Optical System Design of a Laser-Based Stethoscope

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Dedication

For my beloved grandmother Mamite Haile Selassie and my roommate Amanuel Goitom.

God rest your soul in eternal peace.

Abstract

In this paper, we demonstrate the development of a new type of stethoscope using laser technology to visualize the heart beat signal. This heartbeat detection technique could overcome the limitation of the acoustic stethoscope brought by the poor ability of human ears to hear low frequency heart sounds. This is important, as valuable information from sub-audio sounds is present at frequencies below the human hearing range. Moreover, the diagnosis accuracy of the acoustic stethoscope is also very sensitive to noise from the immediate environment. In this laser-based stethoscope, the heartbeat signal is correlated to the optical spot of a laser beam reflected from a thin mirror attached to the patient's chest skin. The motion of the mirror with the chest skin is generated by heartbeat and breathing. A linear optical sensor is applied to detect and record the motion of the optical spot, from which the heart sound signal in time-domain is extracted. The heart sound signal is subsequently transformed to frequency domain through digital signal processing. Both time domain and frequency-domain signals are analyzed in order to classify different types of heart murmurs. A digital filter is designed to remove other activities associated with the movement of chest skin, such as respiration. We developed the prototype of the system and tested the prototype on a dummy human body with various heartbeat patterns and breathing. We compared the laser generated results with the concurrent testing results from phonocardiography. Results reveal that the laser based heart sound detection approach has the advantage over the phonocardiography for low frequency sounds ($\leq$ 50Hz) while the phonocardiography is more sensitive to higher frequency sounds $\geq$ 200Hz).

Thus, the laser heartbeat detection approach could supplement the current heartbeat techniques by being sensitive to low frequency heart sounds and being robust to the environmental noises. It could be helpful in reducing errors in heart sound classification by practitioners and reduce unnecessary referrals. Additionally, the visual aspect of this stethoscope will provide sub- audio (below the human hearing range) and images of sounds to the practitioner.

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List of Abbreviations

CVD - Cardiovascular disease

CHD- Coronary Heart Disease

WHO – World Health Organization

LBS – Linear Based Stethoscope

EKG/ECG – Electrocardiogram

PCG – Phonocardiogram

HPF – High Pass Filter

Hz – Hertz (Frequency)

Chapter 1

Introduction

The three major events that cause heart sounds are: contraction and relaxation of heart, opening and closing of valves, and blood flow turbulance. Cardiac diagnosis uses auscultation to determine the state of the heart. Auscultation is used to determine the condition of the heart before any other tests. It is critical to get the right information from the heart sound; otherwise deadly cardiac problems will be over looked. The stethoscope is the most commonly used device to listen to the human heart. The accuracy of using a stethoscope differs among practitioners depending on experience. There is a big window to make mistakes between beginners and experienced practitioners. The other problem is the human ear is able to hear only between 20Hz – 20KHz. Using the laser based device we can get important information below 20Hz that can help diagnose cardiac problems.

This thesis report is on the study of heart murmur detection/classification using a laser based stethoscope. The goal of the project was to develop a system for the detection and classification of various types of human heart murmurs among heart patients. Especially for those heart murmurs that are impossible to hear with the human ear. This will be a useful for the patient as well as the physicians during the early diagnosis process.

1.1 Background

The history of auscultation goes back to the time of Hippocrates (460-377 BC); he provided the foundation of auscultation. At that time practitioners put their ear against the chest of a patient and described the sound they heard from the patient. The inventor of the stethoscope, Rene Theophile-Hyacinthe Laennec, also used the same method.

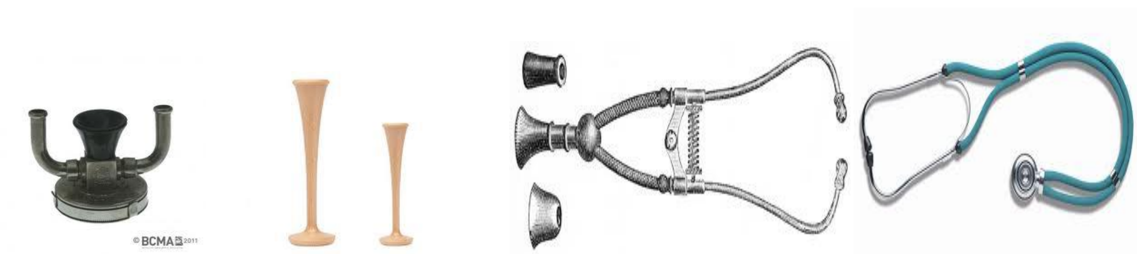


Figure 1 Different types of stethoscope [1]

In the early 1800's a Frenchman named Dr. Lalnnec was examining a young woman patient. As he stated 'The patient's age and sex did not permit direct application of the ear to the chest'. Also percussion and palpation provided little about the state of the patient. He decided to roll up a paper to avoid physical contact and use that to hear the heart beat of the patient. He was surprised and pleased to hear the beating of the heart much more clearly than if he had applied his ear directly to the chest. Even though it was not quickly adopted, the stethoscope became the most widely used diagnostic instrument in the medical world. There have been many changes throughout the years but still the underlying technology remains the same [1].A sample selection of stethoscopes from different eras is presented in figure 1.

The motions of internal parts of the body produce sounds which may indicate the health condition of the individual. This information is very important to decide the status of the patient and has been widely used since 400BC. Today auscultation is one of the widely used diagnostic techniques. Important information about the status of the heart and lung can be provided using auscultation.

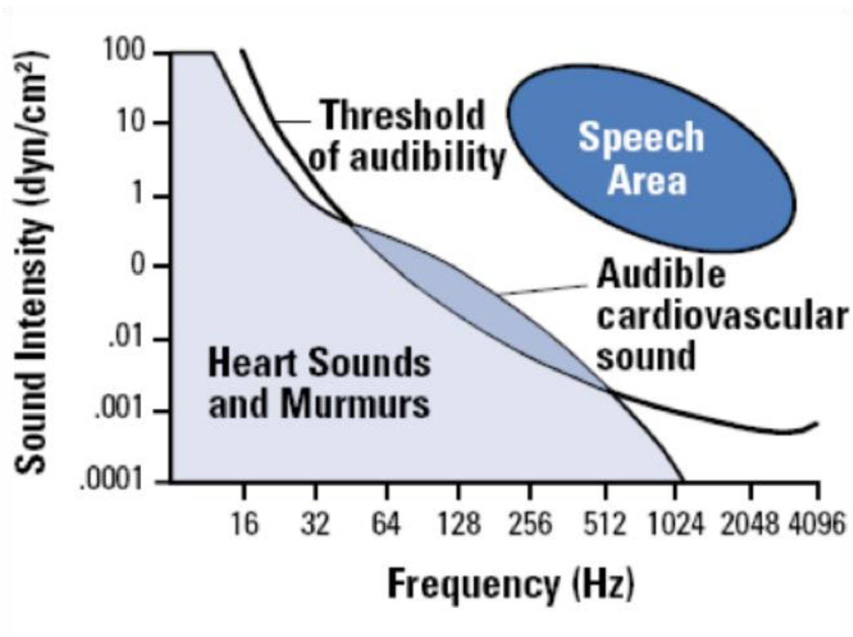


Figure 2 The frequency content of heart sounds and murmurs in relation to the human threshold of audibility.

Heart sounds and murmurs are of relatively low intensity and are band limited to about 10-1000 Hz. 50-80% of the population has murmurs during childhood, whereas only about 1% of these murmurs are pathological [2]. A simple tool able to screen murmurs would be both time and cost saving while relieving many patients from needless anxiety. Meanwhile, human hearing is adapted to speech. The auscultatory skills amongst physicians demonstrate a negative trend. The art of auscultation is often described as quite difficult, partly because of the fact that only a portion of the cardiac-blood vibrations are audible, see Figure 2.

This explains why physicians sometimes find it easier to detect heart sounds by palpation than by auscultation. A laser based Stethoscope will make use of the extra information available in the low frequency range, avoiding unnecessary referrals. Unlike other devices (*i.e* Phonocardiogram, Electrocardiogram) it provides time and frequency domain analysis of human heart beat/murmur making detailed analysis possible.

1.2 Motivation

The human heart is the size of a fist but it is the strongest muscle in the human body. The heart starts to beat in the uterus long before birth, usually by 21 to 28 days after conception. The average heart beats about 100,000 times daily or over 2 and half billion times over a 70 year lifetime. This remarkable system is vulnerable to breakdown and assault from a variety of factors, many of which can be prevented and treated.

According to a World Health Organization (WHO) report, 17 million people around the globe die of cardiovascular disease (CVD) each year. CVD are the number one cause of death globally.

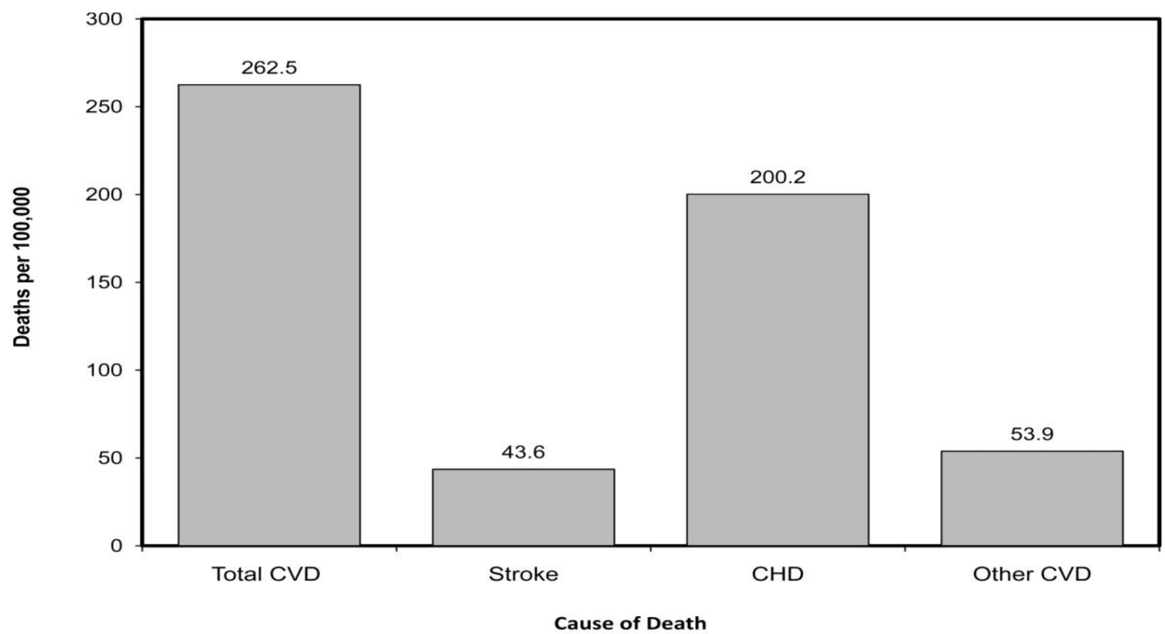


Figure 3 US age-standardized death rates from cardiovascular diseases, 2006[3]

In the United States an estimated 82 million adults have one or more type of CVD [3]. Each year more than 700,000 people die of heart diseases and among those heart diseases cardiovascular disease shares a significant proportion and is the leading cause of death as shown by the graph in Figure 3. Even though the number of deaths due to cancer is increasing each year, CVD is still the major cause of death in the United States.

Cardiovascular diseases are a group of disorders of the heart and blood vessels and include coronary heart disease (CHD), stroke, heart failure, high blood pressure, disease of arteries, cerebrovascular disease and others. Abnormalities in the heart like stroke, heart failure and arthymia are significant contributors in CVD’s and can be detected by listening to the heart sounds and/ or early detection method. Almost 24% of the overall deaths due to CVDs are caused by stroke and heart failure which are potentially due to CVDs as illustrated in the pie chart in Figure 4.

Even though the number of death due to CVDs is declining a large portion of the population suffers due to CVDs. On average, more than 2200 Americans die of CVD each day, an average of one death every 39 seconds. Among an estimated 45 million people with functional disabilities in the United States, heart disease, stroke and hypertension are among the 15 leading condition that caused those disabilities. The estimated direct and indirect cost of CVD for 2007 is $286.6 billion dollars.

