not cross each other. Digital signal lines, especially the clock, must be kept as far as possible from analog inputs and voltage references. Input/Output chips must be placed near to the edge of the PCB and close to the connector. Running traces under clock circuits must be avoided.

High frequency, low-inductance axial glass or multi-layer ceramic capacitors should be used for decoupling ICs. Capacitors must be placed as close to the IC as possible.

Supplying a good grounding system for the circuit is especially important for reducing EMI. Building a ground plane is the best choice. However, if it is not possible, single-point or star-point grounding can be used. These techniques ground all traces to a common terminal point.

5. RESULTS AND DISCUSSION

5.1 System Performance

A biotelemetry system for the acquisition of respiratory sounds has been developed. To test the reliability of the system, microphones were removed and pure sinusoidal waves have been applied to the telemetry transmitters by a signal generator. First wave was at 500 Hz and the other was as 1000 Hz. Reproduced waveforms at the receiver are shown below.

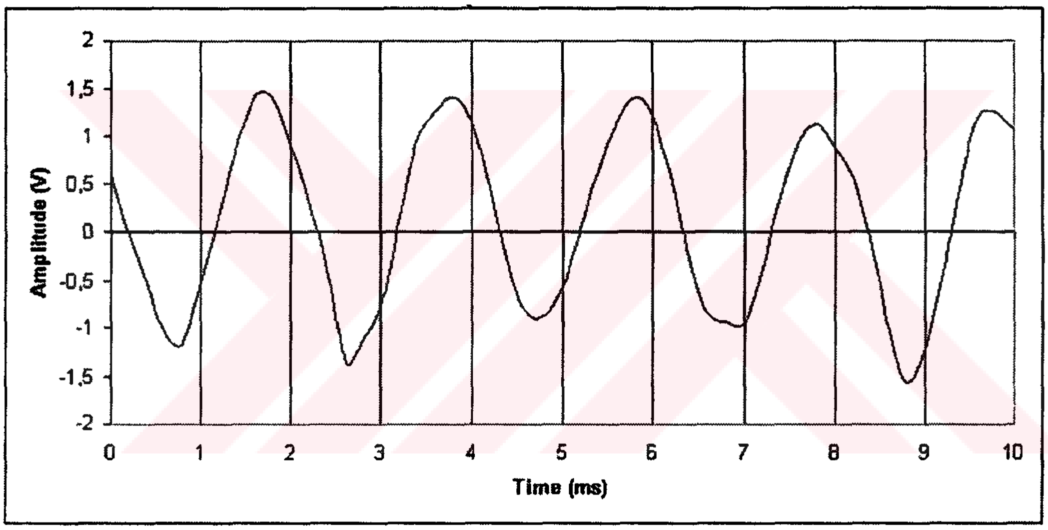


Figure 5.1a Received signal when the input is a 500 Hz sinusoid.

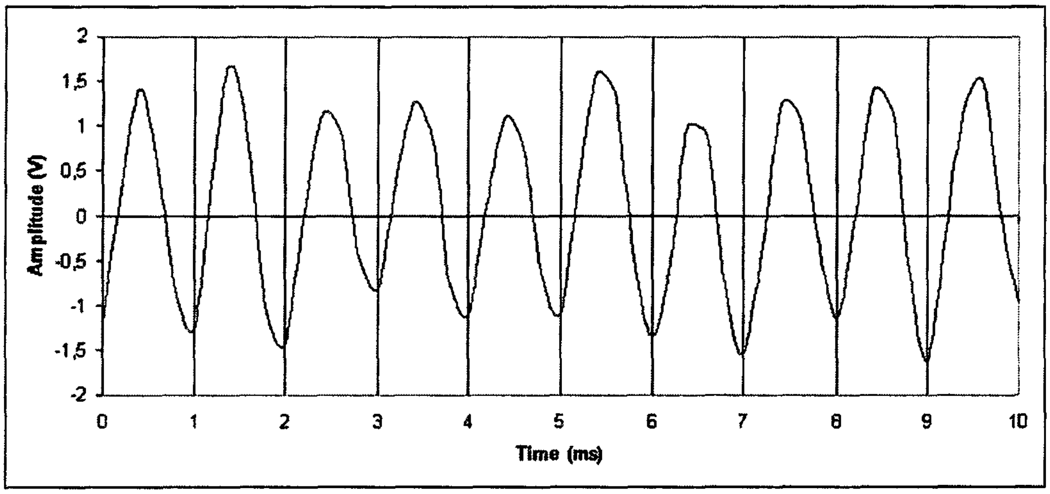


Figure 5.1b Received signal when the input is a 1000 Hz sinusoid.

Above figures give an idea about the performance of the system. Frequencies of the original signals were recovered, but some amplitude changes have occurred. When the received signals are listened it is noticed that it is not a pure sinusoid. Noise contribution of the microphone amplifier is very low. So main contribution to noise comes from the high frequency oscillator and the FM receiver.

When no input was applied to the system receiver had fluctuations less than 20 mV, which may be considered as adequate.

System was also tested on human subjects and recordings were taken at different points on the body. Three representative waveforms from a male, 27 years old subject with a mild restriction are presented in Figures 5.2a to 5.2c. Measurements were conducted in a room where distance between the subject and the information receiver is about five meters.

