Design and Analysis of Respiratory Sounds Simulator For Testing Auscultation Transducers

Kunwoo Kim

Master's Research Project (December 2013)
Advisor: Dr. James E. West

Department of Electrical and Computer Engineering
The Johns Hopkins University

TABLE OF CONTENTS

Abstract:

There are many different kinds of auscultation transducers today such as mechanical and electronic stethoscopes, accelerometers, and microphones. However, testing these devices on human subjects is a difficult task since their lung sounds vary with time, and they are not always available in lab environments. To resolve these problems, a respiratory sounds simulator was designed that produces stable and repeatable lung sounds to be employed for making comparisons of different auscultation transducers. Frequency response evaluation of the device was done using white-noise input and distortion analysis was done using vesicular breath sound and heartbeat inputs. Finally, I included an exemplary testing, ‘obtaining the transfer function of an electronic stethoscope’.

I. INTRODUCTION

Background

Chest auscultation is a technique for listening to internal respiratory sounds to further analyze and diagnose any possible respiratory diseases. Various kinds of transducers each with different purpose exist today. Our lab under Dr. James E. West, designed and constructed prototype transducers mainly for infant chest auscultation in noisy environments. Various techniques were introduced such as noise cancellation, Bluetooth transmission, and employment of microphone array to meet the requirements. We wanted to compare different transducers with the existing stethoscopes to observe and categorize their strengths and weaknesses. However, we realized that we needed a stable testing system to observe and analyze more precisely.

Problem Statement

Testing on human subjects can be a difficult task due to their variability and availability. First, human lung sounds always vary with time. Even at a precisely controlled setting, no lung sound will be identical to one another. Sickness and other possible abnormal status, or sudden increase in heartbeats can cause lung sounds to differ day by day, or even second by second. The person's change in positions such as sitting, lying down, or standing can create some noticeable changes. Change in location of the transducer can yield minor biases. Different environmental noise can be introduced for different measurements.

Second, human subjects are not always available. Thus we cannot always frequently measure their lung sounds. If test subjects need to be special such as infants, patients in highlands with pneumonia, or patients with asthma, it would be costly and often unavailable in lab environments. Also, heartbeats and lung sounds are inseparable when we are directly measuring from human subjects.

Existing Devices

There exists a number of commercial lung sound simulators. Their main purpose is for auscultation training [1-3]. They have different sets of signals inside a humanlike model. Most signals are mechanically driven, and so acoustic variety is limited to their pre-existing testing sets. Also, their focus seems to be more on locations of signals than quality of the signals. Training for quality of signals is mostly achieved through an audio software. Most of them cost over $1,000. I personally observed HARVEY [2] at the Johns Hopkins Medical Institute. I discovered that lung sounds simulator for training purposes is not suitable for precisely comparing transducers. Its expensive cost, large size, poor acoustic quality, and hard surface material are not the most efficient and effective way of resolving our problems.

BioAcoustic Transducer Testing (BATT) System [4] describes a design and constructive prototype of a testing system. This device is most similar to my simulator. Their design implemented Akton material, which is a viscoelastic polyurethane polymer that is similar to human skin on top of a headphone loudspeaker. They made comparisons of transducers by driving the system with white noise, short impulses and lung sounds. BATT System was at prototype stage, and I wanted to come up with a developed prototype that has a better quality loudspeaker (broader frequency range, pre-amplification, easy-to-use), and a closer representation of human chest.

Overview

This testing system has a loudspeaker completely covered by ballistic gelatin. The loudspeaker takes any kind of input, and propagates the signal through the gel that has density similar to that of human muscle-tissue. Thus the surface would vibrate similarly to how our skin reacts to lung sounds. Output of the system will be stable as long as the input signal is the same. Multiple measurements of identical signals can be taken with different kinds of transducers at different times. Also, this system is always available. Various input signals such as heartbeats, wheezing, crackles, and asthma are available from online libraries. Some other advantages are portability, battery power, Bluetooth, controlled gain, less signal-to-noise ratio and skin-like surface. These will be further explained in section II. Design.