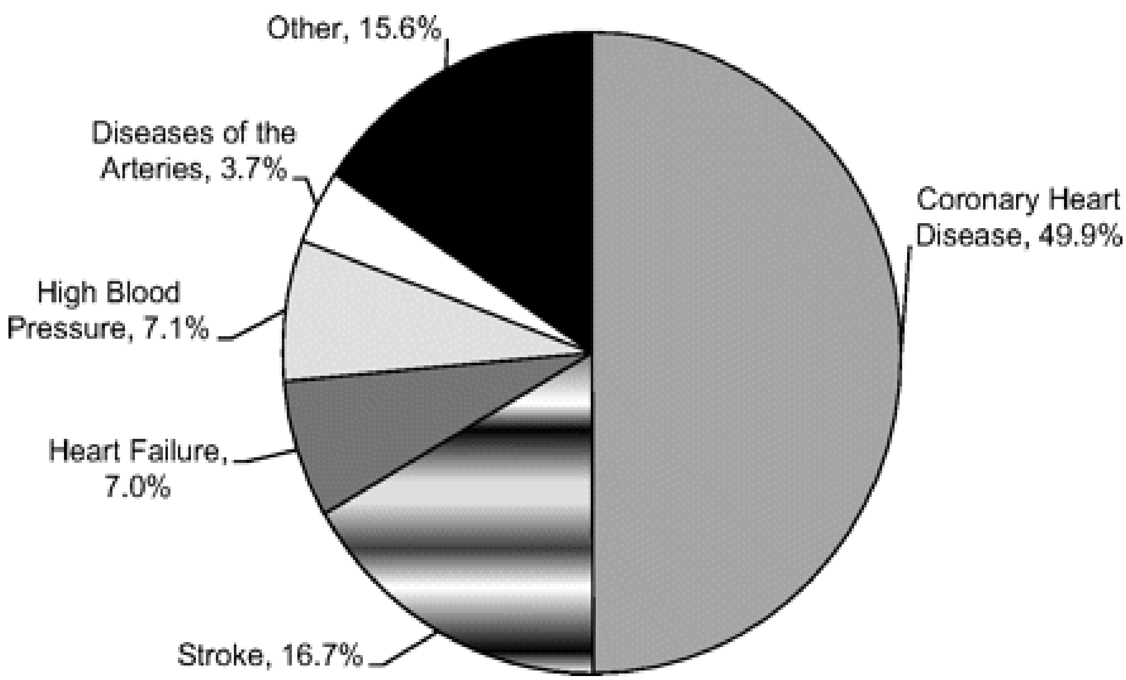


Figure 4 Pie Chart for different CVDs [3]

There is a great impact on life and money that heart disease causes. Early detection is the key to reduce the death rate due to heart diseases. A study of the decrease in US deaths due to coronary heart disease from 1980 to 2000 suggests that approximately 47% of the decrease was attributed to increased use of evidence based medical therapies. Thus it is very important to have correct information on the condition of the heart. Although some advanced testing options are available, due to their operational complexity and cost, much of the early diagnoses are made by a primary care physician using a conventional stethoscope. The auscultation-based process of early heart murmur detection using a stethoscope is very subjective and success rates vary enormously from physician to physician depending on training and practice–experience e.g from 20% for a trainee to 80% for an expert cardiologist [4]. The other issue with auscultation is external noise interference while listening to the patient. New devices being developed like radio frequency (RF) heart beat detection are prone to external noise and RF reflection. The most commonly used device in research and study the phonocardiograph has standardization problems which make it difficult to get uniform results. To mitigate these undesired outcomes, it is essential that the early diagnosis process be made more scientific and rigorous. That is why we need to have a device that is not affected by noise and external factors. This project will explain the laser based stethoscope prototype which is able to detect the human heart beat accurately.

1.3 Scope

Before explaining the concept of the design and development of the laser based stethoscope a brief background information on physiology of the heart and different devices used to measure heart activities will be discussed in chapter 2. Chapter 2 will explain how the heart functions as a pump in our body, the different sounds that are created by the pumping of blood, and different devices used to monitor the activity of the heart by physicians.

In chapter 3, we will discuss the design methodology, prototype setup and the components used in the project. A detailed description of the specification of the devices used in the research will be explained.

In chapter 4, we will discuss the prototype setup, how the project was implemented on a dummy human body, and the testing results. A detailed description will be given how the system is used to classify heart beat/murmurs.

In chapter 5, we will conclude the discussion with some suggestions for future work.

Chapter 2

Background on device of heart beat/murmur detection

Before proceeding to different devices used to classify human heart beat/murmurs, an overview is given on how the human heart works. We will briefly review the physiology of the heart, and heart sound and murmur.

2.1 Physiology of Heart

Human heart plays a fundamental role in the pumping of blood throughout the body. Figure 5 shows the basic anatomy of the human heart. Next-with a brief introduction to the reader about the working of heart, a short tour of heart physiology is provided. Heart consists of four chambers namely left ventricle, right ventricle, left atrium and right atrium.

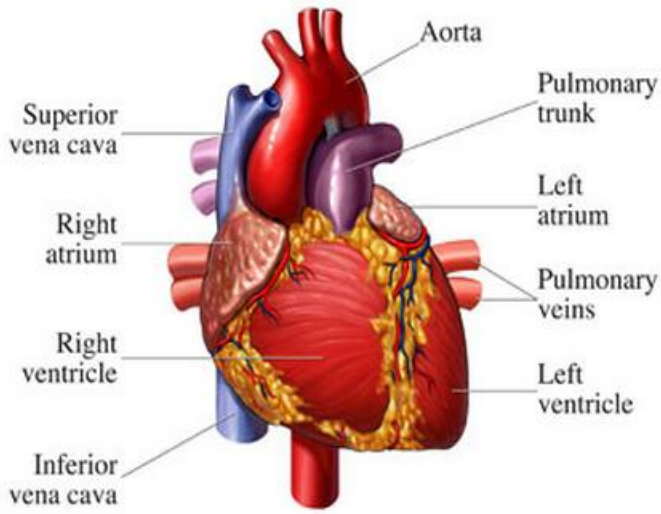


Figure 5 Human heart

The block diagram in Figure 6 shows how the heart works. As shown on the picture deoxygenated blood from upper (via the superior vena cava) and lower (via the inferior vena cava) part of the body enter to the right atrium. Right atrium contract filling the right ventricle (via the atrioventricular valve). Blood from the right ventricle is pumped to the lung (via the right seminular valve). In the lung the de-oxygenated blood picks up oxygen and get to the left atrium (via the pulmonary vein). The left atrium contract pumping blood to the left ventricle (via the left atrioventricular valve). From the left ventricle blood is pumped through the body.

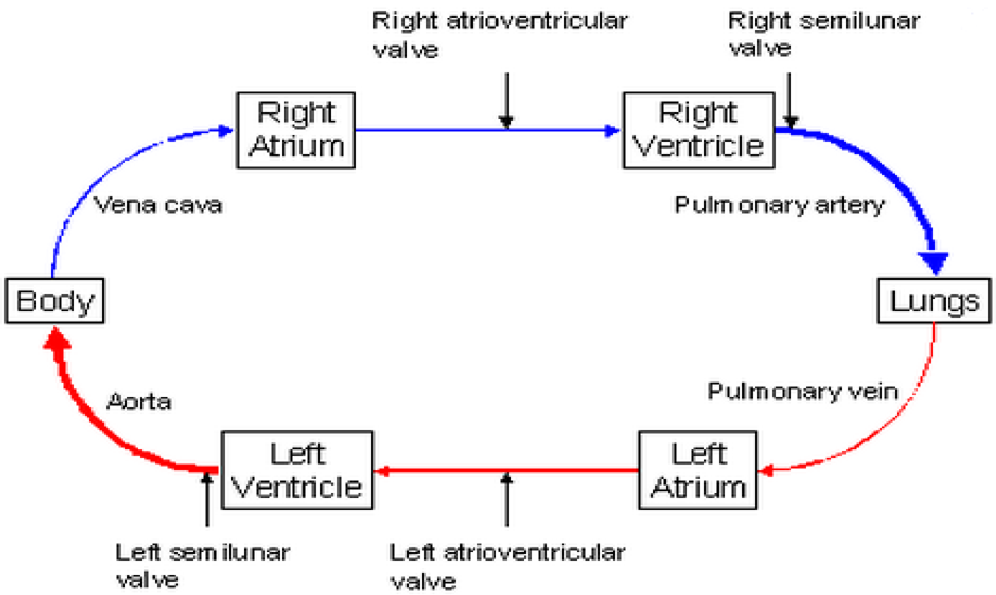


Figure 6 Block diagram of pumping cycle of heart

2.2 Pumping Cycle of the Heart

The pumping of the heart is divided into two parts – the systole and diastole. The period of contraction is called systole and the period of relaxation, diastole. The heart sounds 'lub - dub' occur at the time of the closure and opening of the major heart valves. The first heart sound or S1 ('lub') occurs during systole, and the second heart sound or S2 ('dub') occurs during diastole [5]. Figure 7 shows a one cycle of heart sound with S1 and S2 labeled.

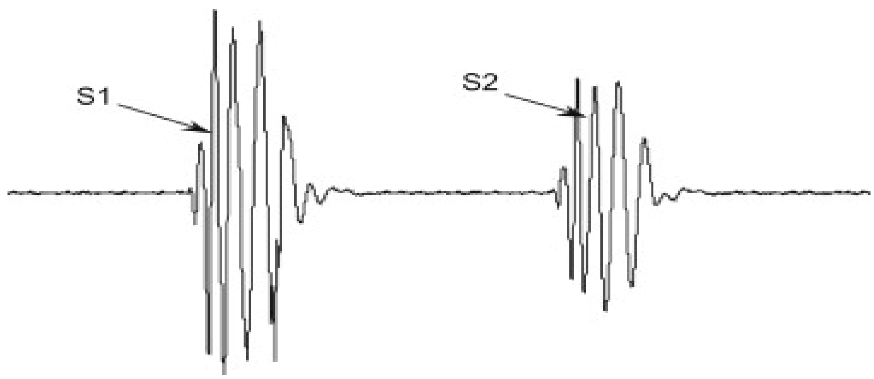


Figure 7 Typical Heart Sound cycle

2.3 Heart Sound and Murmurs

If the heart is working normally, the heart sounds consist of cycles of S1 and S2 only. However, if there is a heart malfunction (e.g., a major valve not closing or fully opening properly, an artery or vein clog etc.), some extraneous sounds – known as heart murmurs – can be heard in the heart pumping cycle [6]. A heart murmur is an extra or unusual sound heard during the cardiac cycle. A heart murmur is not a disease; it could be normal, or a symptom of a heart problem. Some of the common heart sounds are listed in Table 1.

Table 1 List of Common heart sounds [7]

Heart sound	Sound occur during	Associated with
S1	Isovolumetric contraction	Mitral and tricuspid valves closure
S2	Isovolumetric relaxation	Aortic and pulmonary valves closure
S3	Early ventricular filling	Normal in children; in adults, associated with ventricular dilation
S4	Atrial contraction	Associated with stiff, low compliant ventricle

Usually, extraneous heart murmur sounds are quieter than the S1 and S2 sounds, especially if the malfunction is at an early stage [8]. This is one of the major reasons that heart murmurs cannot be always accurately detected using a conventional stethoscope.

Extraneous heart sounds can occur during either the systolic or diastolic periods of the heart cycle. An extraneous heart sound occurring during the systolic period (i.e, between S1 and S2) is called a systolic murmur. Similarly, an extraneous heart sound occurring during the diastolic period (between S2 and S1), is called a diastolic heart murmur. Table 2 list some of the common murmurs, the description, and the information it provides.

Table 2 List of heart murmurs

Murmur	Description	Indication
Presystolic Murmur	Occurs during late diastole, caused by contraction of the atria.	Mitral Stenosis Narrowing of the AV valves
Middiastolic Murmur	Begins after the AV valves have opened in diastole.	Mitral Stenosis
Machinery Murmur	Continuous rumbling murmur, heard throughout systole and diastole.	PatentDuctus Arteriosus
Hemic Murmur Flow Murmur	Murmur heard, but no valvular lesions. Due to blood turbulence.	Anemia
Austin Flint Murmur	Presystolic murmur similar to mitral stenosis, heard at cardiac apex. Caused by regurgitation from Aorta partially narrowing the mitral	Aortic Insufficiency

	valve.	
Ejection Murmur	Diamond-shaped systolic murmur ending before the second heart sound, produced by the ejection of blood into the Aorta or Pulmonary Arteries	Aortic Stenosis Pulmonic Stenosis
Cardiopulmonary Murmur	Related to movement of the heart, and disappearing when the breath is held.	Innocent
Early Diastolic Murmur	Begins right after the second heart sound.	Aortic Insufficiency

2.4 Heart beat detecting devices

The information from murmurs is very essential in cardiac diagnosis. The medical world uses different devices to diagnose the heart pathology. The most commonly used ones are stethoscope, electrocardiogram, and phonocardiograph. These devices help the practitioner to know the condition of the patient.

2.4.1 Stethoscope

A stethoscope is a diagnostic instrument used by health care professionals to listen to a patient’s heart, lungs, various pulse points and bowel sounds. It is most often used to listen to heart sound and lungs. There are two types of stethoscope: acoustic and electronic. The most commonly used stethoscope is the acoustic stethoscope.

The acoustic stethoscope operates on the transmission of sound from the chest piece, via air filled hollow tubes, to the listener ears. A typical stethoscope is shown in Figure 8.The chest piece usually consists of two sides that can be placed against the patient for sensing sound – a diaphragm (Plastic disk) or bell (Hollow cup). The diaphragm and the bell work as two filters, transmitting higher frequency sounds and lower frequency sounds, respectively. If the diaphragm is placed on the patient, body sounds vibrate the diaphragm, creating acoustic pressure waves which travel up the tubing to the listener's ears. If the bell is placed on the patient, the vibrations of the skin directly produce acoustic pressure waves traveling up to the listener's ears. The bell transmits low frequency sounds, while the diaphragm transmits higher frequency sounds. This 2-sided stethoscope was invented by Rappaport and Sprague in the early part of the 20th century.