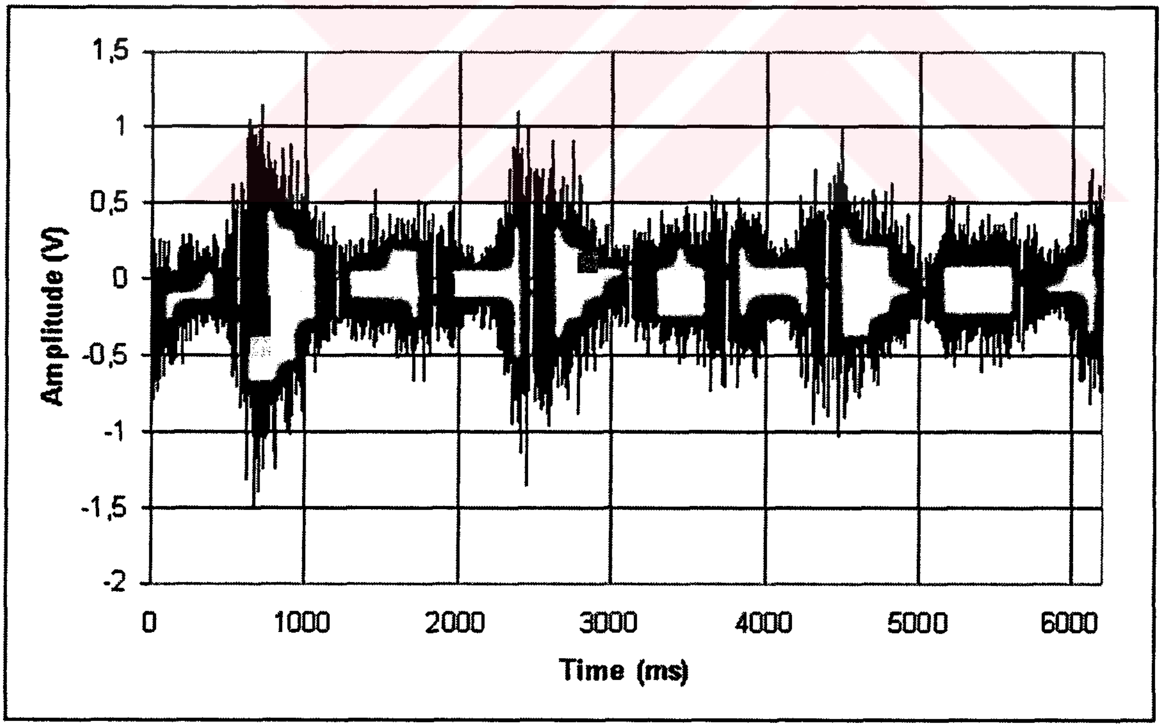


Figure 5.2a Respiratory sounds recorded from trachea.

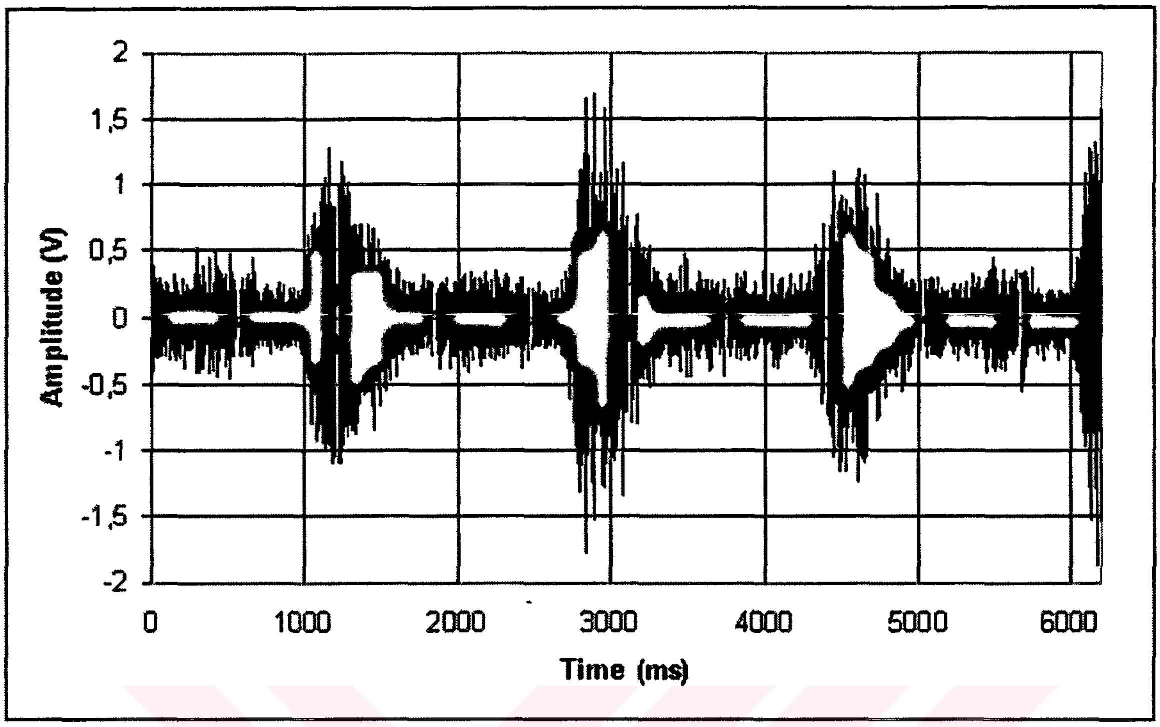


Figure 5.2b Respiratory sounds recorded over the right side of the posterior chest.