II. DESIGN

Overall Schematic

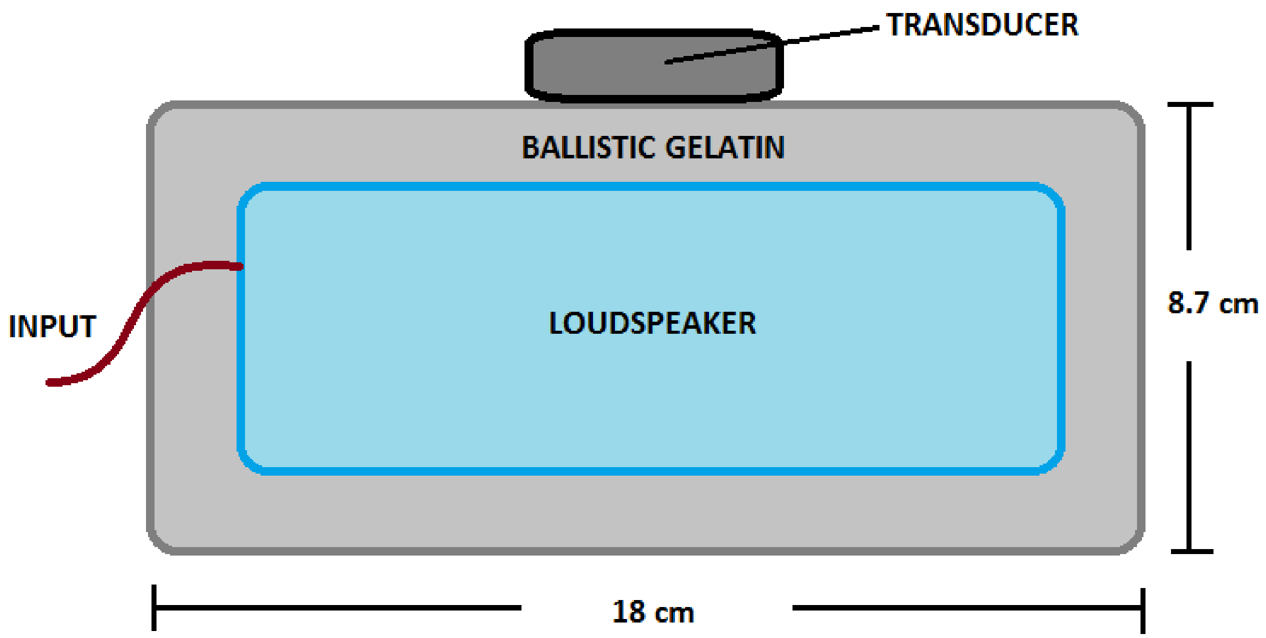


Fig. 1. Front View Schematic of Respiratory Sounds Simulator

Schematic of this device is shown in Fig. 1. This is a general representation of a human chest. The loudspeaker represents the lung, and ballistic gelatin represents muscle and skin that surrounds it. The loudspeaker propagates sound upwards where the transducer is located. Input signal is given from the side. Surrounding ballistic gelatin has a thickness of 1.5 cm. It completely envelops to the loudspeaker. The top surface where measurements are taken is rounded by a small angle.

Loudspeaker

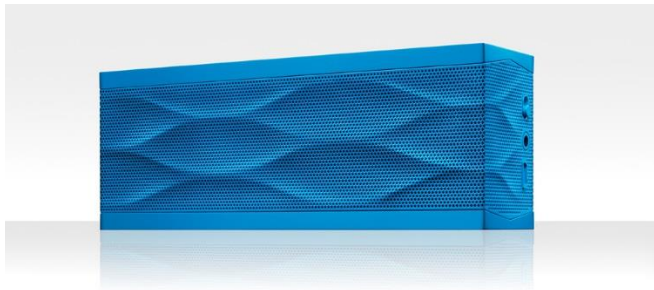


Fig. 2. JAWBONE JAMBOX [5]

JAWBONE JAMBOX [5] loudspeaker is used for this system. It has a frequency response of 60 Hz – 20 kHz. Its dimensions are $151 \times 40 \times 57$ mm. Its battery power lasts for about 10 hours of continuous play and can be charged via USB or the wall. It also has a Bluetooth feature that allows the system to be wireless. It has a volume control that allows gain control of input signals.

This specific loudspeaker was chosen mainly for its high quality in lower frequencies given its cost. It has a proprietary passive bass radiator. This passive radiator allows the speaker to perform better in low frequency given its small volume. Some of the essential respiratory sounds occur in this region. Its overall frequency response allows all kinds of lung sounds to be studied.

Ballistic Gel Surface

Ballistic gelatin closely simulates the density and viscosity of human muscle tissue. It yields readily to light touch, but does not permanently deform. Density of the medium that sound propagates through is a pivotal acoustic feature for this kind of systems. Ballistic gel from Clear Ballistics [6] is used. It is completely reusable, and it mimics human muscle tissue very well. Also, it can be kept at room temperature without deforming. One of its main uses is medical testing.