The drawback of the acoustic stethoscope is that the diagnosis accuracy is limited by the listening capability of human ears, which is between 20Hz – 20KHz. And heart murmur detection using a stethoscope is very subjective and success rates vary enormously from physician to physician e.g from 20% for a trainee to 80% for an expert cardiologist [4].

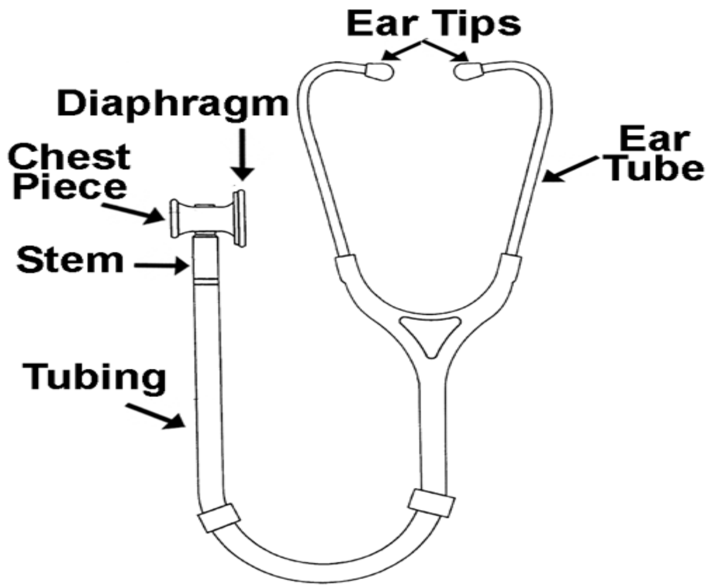


Figure 8 Diagram of stethoscope

2.4.2 Phonocardiogram

The other commonly used device is the phonocardiogram, which converts the acoustic heart sound into an electrical signal. A graphical printing of the waveform of cardiac sounds is called a phonocardiogram, PCG. The PCG has a microphone which is put on the chest of the patient. Sound from the heart and other internal body parts are recorded by this microphone. The microphone changes the acoustic sound to electrical sound, which in turn is processed. The output from the PCG is recorded on paper. Using PCG we are able to record heart sound pattern.

Phonocardiograph is commonly used for research and educational purposes. In this research we will use PCG and compare the results with laser based stethoscope to validate our results.

2.4.3 Electrocardiogram

An electrocardiogram also called an EKG or ECG, abbreviated from the German word "Elektrokardiogramm", is a simple, painless test that records the heart's electrical activity. Invented by Augustus Waller, who was the first to approach the heart from electrical standpoint, the first machine traced the heart beats with an electrometer fixed to a projector which then launched the information onto a photographic plate fixed to a toy train [9]. After that there have been so many improvements to the EKG, but the underlining technology remains the same.

To know how EKG works it is important to understand the electrical activity in the heart. When the heart beats an electrical signal is generated and transmitted from the top part of the heart to the lower part. As it travels, the signal causes the heart to contract and pump blood. This process repeats for each heart beat. The heart cycle is kept by the electrical signal generated. An EKG is able to measure this electrical signal that is transmitted through the tissues and determine the state of the patient. The electrical activities are recorded from twelve different places on the body at the same time.

EKG is able to provide the practitioner:

- The rate of the heart beat
- A heart that is too fast, too slow, or irregular
- The strength and timing of electrical signals as they pass through each part of your heart.

EKG is used to detect and study cardiovascular problems, such as heart attacks, arrhythmias, and heart failure. It can also give information on other disorders that might affect the heart function.

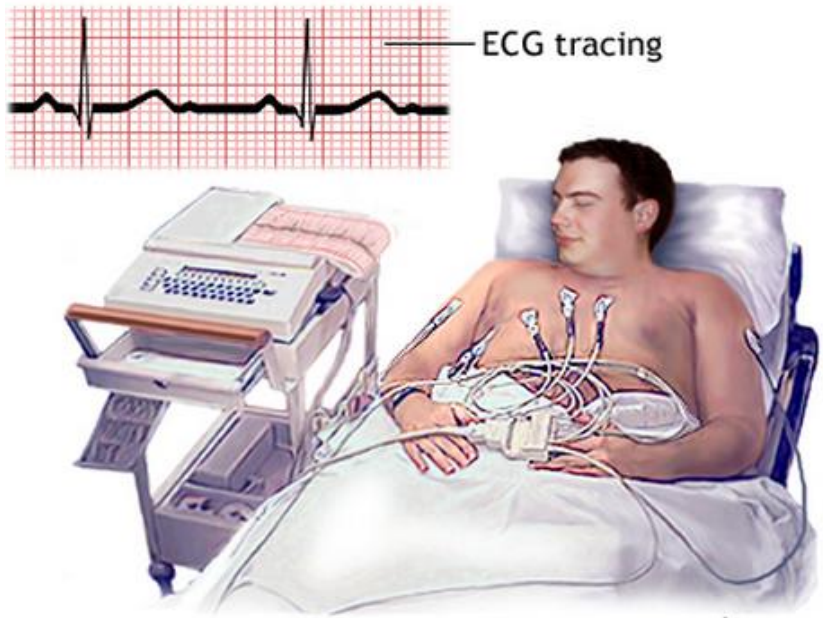


Figure 9 A patient being diagnosed using ECG

The major heartbeat detection approaches reviewed above are based on various signals relating to the heart movement and various detection mechanisms. The acoustic stethoscope and PCG detection are based on the heart sound associated with heart movement while the ECG is based on electric signal generated by the heart. The PCG could display the detected signal in the time-domain, which is the major advantage over the acoustic stethoscope. The laser based heart sound detection method developed in this project aims to extract the heart sound signal from the vibration of the chest skin and visually display the heart sound signal in time-domain and full frequency domain across the full spectrum. This is a new heartbeat detection technique. Based on the detection mechanism, the results could be comparable to the PCG. However, the detection based on the laser system has the unique advantage over the PCG in detecting heart sound signals in the low-frequency range and displaying heart sound in the frequency domain.

Chapter 3

Prototype of system design

In this chapter, we will introduce the prototype of the system design and components in the laser based-stethoscope. The prototype is implemented in the Advanced Physics Lab at MWAH 343 at the University of Minnesota Duluth.

3.1 Design Methodology

In this laser based-stethoscope, the heart signal is correlated to the scattering pattern of a laser beam reflected from the reflective mirror attached to the patient's chest. Vibration of the diaphragm is generated by the acoustic pressure from the heartbeat. With the aid of a time-resolved position sensor, the reflected optical spots can be detected and displayed as continuous waveforms in the time-domain. Optical signal processing and mathematical analysis techniques will be applied to classify the heart signals and transform them to the frequency-domain to reveal more details on heart sound-murmurs. We used the database of approximately 850 heart sounds collected using iStethoscope Pro (the iPhone App) to test the prototype design.

The system design is shown in Figure 10. The reflective mirror with double-side fashion tape on the back will be attached to the chest skin of the patient. Movement of the mirror with the chest is produced by the acoustic pressure from the heartbeat transmitted through chest tissues and skin. The light beam from the laser source arrives at the chest mirror and is reflected toward the linear optical position sensor. The movement of the optical spot reflected from the chest skin can be detected by the two-dimensional (2D) linear position sensor module and recorded as the visible vibration waveform in the time-domain by the data acquisition (DAQ) system of the sensor. Such movement is directly correlated to the vibration amplitude of the chest.

According to [10] the average peak-to-peak chest motion due to respiration is 4~12mm, whereas the chest displacement due to heartbeat alone is about 0.3mm. The resolution of the position sensor is 5.7 μm, which is sufficient for the detection accuracy of chest movement. The signal detected can be displayed in the time-domain on the computer connected with the DAQ system. In addition to the heartbeat, various other activities of the human body could also cause the movement of the chest skin. These activities include the pulmonary respiration, regular body movement, etc. In order to extract the signal solely for heartbeat, a digital frequency filter is designed remove out the signals from other movements based on the fact that both the body movement and pulmonary respiration occur at much lower frequency than the heart sound vibration [11]. Both time-domain and frequency-domain heartbeat signals can be acquired and displayed by the system and aid in the in-depth analysis of heart murmur problems.

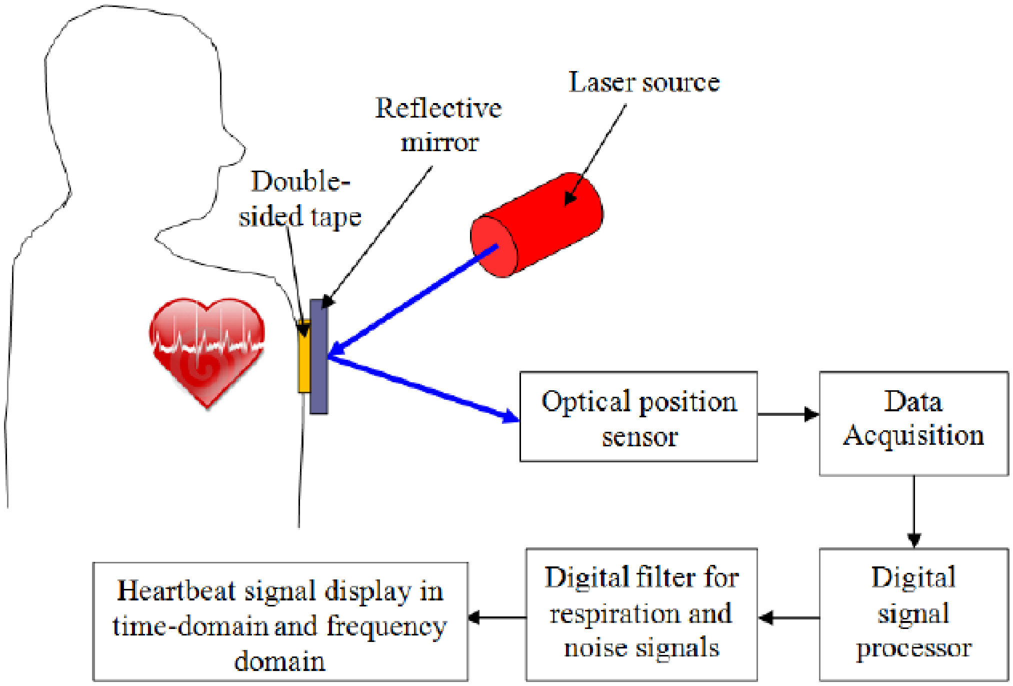


Figure 10 System Design of Laser-based stethoscope

3.2 Prototype setup of the system

In the first phase of the project, the prototype was implemented in the Advanced Physics Lab at University of Minnesota Duluth (UMD). Figure 11 shows the prototype setup of the system. In the prototype system, the chest is replaced by a sound box. The heart sound box simulates the human chest. The sound box was constructed with a speaker at the center and a rubber sheet covering the top. In order to simulate the tiny movement of chest skin with heartbeat [11], we chose rubber material with thickness at 1.6 mm and tensile strength of 1000 Psi (pound per square inch), which is close to the mechanical properties of human chest skin [12]. The vibration of the sound box was generated by heart sound/murmur played by the speaker. We use the Aerotech 110SF 5.0 mW red laser as the laser source. The displacement of the optical spot is detected by the linear position sensor module manufactured by Edmund Optics. The detected signal is recorded in the time-domain by the USB-1608FS system associated with the linear position sensor. The heartbeat signal in time-domain is displayed on a personal computer connected with the DAQ system of the sensor. The time domain signals are converted to frequency domain using Fast Fourier Transform (FFT). In the following chapter, we will introduce in detail each component in the system.