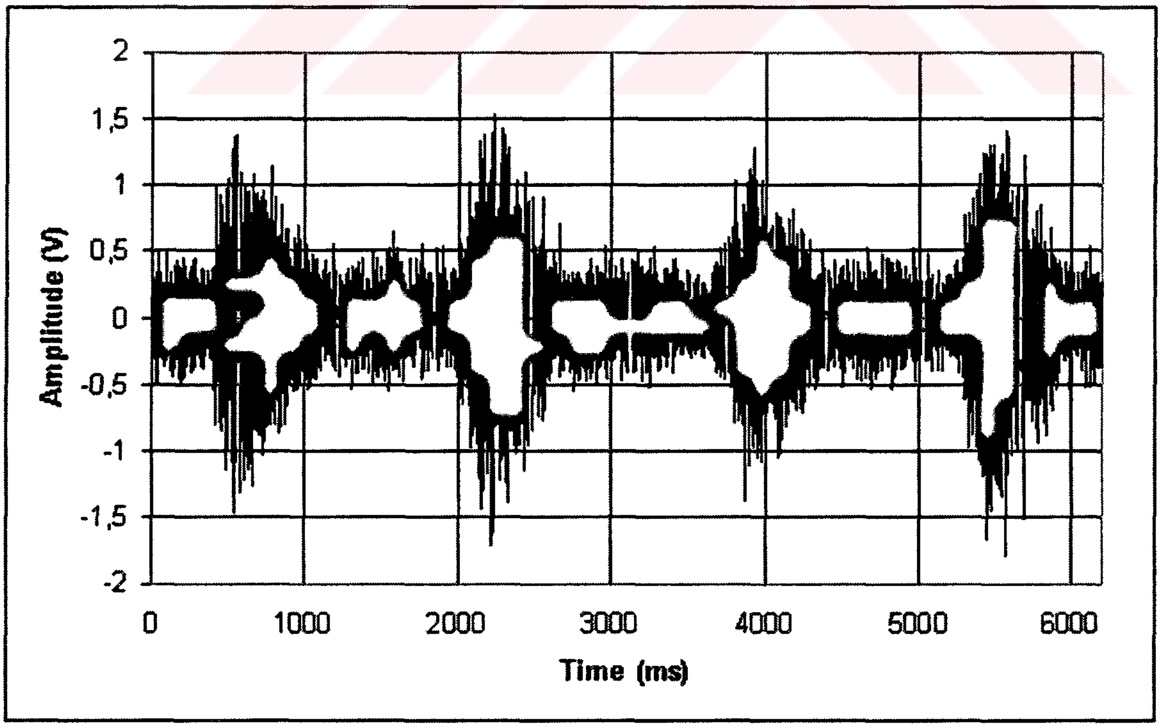


Figure 5.2c Respiratory sounds recorded over the left side of the posterior chest.

Power spectrum of the recorded sounds were calculated. 1024 point fast-fourier transform with 50% overlap were used. These values were shown to be suitable for analyzing respiratory sounds [1]. The Hanning window whose equation is,

$$W_n = 0.5 - 0.5\cos(2\pi n / N) \tag{5.1}$$

was used for windowing data. The calculated power spectral densities are presented in Figure 5.3.

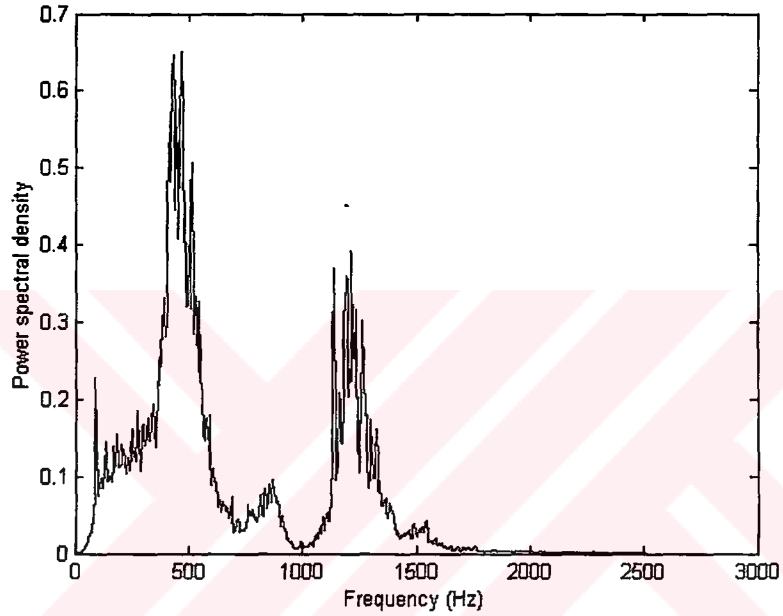


Figure 5.3a Power spectral density of the signal recorded from trachea.

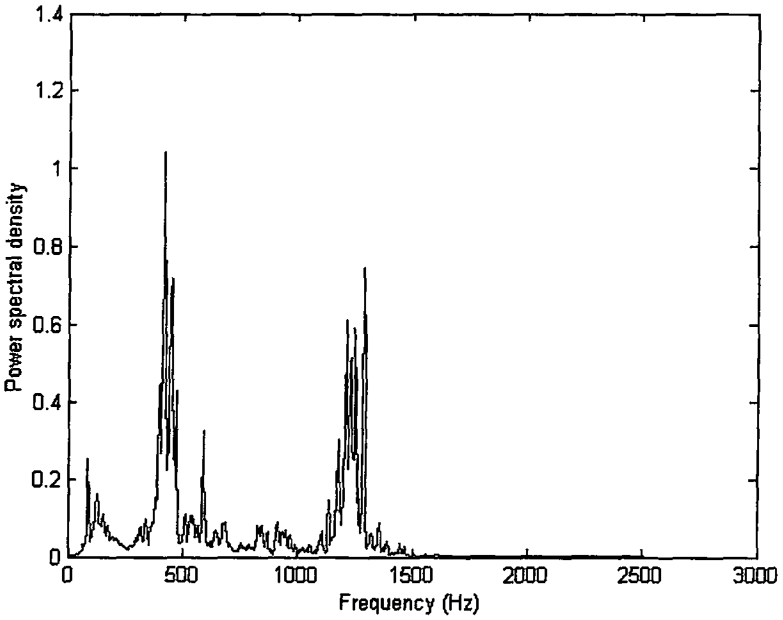


Figure 5.3b Power spectral density of the signal recorded from right posterior chest.