Construction

A mold has to be made to shape this gel as shown in Fig. 1. The gel is melted and poured into the mold with about -10% tolerance. The mold must have negative tolerance as shown in Fig. 3 in order to have no air cavity.

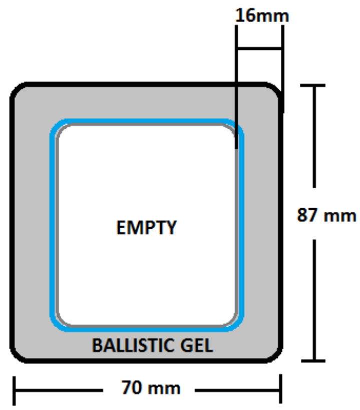


Fig. 3. Side View of Mold Schematic

Slight air cavity between the loudspeaker and the gel can cause major distortions. Small amount of negative tolerance allows the gel to stretch a little bit and fully adhere to the loudspeaker. Ballistic gel inside the mold is then cooled for 24 hours at 4 ℃. It allows the gel to harden enough to retain the density of human muscle tissue. A ballistic gel cap with holes for audio and power inputs was attached to the open end of the mold. Fig. 4. shows the completed model. Acoustic cotton is put on the bottom to attenuate high frequency resonance and table noise.

Complete Construction of the Design

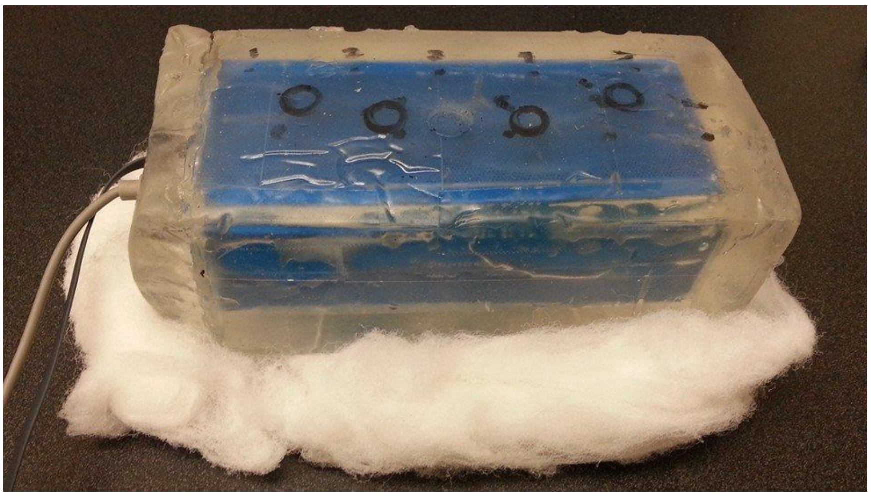


Fig. 4. Overall Design of the System

III. ANALYSIS

Methods

The goal of analysis is to find out if this system effectively simulates lung sounds. Two requirements should be met. One is that our system's frequency response should not be attenuated at the frequency range of clinically evident lung sounds, which is between 200 and 1,000 Hz [4]. The other is that its output should not contain major distortions. Random white noise input is used for the frequency response analysis. Vesicular breath sound and heartbeat samples are used for the distortion analysis.

A condenser microphone [7] was used to calibrate the loudspeaker/gel system. The microphone has a flat frequency response, so it can be a good reference point when making comparisons. As shown in Fig. 5, the microphone was firmly held by a laboratory stand because noise induced by taking measurements by hand-holding often dominates the signal. I used Audacity [8] software to record them. I took 16 recordings, four each at four different locations as shown in Fig. 6 to minimize bias. I ensured that the level of output signals was similar to that of a large lung sound. They should be barely hearable a few inches away from the device.

All output signals were passed through a high-pass filter of 36 dB and 100 Hz cut-off frequency to eliminate noise under the minimum frequency of the loudspeaker. They were further analyzed by signal processing through MATLAB [9].

All data were measured and recorded in Barton Hall 4 at Johns Hopkins University.