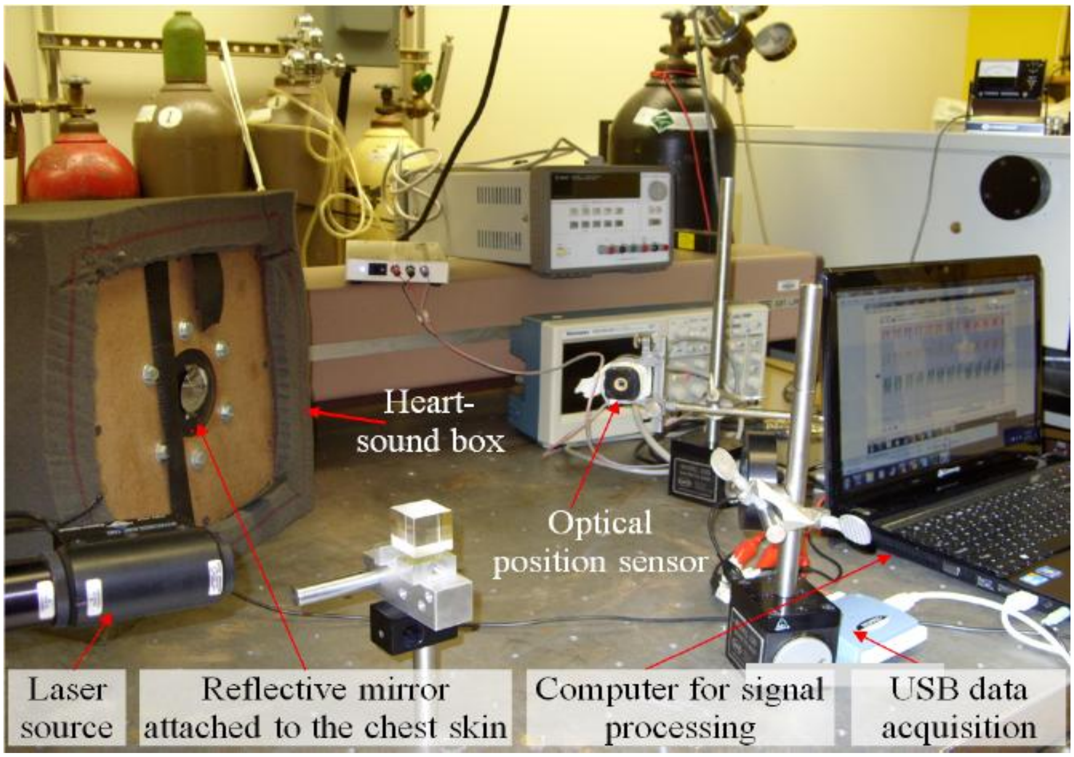


Figure 11 Optical system setup

3.3 Components in the system setup

The general implementation of the project consists of an optical sensor, custom made sound box, laser source, high reflective mirror, data acquisition device, and software for data processing. The project was carried out in two phases- In the first phase that was implemented in the Advanced Physics Lab, a sound-box was used to simulate the human chest. Through the research in the first phase, we confirmed the functionality of the prototype of the design. In the second phase, we performed tests on the dummy human body in the simulation Lab in the Medical School at UMD. With both breathing and heart beat built in the dummy human body (SimMan 3G), we were able to test various types of heart beat patterns and further substantiate the conceptual design of the system. In the next section, we explain in detail the components used in the setup of the system.

3.3.1 Linear Position Sensor Module

The linear position sensor module combines a duo-lateral position sensing detector (PSD), transimpedance amplifiers, and sum/divider circuitry. The sensor (PSD) is used to measure the position of a laser beam along X-Y axis. The detector measures beam displacement on two axes and generates normalized displacement signal range ±10 volts. The values are independent of beam size and intensity and are accurate to within 1% over the central 64% of the sensing area. The signal output is a BNC breakout cable, which is analyzed with a data acquisition system. There are three outputs labeled X, Y and sum. The sum gives output proportional to the power on the detector, is also output for reference. The X and Y give the position along the X and Y axis respectively. Cable also has three banana jacks for easy integration with power supply, 15 volt DC. Figure 12 show Linear Position Sensor.

The bicolor LED indicator located on the back of the module will be green when the Linear Position Sensor Module is on and sufficient light power is incident on the detector. The LED will turn red if the sum signal falls below 100mV. In this situation, either the beam power is too low or the beam is missing the active area of the detector. The X and Y outputs will decrease as the sum signal falls below 100mV, and both outputs will trail to 10 volts as the sum signal approach zero.

The module is easily mounted via a tapped hole, centered on the underside of the assembly. A filter also can be mounted directly to the unit on the front bezel plate. The maximum filter thickness is 6.0mm. The module is supplied with 15volt DC power. Both the linear position sensor and the power supply were purchased from Edmund optics [13].

Figure 12 Linear Position Sensor

At the back of the sensor there is a switch if the switch is in the upward position, the PSD preamplifiers provide a 10^5 V/A transimpedance gain. When the switch is in the downward position, the transimpedance gain is 10^4 V/A. If the laser power on the sensor is less than 0.5 volts in the low gain setting, the high gain setting may be used to provide a better signal to noise ratio. However, if the sum voltage approaches 10 volts in the high gain setting, the lower gain setting should be used. If this still provides too much gain, an attenuating filter should be inserted in the front bezel to lower the input light level.

3.3.2 Data acquisition Device (DAQ)

The data acquisition device contains two parts, *i.e.*, the module USB-1608FS for signal acquisition and the Power Lab DAQ for signal conversion, which are introduced in the following sections.

3.3.2.1 USB-1608FS

The data acquisition used in the first phase is a USB-based signal and digital I/O module USB-1608FS. The USB-1608FS is a USB 2.0 full-speed device supported under Microsoft Windows operating system. The DAQ offers true simultaneous sampling of up to eight channels of 16-bit single-ended analog input. This is accomplished through the use of one A/D converter per channel. The range of each channel is independently configurable via software. Eight digital input-output lines are independently selectable as input or output. A 32-bit counter is capable of counting TTL pulses. The USB-1608FS is powered by the +5 volt USB supply from a computer. Figure 13 show the block diagram of USB-1608FS.

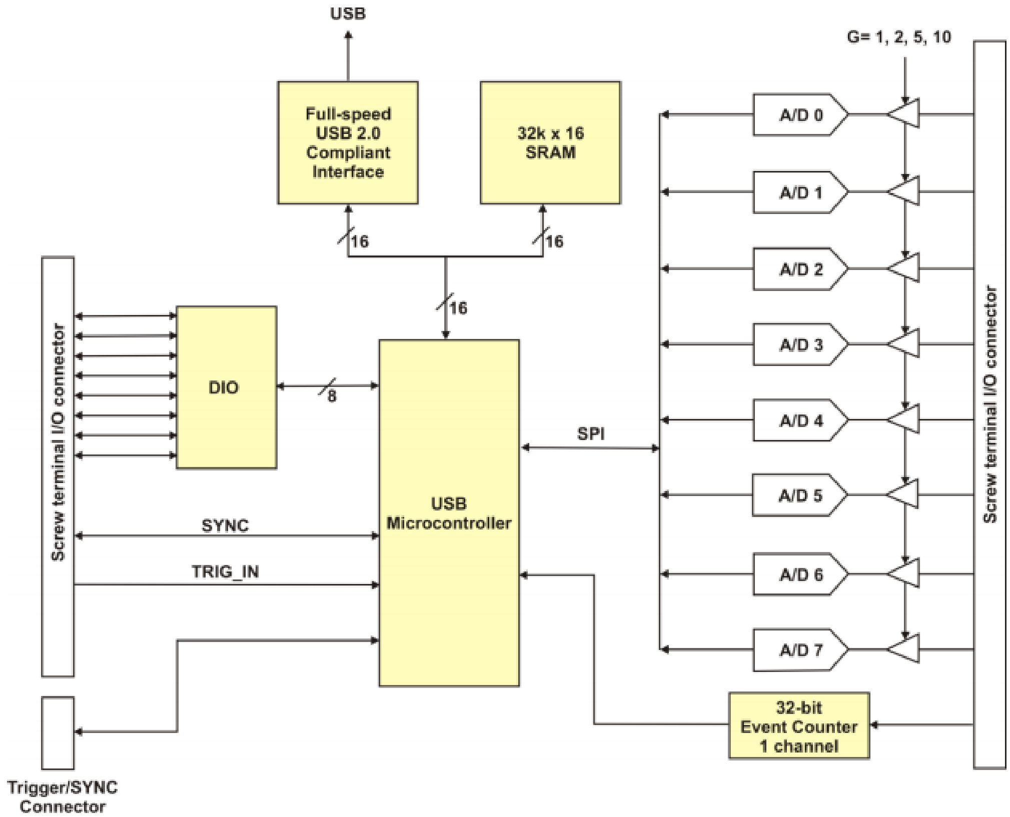


Figure 13 USB-1608FS Functional Block Diagram [14]

The analog input acquisition mode inputs data in three modes: software paced mode, continuous scan mode, and burst scan mode [14].

In the software paced mode the DAQ acquires one analog sample at a time, we do this by calling the software command. The analog value is converted to digital data and returned to the computer, we can repeat until we have the total sample.

In continuous scan mode DAQ can acquire up to eight channels simultaneously. The analog data is continuously acquired, converted to digital values, and written to an on-board FIFO buffer on the USB-1608FS until you stop the scan. The maximum sampling rate is an aggregate rate, where the total sample rate for all channels is 100 KS/s divided by the number of channels, with a maximum rate of 50 KS/s for any channel. Using this equation, DAQ can acquire data from one channel at 50 KS/s, two channels at 50 KS/s each, four channels at 25 Ks/s each and so on, up to eight channels at 12.5 KS/s.

For this project we used the burst scan mode in which the DAQ can acquire using the full capacity which is 32 K sample FIFO. The acquired data is then read from the FIFO and transferred to a user buffer in the computer. We can access up to eight channels using this mode. This mode is limited to the depth of the on-board memory, as the data is acquired at a rate faster than it can be transferred to the computer. The maximum sampling rate is an aggregate rate, where the total acquisition rate for all channels is 200 KS/s divided by the number of channels, with a maximum rate of 50 KS/s for any channel.

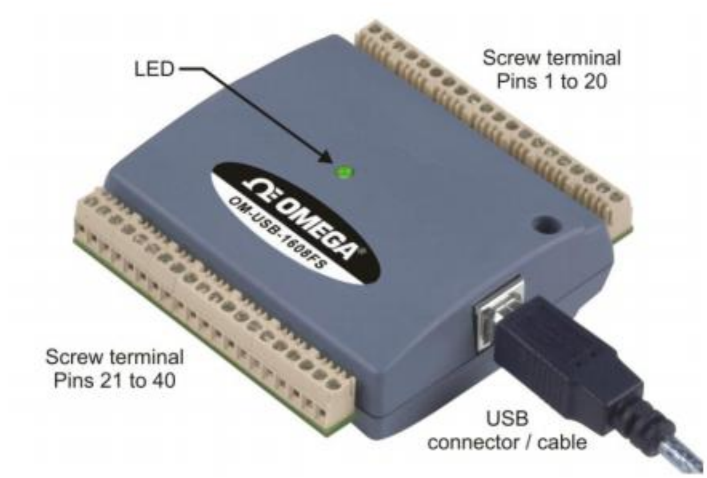


Figure 14 USB-1608FS Module

The LED on the front indicates the communication status. When the LED is steady green the DAQ is connected to a computer. When it blinks continuously data is being transferred. The accuracy of the USB-1608FS is affected by offset and gain error. The typical on the ±10V range is ±1.66mV. Offset affects all codes equally by shifting the entire transfer function up or down along the input voltage axis. Gain error is a change in the slope of the transfer function from the ideal, and is typically expressed as a percentage of full-scale. Combining this two error sources in Figure 15, we have the plot of the error band for USB-1608FS.

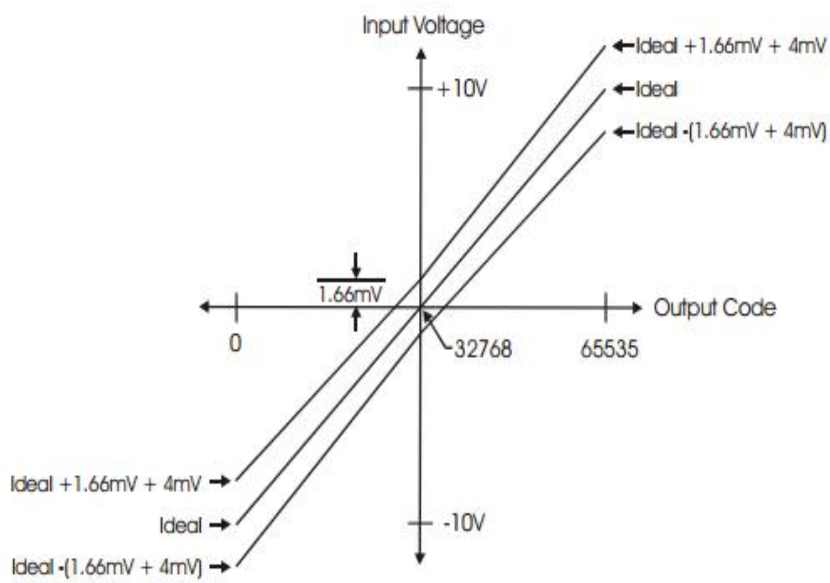


Figure 15 Error band plot

3.3.2.2 Power Lab DAQ

The power lab DAQ is used on the second phase of the project it takes an analog signal of variable amplitude and converts it to a digital signal. The powerlab system consists of a recording unit and application programs that run on the computer to which the unit is connected. It provides an integrated system of hardware and software designed to record, display, and analyze experimental data. Figure 16 show a picture of the PowerLab DAQ.

Figure 16 PowerLab data acquisition device

The front end on the top are auxiliary devices that connect to the PowerLab recording unit to extend the system’s capabilities. They provide additional signal conditioning and other features, and extend the types of experiments that you can conduct and the data you can record.