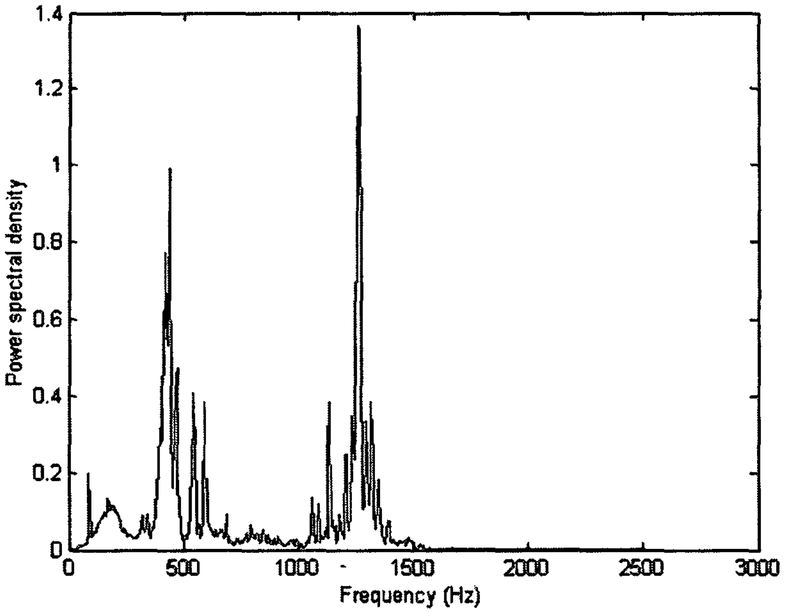


Figure 5.3c Power spectral density of the signal recorded from left posterior chest.

Results are consistent with previous findings [1], [3-4]. Frequency components are generally populated between 400-500 Hz and 1200-1300 Hz which is characteristic for restrictive patients.

5.2 Discussions for Performance Improvement

As noted in Section 4.2, an LC oscillator is used to perform FM modulation. In fact, this is a risky choice. Because LC oscillators have stability problems. An alternative might be a crystal oscillator. Some types of crystal oscillators have also been built and tested. However, they didn't yield promising results. Modulating a crystal oscillator's frequency over the entire range of respiratory sounds is difficult. A better choice is establishing a phase-locked loop (PLL), which overcomes the problem of frequency stability. However, the need for a small transmitter and keeping the number of components low, make it difficult to use a PLL transmitter.

In RF designs it is good practice to use surface mount devices (SMD). Not only reducing size, they also increase the signal-to-noise ratio of the systems. However, due to the difficulty of obtaining SMDs in small quantities, it has not been practical to use them in the present circuit realizations.

6. CONCLUSIONS

In this study, a telemetric approach to measure respiratory sounds is presented. As noted in the abstract, it must be regarded as a preliminary work. Although promising results are obtained, system needs improvements before it may be employed in the respiratory sound acquisition processes.

One additional thing I can conclude from this study is that, working in the RF range is difficult. It needs experience and patience. I think that most of the problems with the equipment presented here may be solved by small changes. However, before gaining the capability of doing that "small" changes, you must spend a lot of time to understand the behaviour of RF circuits.

6.1 Recommendations for Future Work

Reducing the size of the transmitter must be one of the main principles in newer designs. Feasibility of developing a custom chip for performing the primary tasks of respiratory sound acquisition has to be investigated.

Developing an algorithm for the detection of respiratory sounds is a challenging subject. If an algorithm like this can be developed, receiver may search a frequency range and lock itself to the frequency where a respiratory sound signal is detected.

Developing data compression algorithms for respiratory sounds is especially important for performing longterm measurements in which data is not monitored in real-time, but recorded on a unit carried by the patient.

Since respiratory sound analysis is usually performed with respect to the respiratory flow signal, building a biotelemetric apparatus for flow measurements is another important topic. It may be guessed that future of the biotelemetry of respiratory sounds will be determined by the success in developing a novel technique to telemeter flow data.