3.3.3 Sound Box

To test the functionality of the system design in the first phase of the experiment, we employed a heart sound-box to emulate the human chest. The heart-sound box was built by Prof. Glenn Nordehn at Midwestern University. The device is able to play hear sounds that will vibrate the membrane as human chest.

The parts in the sound box contain wood, rubber sheet, reflective mirror and sponge. The whole box was made of wood, the wood was covered with sponge to make it sound proof and avoid sound reflection. Inside the wooden box was a 10W speaker which was put very close to the top part of the box. The speaker could be driven with different heart sound recording. The top part of the box was covered by a rubber sheet, which acts the vibrating membrane simulating the body surface. The sound box picture is shown in Figure 17.

Figure 17 Sound Box picture

The rubber sheet we chose is 1/32 inch thick and with 300% elongation. This selection of rubber sheet is based on the similarity of its mechanical property with human chest skin [15]. A reflective mirror is attached to the rubber sheet by a double-sided tape. The mirror is chosen based on the tradeoff among thickness, reflectivity, shape and size. To best detect the tiny movement of the chest skin, the mirror should be as thin as possible; however, with the same reflectivity, the thin the mirror, the larger the planar area of the mirror, which is restricted by the manufacture process. All the mirrors we tested are listed in Table 3. All of them have higher than 90% reflection of visible light. Based on our comparison through testing with three mirrors listed, we found that the mirror in circular shape could better cope with the movement range of the incident optical spot. So, we finally chose the mirror Type B in Table 3 for our system.

Table 3 List of reflective mirrors

Glasses	**Thickness**	**Size**	**Shape**
Type A	1.0mm	9*9 mm	Square
Type B	0.5mm	D - 6.3mm	Circular
Type C	1.0mm	D – 19mm	Circular

Using the type B rubber sheet the top part of the box was covered; right under the rubber sheet was the speaker. Type B reflective mirror was attached to the rubber sheet. This emulates the chest of a human person as it vibrates due to different heart beat played through speaker. Using the sound box we were able to see the effects of changes in volume. The increase or decrease in volume will bring changes in the amplitude response of the time and frequency domain. The sound spectrum range will not change except for amplitude.

3.3.4 Laser Source

The laser source used on the experiment is a 5mW helium-neon laser made by Aerotech. It requires a 13V DC power supply. It supplies a continues-wave coherent red light source. The laser source has a spot size of 2mm diameter which is small enough for our

4mm*4mm (16mm^2) sensor area. Due to the limitation of sensing area, the smaller the laser spot, the more accurate the detection results. Figure 18 shows the laser pointer used in this project. Since direct contact with a laser (>5mW) can bring damage to the eye. Participants are warned to avoid visual contact and are required to wear the eye protection glasses.

Figure 18 Picture of Laser-Pointer

3.3.5 Softwares

The software involved in this project included the programming software for Fourier transform and the data acquisition software to convert the electrical signal to digital signal. The programming software we used for Fourier transform is Matlab. In the first phase, we use the Tracer DAQ software associated with the linear position sensor for data acquisition. In the second phase, we used the Lab Chart Pro7 associated with the PCG device for the data acquisition. With Lab Chart Pro7, we could display the data acquired from both PCG and the optical sensor and process the signals together using its multichannel function. Apparently, Chart Pro7 is much more powerful software than the Tracer DAQ. Next, we will introduce the two types of data acquisition software.

3.3.5.1 Tracer DAQ

Tracer DAQ is used to access the input from the Data acquisition device (USB-1608FS), it runs on Microsoft operating system. It is a virtual instrument which is able to graphically display and save input data. Using the strip chart application we are able to visualize the analog input from the laser position sensor, via the USB-1608FS. Using this software we have control over the data acquisition device. It enables us to set the sampling rate and duration of measurement. The tracer DAQ saves data in an excel format which make it very easy to process in Matlab. The tracer DAQ has the option of selecting channels, for separate data processing. Figure 19 shows the graphic user interface of tracer DAQ. Tracer DAQ first install the hardware of the device enabling the user to access the hardware through the software. Using tracer DAQ we are able to start, stop and save data.

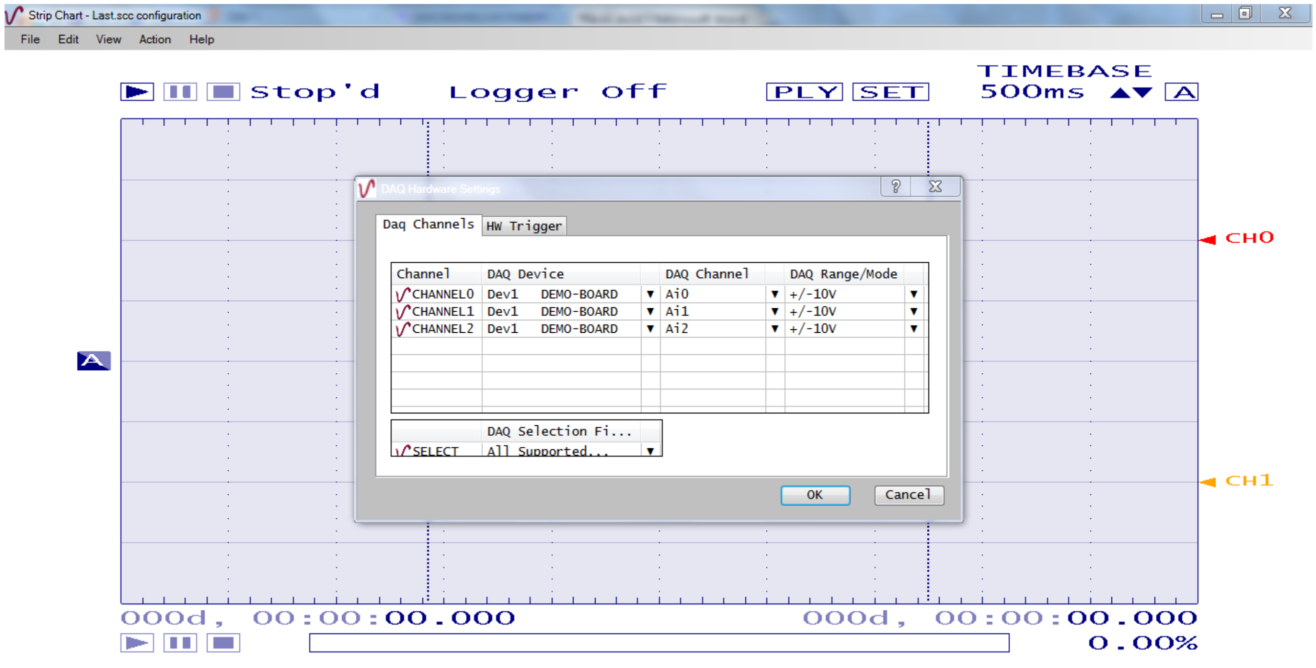


Figure 19 Tracer DAQ control panel GUI

3.3.5.2 LabChart 7 pro

This software combines a strip chart recorder with powerful analysis features of a digital acquisition system. It provides multipurpose data recording and analysis. It gives different option to visualize saved data. The virtual tools give additional options to analyze data using different types of software filters. LabChart 7 prois used in the second phase of the project, medical lab. Figure 20 shows the GUI of LabChart 7 pro.

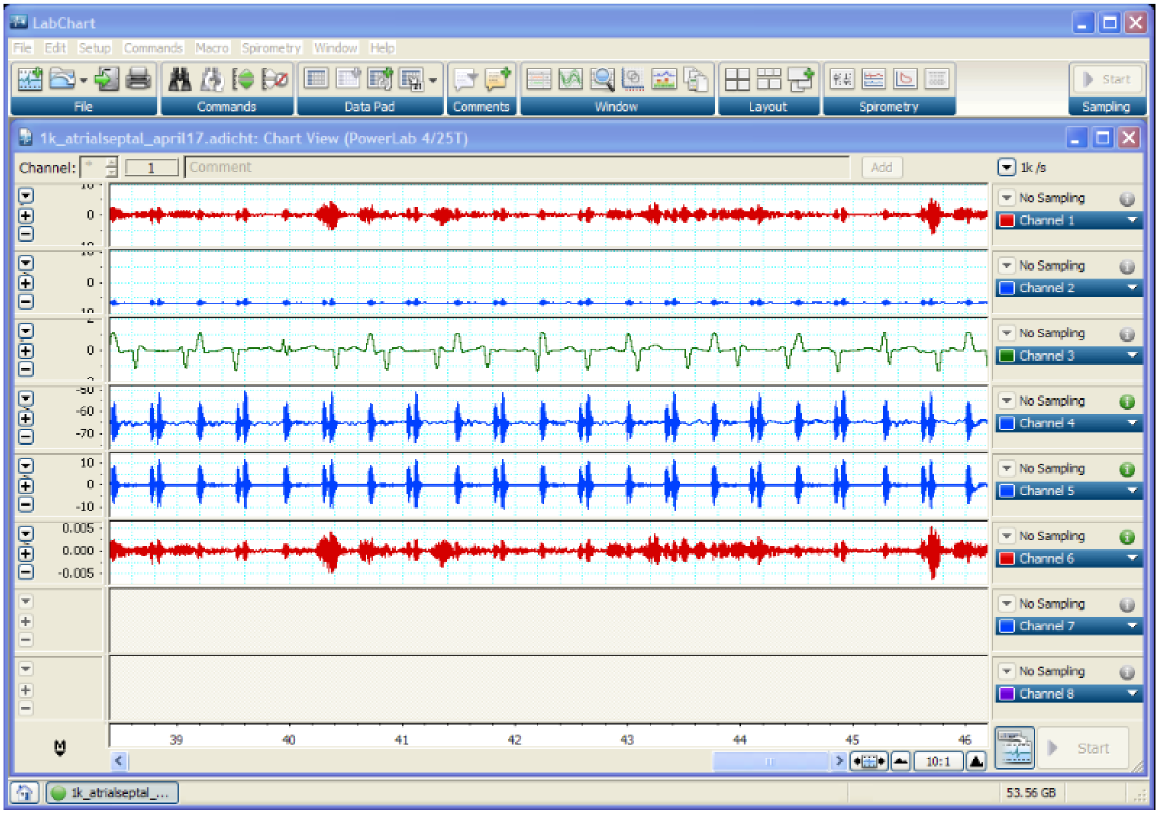


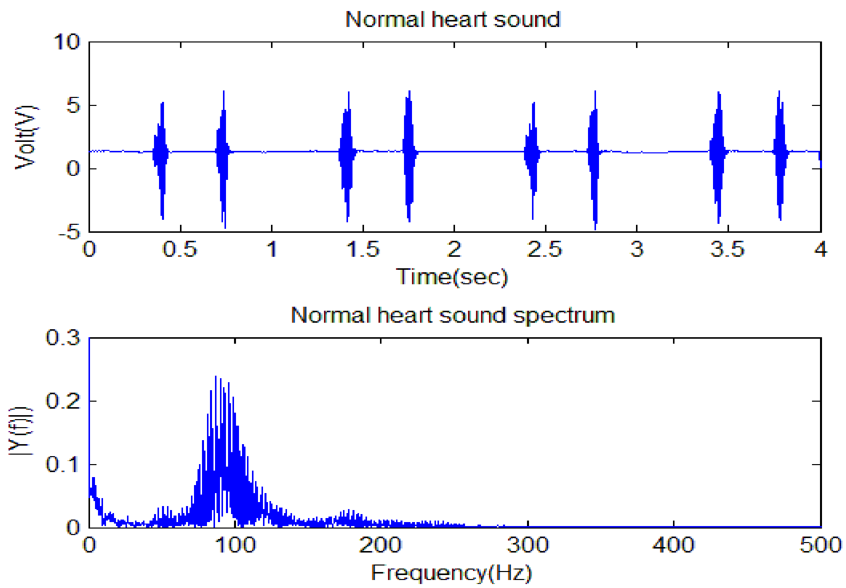
Figure 20 LabChart 7 prographical user interface

As seen on the GUI we can record more than one channel, when we click the start button the signal starts to scroll across the screen, and is being recorded on the hard disk of the computer. If we want to stop the recording we can click stop at any time. The power lab DAQ sampling is controlled by the GUI sampling rate was set high enough to capture all significant changes in the signal, but low enough to avoid excessive over-sampling without necessarily providing more relevance to the analysis. The GUI gives the option to scale the data; amplitude axis of each channel can be independently shifted, stretched, or compressed for optimum data display. We can save data in different format to export or process at a later time. The LabChart 7 prois powerful data analysis tool compared to TracerDAQ. It gives us the option of setting up filters with different specifications making signal processing easier. In our case we used a high pass filter with a 50Hz cut-off frequency, this enabled us to see the signal in separate frequency ranges. The other main advantage of using the LabChart 7 prois we can access different signals simultaneously making comparison easier.

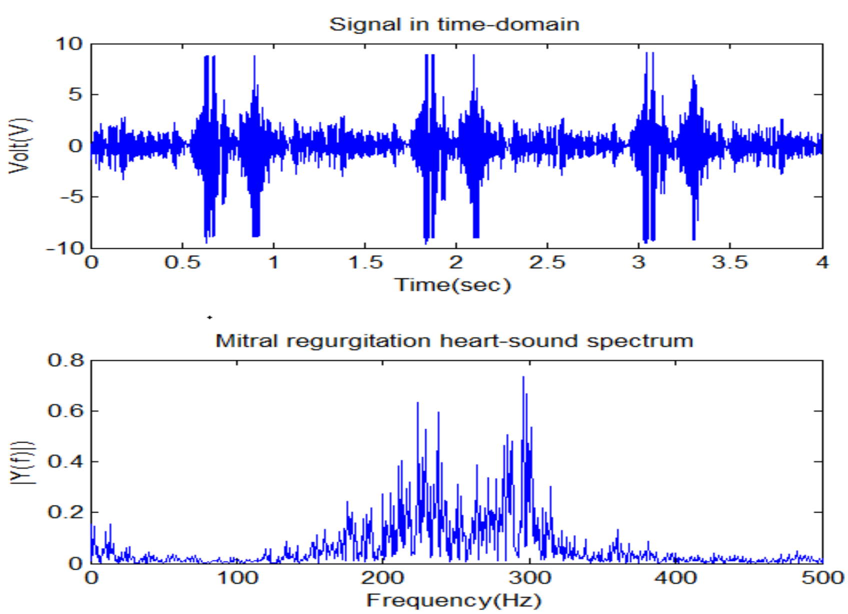
In this first phase of the research we used three types of heart sounds, normal heart beat, mitral regurgitation, and mitral stenosis. The heart sounds were collected from the real patient using the iStechosope (iPhone App.) The sound box was activated using the sounds from the database. Please note that in the first phase, the sound box vibration was activated using heart sound, there was no respiratory movements involved. But in the real human’s, chest movement is due to the effect of heart beat and breathing. which we will include in the second phase testing with a dummy human body. Next we will analyze the detection results with the sound box on three different heart sounds.

3.4 Heart sound detection results using the prototype of the system with the sound box

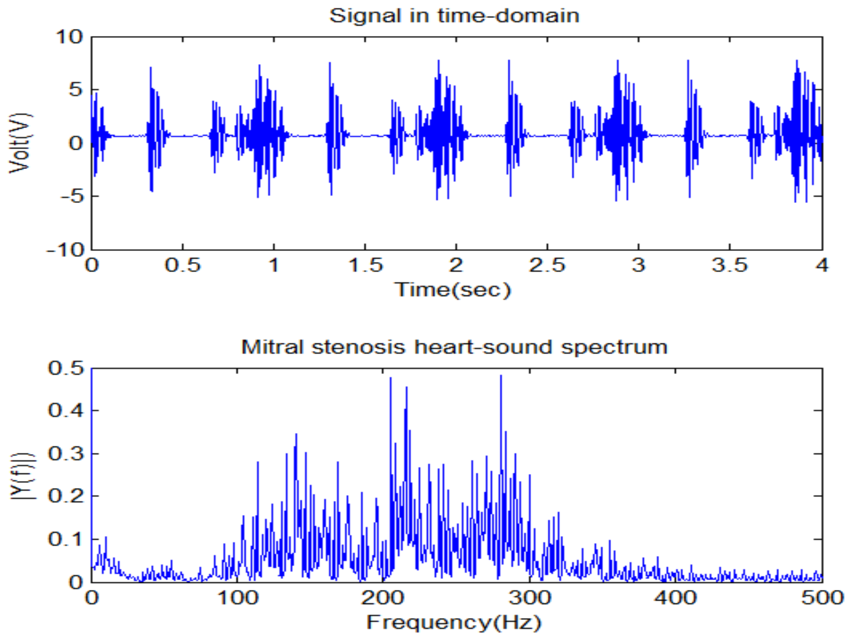
As explained in the previous section after acquiring the sound signal in electrical form it was converted to the time domain and frequency domain. The electrical signal from the sensor varies from -10V to +10V depending on the vibration amplitude of the sound box diaphragm, which is correlated to the heart sound. The sampling frequency of the optical sensor is chosen to be 8000Hz. The sampling duration of each heart sound is 4sec. The frequency scan is 0 to 500 Hz, which reasonably cover the heart sound range of a human [16].The vibration amplitude of the diaphragm on the sound box can be adjusted through the volume of the speaker. We set it to very low volume in order to approximate the tiny movement of the chest due to the heartbeat. We took a typical cycle of one normal and two abnormal heart beats; mitral regurgitation and mitral stenosis as shown in Figure 21.



(a)



(b)



(c)

Figure 21 Time domain and frequency domain acquired from the system: (a) Normal heart beat (b) Mitral regurgitation (c) Mitral stenosis

The output from the normal heart sound contains sound S1 and S2, as can be seen on the figure. There are no additional murmurs. However if there is any malfunction (e.g problem with heart valves) there will be extraneous sounds. As can be seen on the figure there are extraneous sounds in mitral stenosis and mitral regurgitation.

Mitral stenosis is characterized by the narrowing of the orifice of the mitral valve of the heart. The blood flow through the narrowed valve opening results in a flow pattern of higher velocity and greater turbulence. As seen on figure 21(c), comparing to the normal heartbeat, the time-domain signal of the mitral stenosis has a sound between S1 and S2, which corresponds to the presystolic reinforcement. In mitral regurgitation the mitral valve does not close properly when the heart pumps out blood. This causes the blood to flow backwards into the atrium during ventricular systole. The time domain on Figure 21(b) show less intensive and more extended S1 sound which corresponds to the incompetence in the closing of the mitral valve.

In order to better analyze the heart murmur patterns, in addition to the time-domain signal, we also acquired the frequency-domain signal through the Fourier transform technique. As can be seen on the spectral content of the three heart murmurs there is a similarity between the three heart sounds in the range between 0-15 Hz. Above that there is a clear pattern difference between the murmurs. The normal heart sound covers the frequency range between 50-150Hz having peak frequency at 100Hz. Mitral regurgitation frequency response show it covers the frequency range between 150-350Hz having peaks at 240Hz and 300Hz. Also the mitral stenosis frequency domain shows the spectrum is between 100-350Hz having peaks at three points-150Hz, 220Hz and 280Hz.

The first phase provided us with information that the system as a whole is able to pick up the heart beat signal. Results acquired in the first phase of study demonstrate the prototype of this system could realize the function of displaying the heartbeat signal in the time domain and frequency domain. We tested the system with three different types of heart sounds, and results on the time-domain and frequency-domain signals could help to explain the pathological nature of the distinction of each heart sound type. We therefore move forward to test the system on a dummy human body, which is a better simulation of a real human being.

Chapter 4

Testing on Dummy Human Body

With the successful demonstration of the detection results with the sound-box in the system, we then tested the prototype system on the dummy human body located in Dummy lab of the Medical School at UMD. We called this the second phase of our study.

4.1 Setup up of the prototype on dummy human testing

The dummy used in the project is a male dummy which is controlled wirelessly from a central control station. Wirelessly we can control the breathing and heart beat of the dummy. The control station has a database of different heart beat sounds normal and abnormal. We also can also control the breathing from the control station. This way the dummy chest vibrates based on the heartbeat and breathing which emulates that of a human being.

The dummy human has three plugs on the chest for electrocardiogram (EKG). The phonocardiogram is accessed via a microphone, taped to the chest near the site of the mirror. We access the outputs via LabChart 7 pro(on a laptop) which accesses the analog signal of PCG and EKG through the power lab data acquisition device (DAQ). This gives us the option to simultaneously access PCG and EKG. The LabChart 7 pro has the ability to access more than two channels through DAQ. The LabChart 7 pro comes along with the Power lab DAQ. The reason we are using LabChart 7 pro is also because we can read data from the dummy using PCG, EKG and the laser based stethoscope simultaneously and make comparison easier. The picture below shows how the device was setup in the second phase. The testing with the dummy could best approximate the results we expect when doing a clinical trial with a real human patient since the dummy emulates the internal movement of an actual person. It could also help us avoid the difficulty we may have for real human tests before the system becomes more compact and portable.

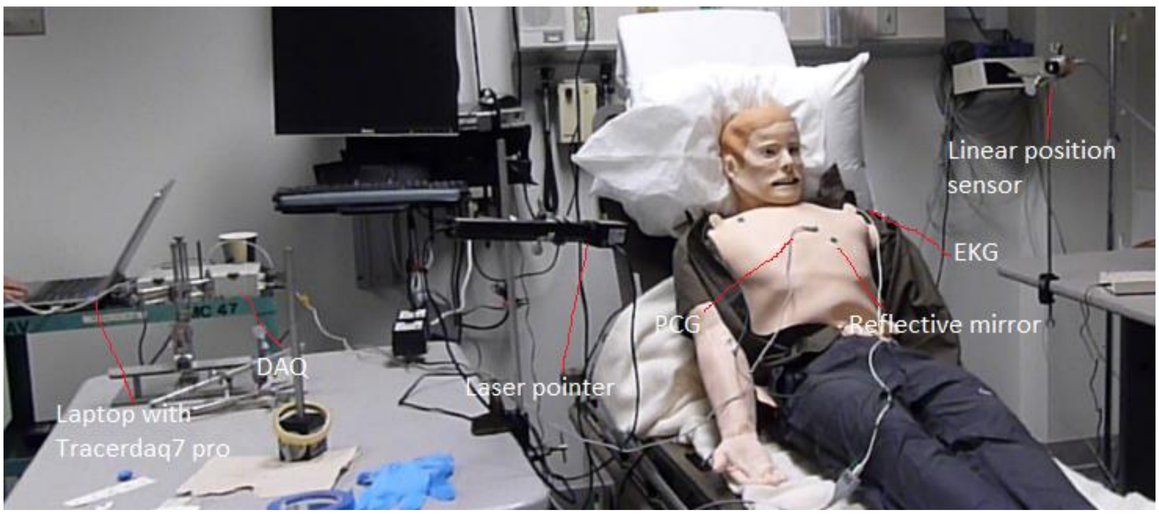


Figure 22 System setup

The setup for the dummy testing is shown in Figure 22. The reflective mirror is attached to the chest of the dummy. The laser beam is incident on the mirror attached to the dummy body chest. The beam reflected from the mirror is directed to the linear position sensor. The linear position sensor measures the movement of the reflected spot in the time-domain. Such movement is correlated to the vibration of the chest skin with the heart sound. The output from the optical sensor is an electrical voltage signal between -10V and +10V depending on the position of the laser beam on the sensor. This analog signal is fed to the power lab DAQ which in turn is attached to a PC running Labchart 7 pro. Along with the measurement with the laser system, the PCG and ECG measurements are performed simultaneously and used as the reference for the laser-based system. As we mentioned previously, ECG signal corresponds to the signal of the heart, which is different in nature from the heart sound signal; however, here we can use ECG signal to indicate time period within the cardiac cycle. The PCG signal could be used as the bench mark or reference for the measurement using our laser system. The DAQ software is originally associated with the PCG device. Its multiple input channels allow the convenience of simultaneously feeding and displaying all measured signals from three systems, which makes easier.

We picked several heart sound patterns including the normal and abnormal from the database of the dummy body system to demonstrate the measurement results. For each heart pattern, we analyzed and compared results from the PCG and laser system. The analysis helped prove the conceptual design of this system and the targeted advantage of the system over other heart sound detection systems.

4. 2 Data Processing Procedure on Detection Results

We chose a normal heart beat and pathological heart beats including aortic stenosis, mitral regurgitation, Austin flint, and atrial septal defect as the signals for measurement. We utilized the data processing functions, such as amplitude amplification and frequency filtering, offered in the DAQ software Lab Chart Pro7 to process the measured signal. Here, we take the example of normal heart sound to explain our data processing procedure for each set of measurements. In the following context and figures, the CH# represents the channel number.