APPENDIX A

LISTING OF THE ASSEMBLER PROGRAM OF MC68HC705B16

```
TEZ1_1.ASM          Assembled with CASMW  8/19/01  9:01:21 PM  PAGE 1


                    ****************************************
                    *** program inside MC68HC705B16 *******
                    *** microcontroller tunes the receiver according to
                        the commands issued by the PC ***
                    *** sends digital data to PC via serial port
                    *** frequency of the external crystal is 3.6864 MHz
                    ****************************************
                    ****************************************
0000                    porta          equ    $00
0000                    portd          equ    $03
0000                    ddra           equ    $04
0000                    addata         equ    $08
0000                    adstat         equ    $09
0000                    misc           equ    $0c
0000                    baud           equ    $0d
0000                    sccr1          equ    $0e
0000                    sccr2          equ    $0f
0000                    scsr           equ    $10
0000                    scdat          equ    $11

                    ********************************************

0050                                   org    $0050
0050                    scdat_backup   rmb     1
0051                    mod            rmb     1

                    ********************************************

0300                                   org    $0300

0300 [02] 9C            init           rsp
0301 [02] A6FF                         lda     #$ff ;PORTA used to control the DAC
0303 [04] B704                         sta     ddra
0305 [02] A601                         lda     #$01 ;set DAC to default channel
0307 [04] B700                         sta     porta
0309 [03] B609                         lda     adstat ;AN7 is for analog data
030B [02] AA07                         ora     #%00000111
030D [04] B709                         sta     adstat
030F [05] 1A09                         bset    5,adstat ;turn on ADC
0311 [02] A600                         lda     #%00000000 ;baud rate set to 115200
```

```
0313 [04] B70D                     sta    baud
0315 [02] A600                     lda    #%00000000
0317 [04] B70E                     sta    sccr1
0319 [02] A62C                     lda    #%00101100
031B [04] B70F                     sta    sccr2
031D [05] 3F51                     clr    mod
031F [05] 190C                     bclr   4,misc
0321 [02] 9A                       cli                ;turn on interrupts

             ****************************************

0322 [03] 20FE      wait           bra    wait

             ****************************************

0324 [05] 0B107D    sci_int        brclr  5,scsr,int_end
0327 [03] B611      store_data     lda    scdat
0329 [04] B750                     sta    scdat_backup
032B [03] B651                     lda    mod
032D [02] A101                     cmp    #$01
032F [03] 270B                     beq    chk_stop
0331 [05] 0F10FD    confirm        brclr  7,scsr,confirm ;send PC confirmation
0334 [02] A641                     lda    #$41
0336 [04] B711                     sta    scdat
0338 [02] A601                     lda    #$01
033A [04] B751                     sta    mod
033C [03] B650      chk_stop       lda    scdat_backup
033E [02] A144                     cmp    #$44 ;stop byte received? stop
0340 [03] 2609                     bne    listen
0342 [02] A601                     lda    #$01
0344 [04] B700                     sta    porta
0346 [05] 3F51                     clr    mod
0348 [03] CC03A4                   jmp    int_end
034B [03] B650      listen         lda    scdat_backup
034D [02] A4F0                     and    #$f0
034F [02] A150                     cmp    #$50
0351 [03] 2618                     bne    record
0353 [03] B650      chk_nib2       lda    scdat_backup
0355 [02] A40F                     and    #$0f
0357 [02] A105                     cmp    #$05
0359 [03] 2605                     bne    mic2
035B [02] A601      mic1           lda    #$01
035D [03] CC0366                   jmp    nib2_end
0360 [02] A10A      mic2           cmp    #$0a
0362 [03] 2640                     bne    int_end
0364 [02] A6F6                     lda    #$f6
0366 [04] B700      nib2_end       sta    porta
0368 [03] CC03A4                   jmp    int_end
036B [03] B650      record         lda    scdat_backup
```

```
036D [02] A4F0      89                    and    #$f0
036F [02] A170      90                    cmp    #$70
0371 [03] 2631      91                    bne    int_end
0373 [03] B650      92 chk2_nib2          lda    scdat_backup
0375 [02] A40F      93                    and    #$0f
0377 [02] A105      94                    cmp    #$05
0379 [03] 2605      95                    bne    mic22
037B [02] A601      96 mic12              lda    #$01
037D [03] CC0386    97                    jmp    nib22_end
0380 [02] A10A      98 mic22              cmp    #$0a
0382 [03] 2620      99                    bne    int_end
0384 [02] A6F6      100                   lda    #$f6
0386 [04] B700      101 nib22_end         sta    porta
0388 [02] A627      102 a_d_converter     lda    #$27
038A [04] B709      103                   sta    adstat
                    104
038C [02] AE39      105 convert_next -    ldx    #$39 ;data is sampled at every 200us
038E [03] 5A        106 wait_200us        decx
038F [03] 26FD      107                   bne    wait_200us
0391 [05] 0B1006    108                   brclr  5,scsr,send_dat
0394 [03] B611      109                   lda    scdat
0396 [02] A133      110                   cmp    #$33 ;process continues
0398 [03] 270A      111                   beq    int_end ;until "stop" command
039A [03] B608      112 send_dat          lda    addata
039C [05] 0F10FD    113 line_empty        brclr  7,scsr,line_empty
039F [04] B711      114                   sta    scdat ;digital data is sent to PC
03A1 [03] CC038C    115                   jmp    convert_next
                    116
03A4 [09] 80        117 int_end           rti
                    118
                    119 ***********************************************
                    120
03A5 [05] 100C      121 reset2            bset   0,$0C ;routine to overcome a bug in the
03A7 [02] 8E        122               STOP           ;microcontroller
                    123                              ;mc needs a power-on-reset for
                    124                              ;proper operation
                    125
                    126 ***********************************************
                    127
3FF0                128                   org    $3ff0
3FF0     03A5       129                   fdb    reset2
3FF2     0324       130                   fdb    sci_int
3FFA                131                   org    $3ffa
3FFA     0300       132                   fdb    init
3FFE                133                   org    $3ffe
3FFE     0300       134                   fdb    init
                    135
```

Symbol Table

ADDATA	0008
ADSTAT	0009
A_D_CONVERTER	0388
BAUD	000D
CHK2_NIB2	0373
CHK_NIB2	0353
CHK_STOP	033C
CONFIRM	0331
CONVERT_NEXT	038C
DDRA	0004
INIT	0300
INT_END	03A4
LINE_EMPTY	039C
LISTEN	034B
MIC1	035B
MIC12	037B
MIC2	0360
MIC22	0380
MISC	000C
MOD	0051
NIB22_END	0386
NIB2_END	0366
PORTA	0000
PORTD	0003
RECORD	036B
RESET2	03A5
SCCR1	000E
SCCR2	000F
SCDAT	0011
SCDAT_BACKUP	0050
SCI_INT	0324
SCSR	0010
SEND_DAT	039A
STORE_DATA	0327
WAIT	0322
WAIT_200US	038E