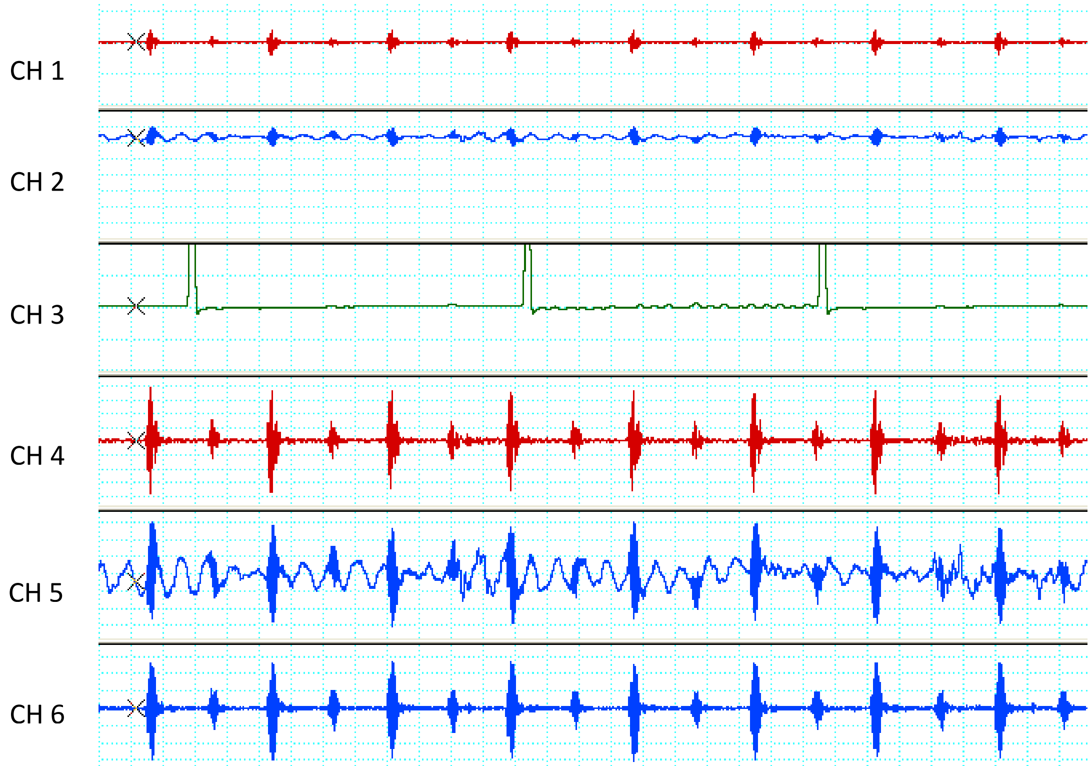


Figure 23 Time domain for normal heart beat using PCG, EKG, LBS, LBS with HPF

The Normal heart beat is taken at a sample rate of 1000 samples/sec. The CH1 shows the output from PCG. The CH2 is an output from the laser based stethoscope (LBS). The CH3 is EKG output. The CH4 resembles the 10 times amplified PCG signal (CH1) and CH5 is the 10 times amplified LBS signal (CH2). In order to filter out the internal external noises on the dummy heart, the CH5 signal is passed through the 50 Hz high-pass filter (HPF) built in the LabChart Pro and presented as CH6 signal. For measurement of each case of heartbeat, we used the similar signal processing procedure for the time-domain signals. Then for each set of measurements, we compare the signal from CH4, CH5 and CH6, which represents the amplified PCG signal, amplified LBS signal and LBS signal after HPF. For the signal on each channel, after acquiring the required data from Labchart 7 pro, we saved the data to a text file so that we can acquire the frequency-domain signal on each channel through Fourier transforming the corresponding time-domain signal. The Fourier transform is programmed using Matlab software. In this way, we could compare the measurements from LBS and PCG in both frequency and time-domain.

4. 3 Analysis on detection results

The first we will look at is the normal heart sound. The heart beat is processed in a way so that we can relate the time domain and frequency domain of PCG, LBS before passing through a filter and after passing through a filter of 50Hz cut off. Figure 24 shows the output of our Matlab program after processing the text file from Labchart7 Pro.

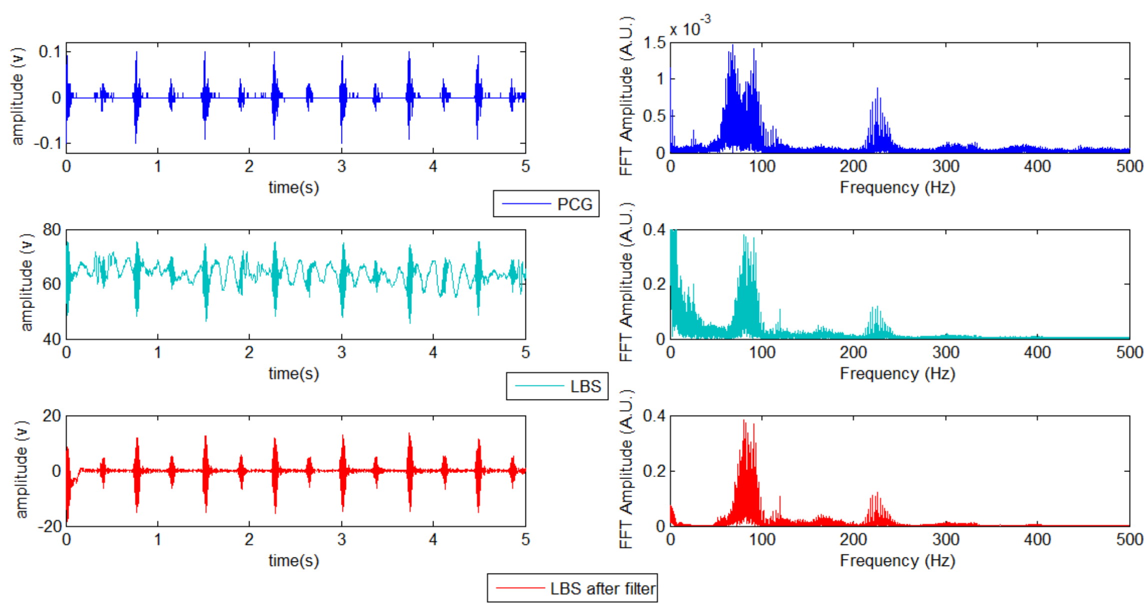


Figure 24 Time-domain and frequency-domain signals for normal heart sound from PCG, LBS and LBS after HPF

As can be seen on the figure above on the frequency domain LBS is able to extract more information in the low frequency (*i.e.* between 0 – 50Hz) compared to the PCG. After being passed through the high pass filter (HPF) we see the PCG and LBS after filter, are similar because the extra information in the low frequency of LBS is filtered out.

The next heart sound we will look is a pathological heart beat, aortic stenosis. The time domain of the aortic stenosis was acquired using Labchart7 pro as done for the normal heart beat. After saving the time domain signal as a text file further data processing was done using Matlab, Figure 25 shows the time domain and frequency domain of aortic stenosis. Aortic stenosis is the abnormal narrowing of the aortic valve. The sampling for the aortic stenosis was taken at 4000 sample/sec. Output of the PCG, LBS before and after the 50Hz high pass filter is shown on the picture.

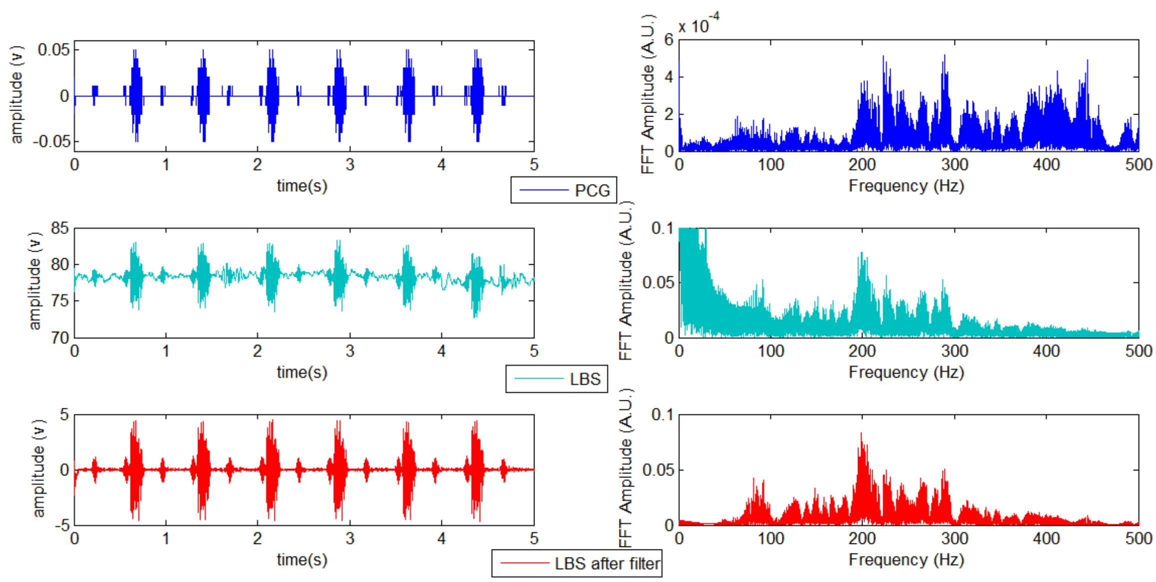


Figure 25 Time-domain and frequency-domain signals for aortic stenosis heart sound from PCG, LBS and LBS after HPF

As can be seen on the picture information of the heart beat in the low frequency is displayed by the LBS, and higher frequency information of the heart sound are displayed by the PCG.

As can be seen from the above result LBS is able to extract information in the low frequency range and this will give more information for diagnosing heart patients. Using similar methods we used different heart sounds to see the output of the LBS.

In Figure 26 is shown a result from a pathological heart beat named atrial septal, defect which is a form of congenital heart defect that enables blood flow between the left and right atria via the interatial septum. The sampling was 4000 samples/sec.

Figure 27 shows the result of the system to a pathological heart beat called Austin flint, which is due to mitral valve displacement. The sampling was taken at 4000 samples/sec.

Figure 28 shows the output of the system for a pathological heart beat called mitral regurgitation (also called mitral prolapse), which results due to a problem with the mitral valve. The sampling was done at 1000 samples/sec.

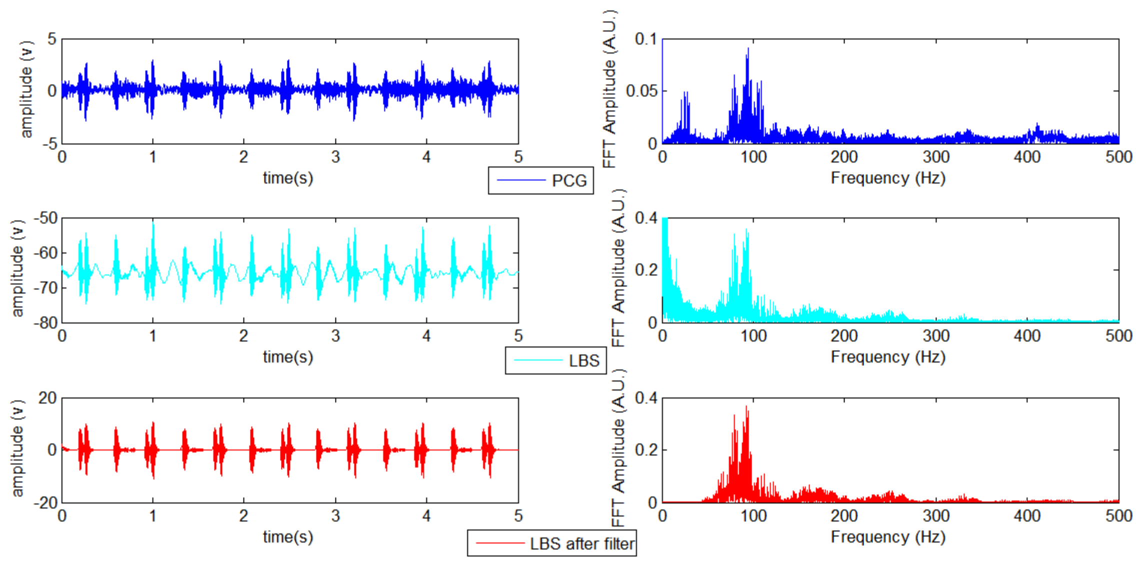


Figure 26 Time-domain and frequency-domain signals for atrial septal defect heart sound from PCG, LBS and LBS after HPF

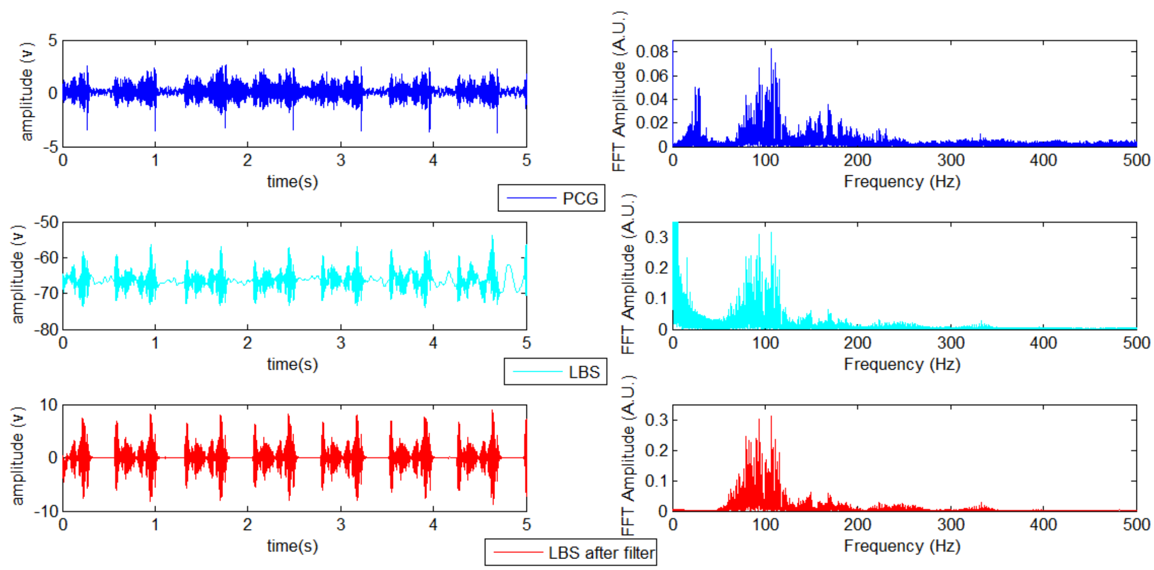


Figure 27 Time-domain and frequency-domain signals for Austin Flint heart sound from PCG, LBS and LBS after HPF

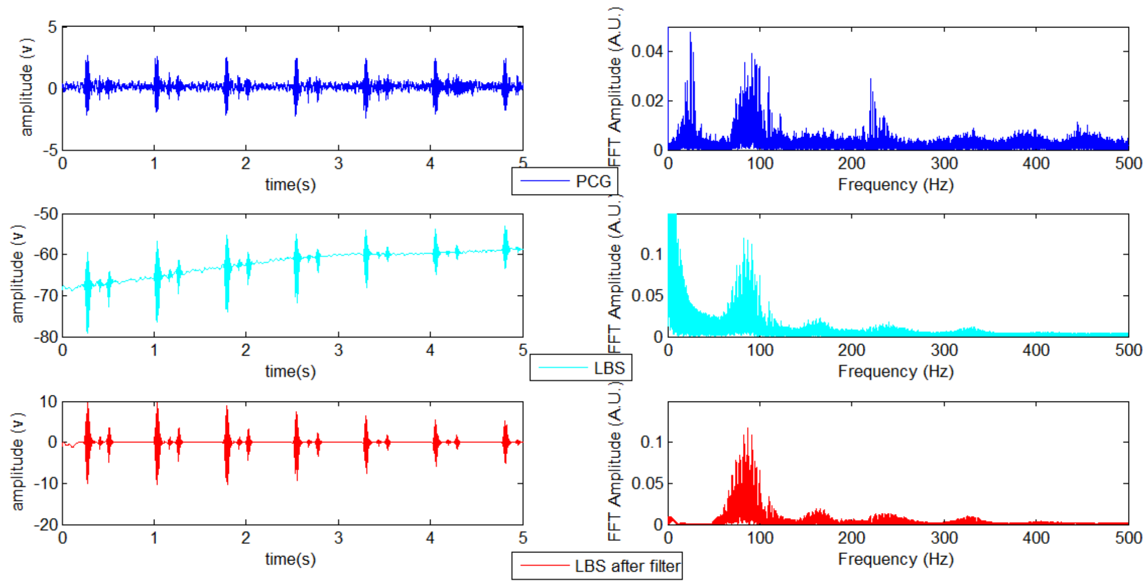


Figure 28 Time-domain and frequency-domain signals for Mitral prolapse heart sound from PCG, LBS and LBS after HPF

As can be seen from the above result we can conclude that LBS can extract information more clearly in the low frequency heart sounds compared to the PCG. This is important for diagnosis because we can clearly see the whole frequency band of the heart beat. Similar result were obtained for other heart sounds, the LBS clearly show more information for heart sounds below 50Hz. And the PCG gives more visual result for heart sounds above the 50Hz range.

In the final experiment we combined breathing and heart beat; and evaluate what the output of the system will be. We tried this for all the heart sounds and see how the filter and signal processing will get rid of the breathing and extract the heart beat. In this report we included two results. Figure 29 shows the result when we have a normal heart beat and breathing together. The sampling is taken at 1000 samples/sec, we acquired the data in a similar way to the previous results. Figure 30 shows the output when mitral prolapse and breathing are together. The sampling is taken at 4000 samples/sec.

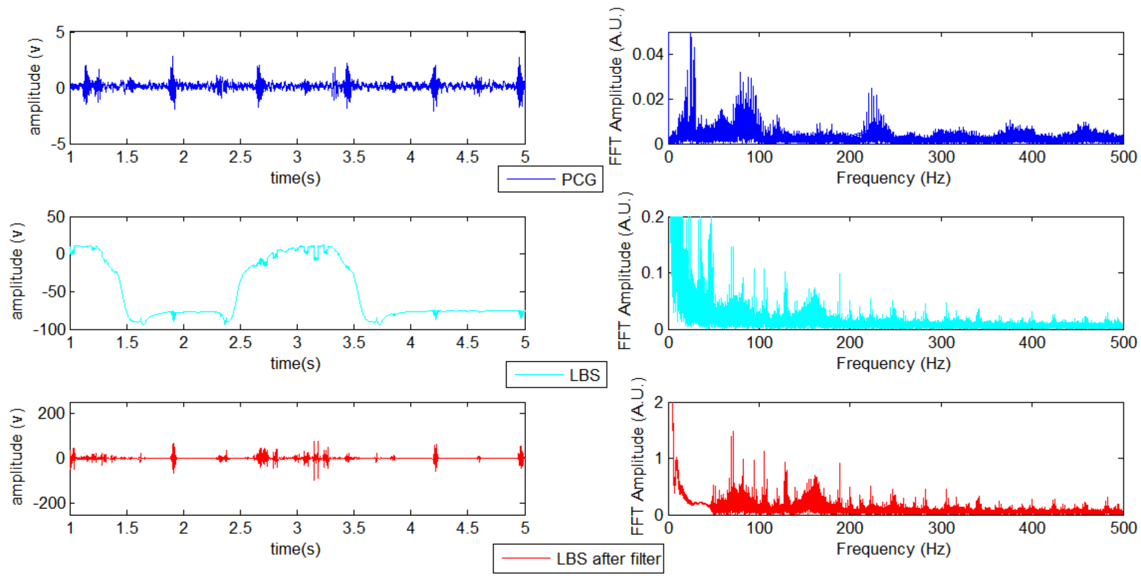


Figure 29 Time domain and frequency domain for normal heart beat and breathing from PCG, LBS, LBS with HPF

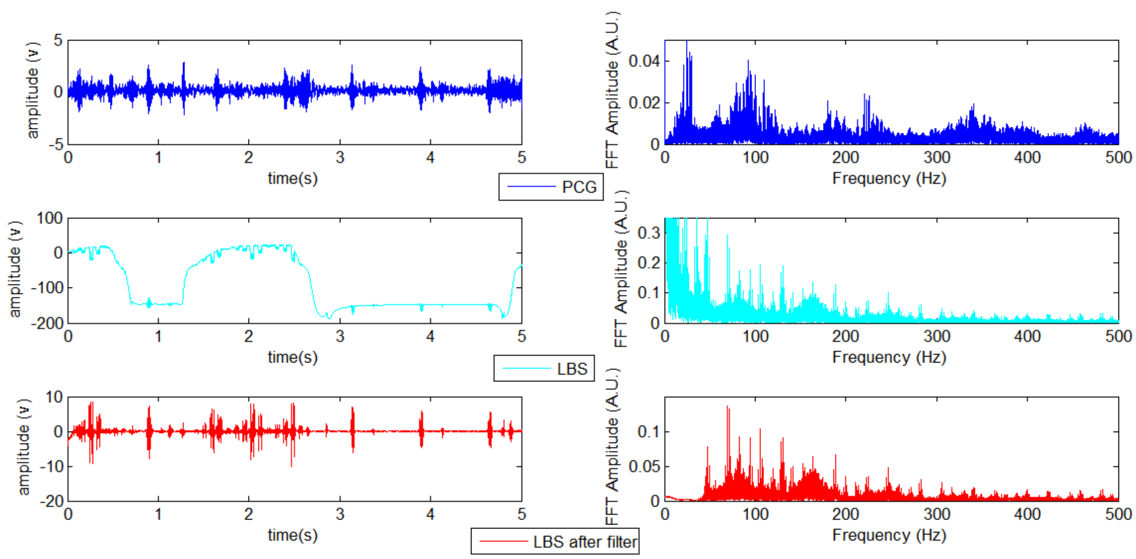


Figure 30 Time domain and frequency domain for Mitral prolapse and breathing from PCG, LBS, LBS with HPF

As can be seen the system is able to extract the heart beat when breathing is involved. We still need to further work on the signal processing to increase the performance of the system when breathing is involved The human chest skin movement caused by breathing is much larger than that due to the heart sound. It always causes the reflected spot to move out of the detection area of the optical sensor. Thus, in order to increase the accuracy of the laser based stethoscope for purely heart sound detection, we might need to ask the patient to hold their breathing for 10 seconds in real clinical trial on patients. At the same time, we will continue to seek an optical sensor with a larger detection area to overcome this problem.

4.4 Summary on testing results on dummy human body

In this section we summarize the results obtained in the previous section. We compared the results from our LBS prototype and the PCG for various types of heart-sound patterns. This comparison indicates that more information from the heart sound in the low frequency (<50Hz) was detected using the LBS than using PCG. The PCG could reflect more heart-sound information on high-frequency range. These results meet our expectation of the conceptual design of the system, which is to reflect more information on low-frequency heart-sound in both the time-domain and frequency-domain.

Another important note is the range of frequency spectrum for different heart sounds. As seen on the Figure 24 normal heart sound cover the frequency range between 0-250 Hz with peak frequency at 100 and 220 for both PCG and LBS. On Figure 25 frequency domain of aortic stenosis on LBS is from 0-300Hz with peak frequency at 200Hz. Atrial septal defect frequency spectrum as displayed on LBS on Figure 26 show it covers between 0 – 200Hz with peak frequency at 100Hz. The frequency spectrum of the heart sound has a unique pattern for each type of heart murmur. This will give the importance of categorizing the heart beat based on the spectrum they cover in the frequency domain. The capability of LBS on reflecting these patterns is comparable to that of the PCG, whereas LBS is more sensitive on the low frequency end and the PCG is more sensitive in the high-frequency range.

The implementation of the second phase was challenging due to the fact that the linear position sensor has a small sensing area (4mm*4mm). We had to arrange the laser source and reflective mirror correctly so that the reflection of the laser spot was on the linear position sensor sensing area. The introduction of breathing in addition to the heart beat also was challenging because the laser spot will sometimes exit from the sensing area. As seen on figure 29 and 30 the system picked up some part of the heart beat signal but more accurate results can be found either by increasing the sensing area of the linear position sensor or making the patient hold their breath for a short time. This demonstrates the importance of our future work on this research, *i.e.,* implementation of a more compact and portable system based on the prototype design. This will make the trials on real patients more convenient.

Chapter 5

Conclusion and recommendation

In this chapter, we summarize the results from our development of the prototype of the heart sound detection system based on on laser technology and mention the recommendations for future work on this research.

5.1 Summary

The objective of this project was to investigate and develop a new tool, *i.e.*, the laser-based stethoscope to improve physician's daily work on heart sound detection. Heart evaluation is a complex task, in which auscultation is one piece of the puzzle. We believe the new system will be able to help practitioners make a better judgment of their patient's condition.

The main goal of the project was to detect low frequency vibrations from the human chest and extract information from the heart. Throughout the project, the prototype of the system including hardware and software was developed. We performed the trial of the prototype on a dummy human body at the Medical School. In this laser-based stethoscope, the heartbeat signal is correlated to the optical spot of a laser beam reflected from a thin mirror attached to the patient's chest skin. The motion of the mirror with the chest skin is generated by heartbeat and breathing. A linear optical sensor is applied to detect and record the motion of the optical spot, from which the heartbeat signal in time-domain is extracted. The heartbeat signal is then transformed to the frequency domain through digital signal processing. The trial results on the dummy human body proved that the conceptual design of the system is successful. Both time domain and frequency-domain signals could be obtained and be used to classify different types of heart murmurs. In the trail with dummy human body, we tested the prototype system with various heart sound patterns including the normal one, the aortic stenosis and mitral prolapsed. The combined time-domain and frequency domain information displayed by our system could identify the unique pattern for each type of heart sound. The results agree well with the simultaneous detection results by the PCG. Moreover, it is found that our system is more capable of disclosing the low-frequency heart sound information and PCG is better on high-frequency heart sounds. Since very valuable heart murmur information is present in low-frequency heart sounds, our system has its unique advantage on assisting health practitioners to disclose in-depth heart problems that could not be detected using the acoustic stethoscope or PCG.

5.2 Future work

At this stage, the conceptual design of the laser-based stethoscope was successfully demonstrated and tests were performed on the dummy human body from the Medical School at UMD. Based on the current results achieved on this research, we make the following recommendations on the future research:

(1) A compact and portable system based on the prototype will be implemented. The proposal on this is that all components of the system are packaged into a box with reasonable size for carrying. Each components of the system must re-selected with minimized size while preserving the satisfactory function. For example, the laser source with size on centimeter (cm) level is preferred; however, at the same

time, we must consider adequate functionality of such a laser source for the system, such as the beam confinement, optical spot size and the safety to human eyes and body, etc. The optical sensor with smaller size, larger detection window and enough sensitivity is another challenge in the future research on the compact system. The current optical sensor used has enough detection sensitivity but small detection window and large size. We will seek on the market to find a satisfactory replacement.

(2) Clinical trials on real patients or campus volunteers will be performed with the compact system. The clinical trials in either case must follow the successful pursuit of the approval from Institutional Review Board (IRB).

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