APPENDIX B

LISTING OF THE USER INTERFACE PROGRAM

```
unit solseskay;

interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, ExtCtrls, TeeProcs, TeEngine, Chart, Spin, Menus, Grids,
  Calendar, Serial, Series, jpeg, Gauges, ComCtrls;

type
  TForm1 = class(TForm)
    SaveDialog1: TSaveDialog;
    GroupBox1: TGroupBox;
    Label1: TLabel;
    Label3: TLabel;
    Label5: TLabel;
    Edit1: TEdit;
    Edit2: TEdit;
    Edit3: TEdit;
    GroupBox2: TGroupBox;
    Label2: TLabel;
    SpinEdit1: TSpinEdit;
    RadioGroup1: TRadioGroup;
    RadioGroup2: TRadioGroup;
    Label6: TLabel;
    Button1: TButton;
    Button2: TButton;
    Chart1: TChart;
    Series1: TLineSeries;
    Button3: TButton;
    Button4: TButton;
    Button5: TButton;
    Button6: TButton;
    SerialPort1: TSerialPort;
    Timer1: TTimer;
    Timer2: TTimer;
    procedure FormCreate(Sender: TObject);
    procedure Button1Click(Sender: TObject);
    procedure Button2Click(Sender: TObject);
    procedure SerialPort1WhenReceive(Sender: TObject; data: string);
    procedure Button3Click(Sender: TObject);
    procedure Button4Click(Sender: TObject);
    procedure Button5Click(Sender: TObject);
    procedure Button6Click(Sender: TObject);
```

```
    procedure Timer1Timer(Sender: TObject);
    procedure Timer2Timer(Sender: TObject);

  private
    { Private declarations }
  public
    { Public declarations }
  end;

var
  Form1: TForm1;
  datarray: array of real;
  datalength: integer;
  connected: boolean = false;
implementation
{$R *.DFM}

procedure TForm1.FormCreate(Sender: TObject);
begin
  if not SerialPort1.OpenPort(cpCom1) then
     MessageDlg('Seri porta erişilemedi!',
    mtError, [mbOK], 0) ;
     SerialPort1.SendData('F',1); //check if the receiver is connected
    Timer2.Interval:= 1000;       // receiver must give an ansver in 1 sec
    Timer2.Enabled:= true;
end;

procedure TForm1.Button1Click(Sender: TObject);
begin
   if edit1.text <> '' then
   if edit2.text <> '' then
   if edit3.text <> '' then begin
   Series1.clear;
   Timer1.Interval:= SpinEdit1.Value;
   Setlength(datarray,0);
   if RadioGroup1.ItemIndex = 0 then      //"record" command is sent
        SerialPort1.SendData('u',1)        //to the receiver
              else
        SerialPort1.SendData('z',1);

        Timer1.Enabled:= true;
   end;
end;

procedure TForm1.Button2Click(Sender: TObject);
begin
        Series1.Clear;
        if RadioGroup1.ItemIndex = 0 then
        SerialPort1.SendData('U',1)       //"listen" command is sent
```

```
               else                                //to the receiver
       SerialPort1.SendData('Z',1);
end;

procedure TForm1.SerialPort1WhenReceive(Sender: TObject; data: string);
var
    i: integer;
begin
   datalength:= length(data);
   if  (datalength = 1) and (data = 'A') then connected:= true;
      //if 'A' is received receiver is OK
   if datalength > 10 then
   begin
   Timer1.Enabled:= False;
   Setlength(datarray,datalength);
   for i:= 1 to datalength do
          datarray[i-1]:= ord(data[i]);   //get data in buffer
   for i:= 0 to datalength - 1 do
     datarray[i]:= 5 - (((255 - datarray[i]) / 255) * 5) - 2.35;
    for i:= 0 to datalength - 1 do          //draw the chart
      Series1.addxy(i*0.2,(datarray[i]),'', clBlue);
   end;
end;

procedure TForm1.Button3Click(Sender: TObject);
begin
  SerialPort1.SendData('D',1);     //send receiver "stop" command
  SerialPort1.ClosePort;
  close;
end;

procedure TForm1.Button4Click(Sender: TObject);
begin
 Chart1.AllowZoom:= true;
end;

procedure TForm1.Button5Click(Sender: TObject);
begin
 Chart1.UnDoZoom;
end;

procedure TForm1.Button6Click(Sender: TObject);
var
      i: integer;
      F1: TextFile;
begin
//save data with personal knowledge about the patient
 with SaveDialog1 do
   begin
```

```
    Filter := 'TextFile';
    Filename := Edit1.text + Edit2.text;
    Options := [ofPathMustExist];
    if Execute then
    begin
        AssignFile(F1, Filename);
        Rewrite(F1);
        writeln(F1,Edit1.text);
        writeln(F1,Edit2.text);
        if  Radiogroup2.ItemIndex = 0 then writeln(F1,'kadın')
              else    writeln(F1,'erkek');
        writeln(F1,Edit3.text);
        writeln(F1,'Toplam ' + inttostr(datalength) + ' örnek');
        for i:=0 to datalength - 1 do
            writeln(F1,floattostr(datarray[i]));
        closefile(F1);
    end;
    end;
end;

procedure TForm1.Timer1Timer(Sender: TObject);
begin
  SerialPort1.SendData('3',1);
end;

procedure TForm1.Timer2Timer(Sender: TObject);
begin
   Timer2.enabled:= false;
   if not connected then
   //if receiver cannot be sensed ask the user
   //whether to try again or not.
   begin
   if MessageDlg('Bağlantı kurulamadı. Yeniden dene?',
   mtConfirmation, [mbYes, mbNo], 0) = mrNo
   then
   begin SerialPort1.ClosePort;
   close end
   else begin
      SerialPort1.Senddata('F',1);  //check for the receiver again
      Timer2.enabled:= true; end;
   end;
end;

end.
```

APPENDIX C

PCB DRAWINGS OF THE CIRCUITS USED IN THE SYSTEM

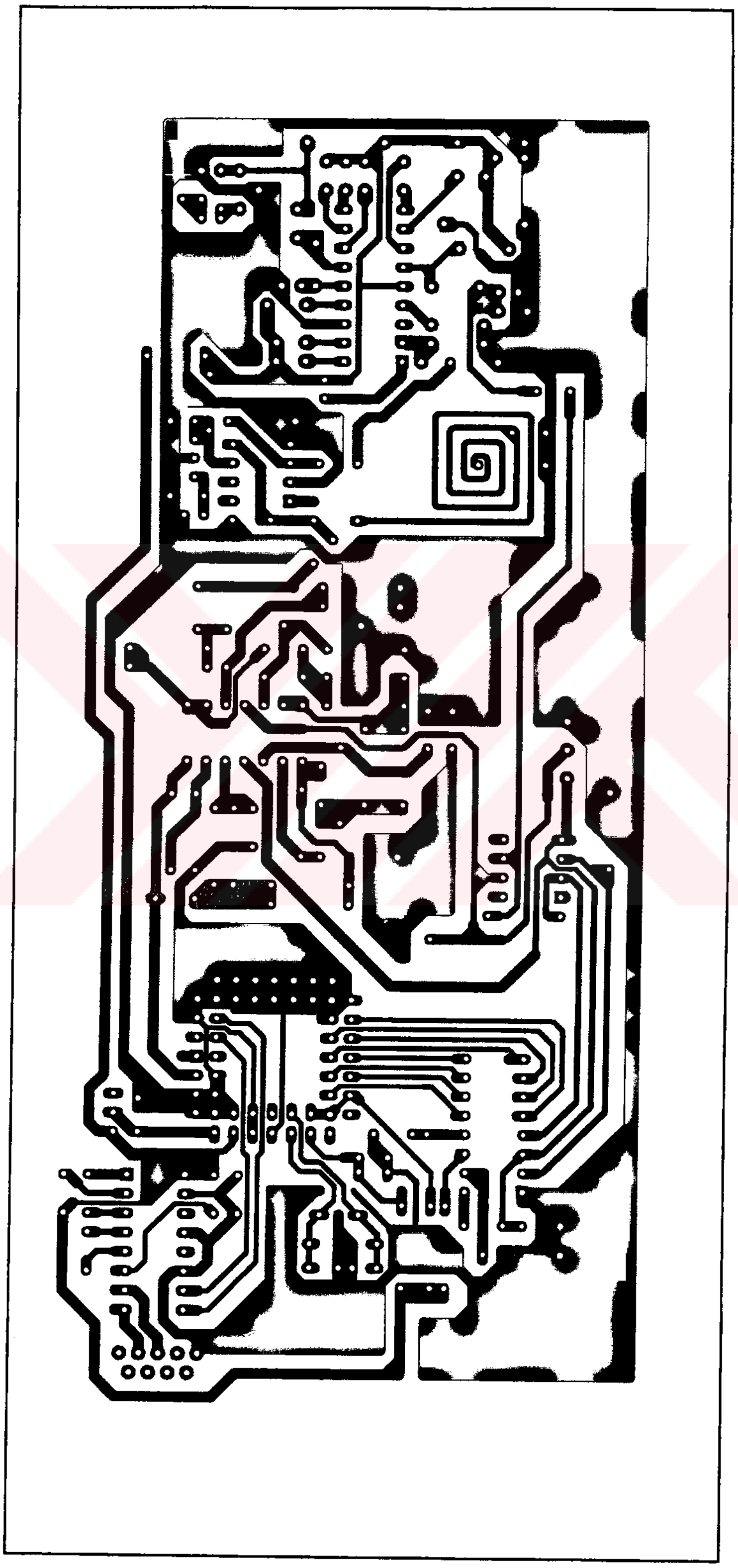


Figure C.1 PCB drawing of the data management unit.

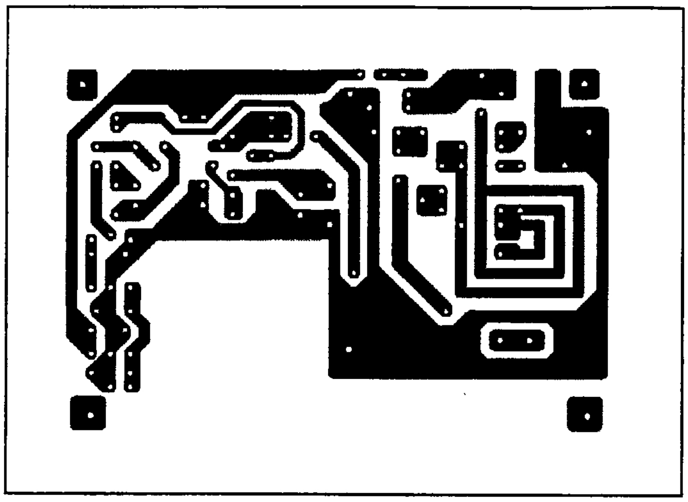


Figure C.2 PCB drawing of the telemetry transmitter.

APPENDIX D

TABLES AND CHARTS FOR FILTER DESIGN

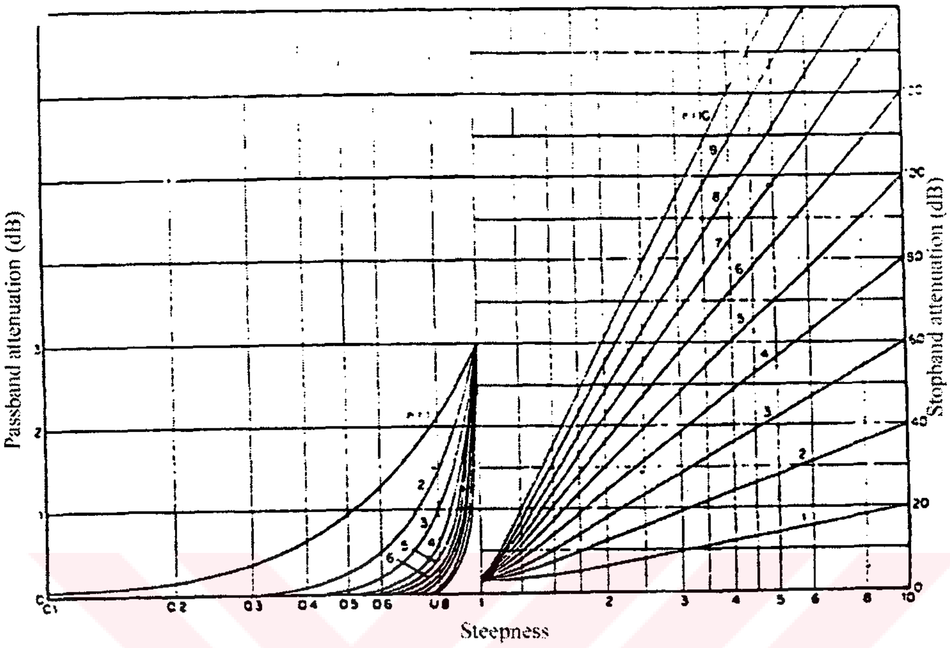


Figure D.1 Attenuation characteristics for Butterworth filters [39].

Table D.1
Butterworth active low pass values [39].

Order *n*	C_1	C_2	C_3
2	1.414	0.7071	
3	3.546	1.392	0.2024
4	1.082	0.9241	
	2.613	0.3825	
5	1.753	1.354	0.4214
	3.235	0.3090	
6	1.035	0.9660	
	1.414	0.7071	
	3.863	0.2588	
7	1.531	1.336	0.4885
	1.604	0.6235	
	4.493	0.2225	
8	1.020	0.9809	
	1.202	0.8313	
	1.800	0.5557	
	5.125	0.1950	
9	1.455	1.327	0.5170
	1.305	0.7661	
	2.000	0.5000	
	5.758	0.1736	
10	1.012	0.9874	
	1.122	0.8908	
	1.414	0.7071	
	2.202	0.4540	
	6.390	0.1563	

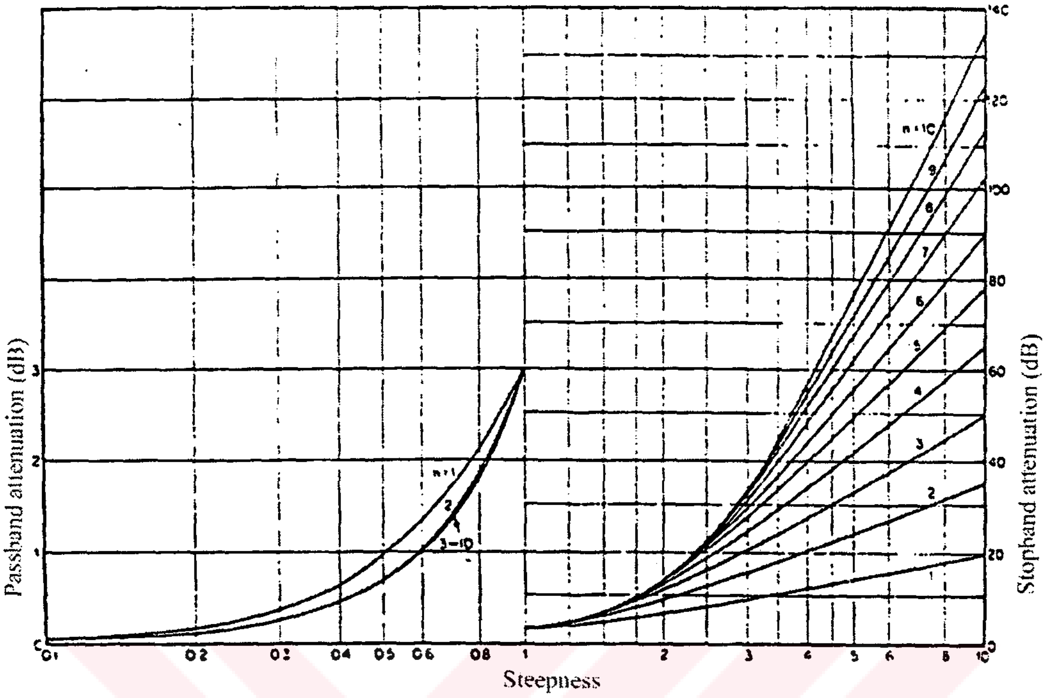


Figure D.2 Attenuation characteristics for Bessel filters [39].

Table D.2
Bessel pole locations [39].

Order n	Real part -α	Imaginary part ±β
2	1.1030	0.6368
3	1.0509 1.3270	1.0025
4	1.3596 0.9877	0.4071 1.2476
5	1.3851 0.9606 1.5069	0.7201 1.4756
6	1.5735 1.3836 0.9318	0.3213 0.9727 1.6640
7	1.6130 1.3797 0.9104 1.6853	0.5896 1.1923 1.8375
8	1.7627 0.8955 1.3780 1.6419	0.2737 2.0044 1.3926 0.8253
9	1.8081 1.6532 1.3683 0.8788 1.8575	0.5126 1.0319 1.5685 2.1509

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