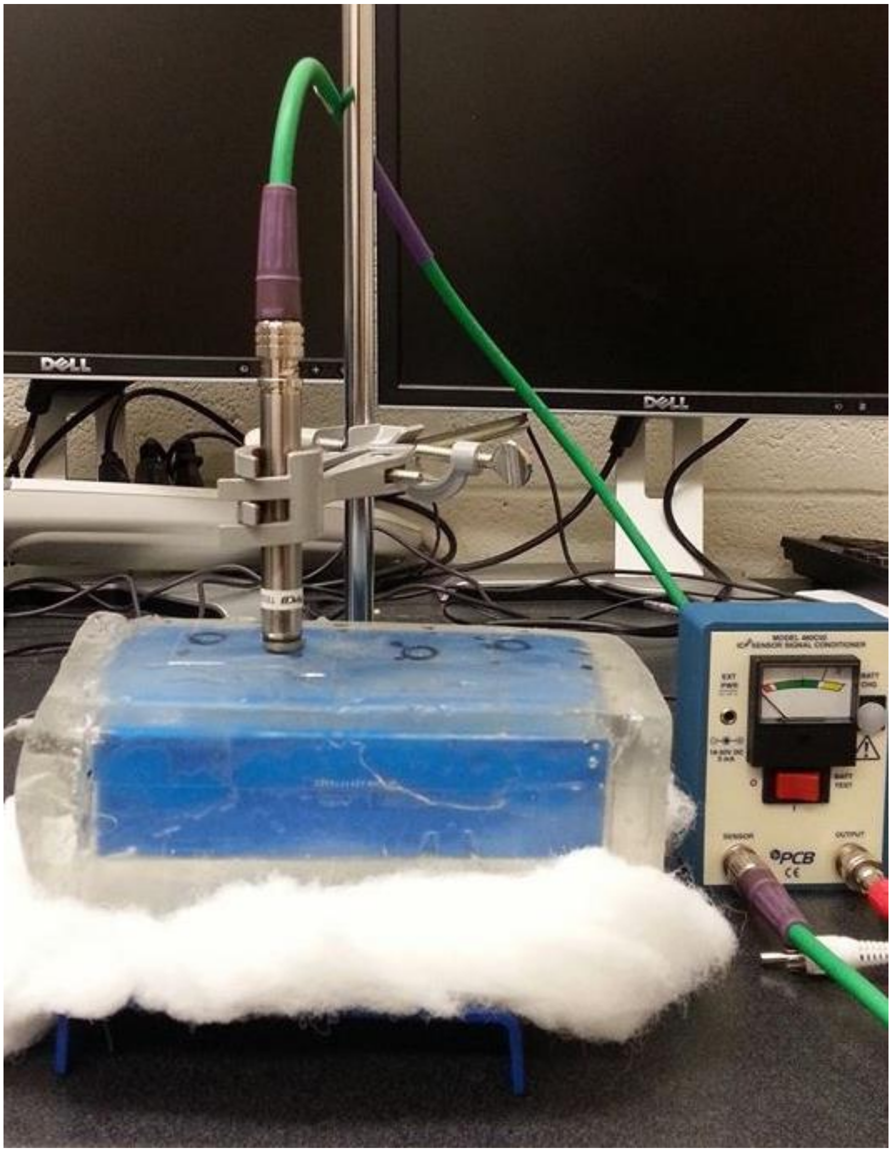


Fig. 5. Measurement Setup.

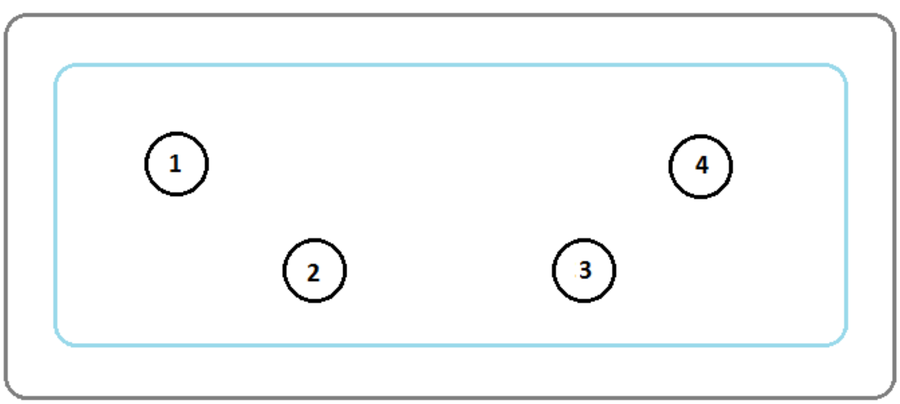


Fig. 6. Four different positions where measurements were taken

Experiment 1 – Frequency Response Analysis

The goal of this experiment is to first find the general frequency response of the system, and second compare frequency responses at different locations shown in Fig. 6. The first part can be obtained by averaging the frequency responses of the 16 output samples. The second part can be obtained by comparing each point's frequency response average of four output samples. White noise has a flat frequency spectrum in all frequencies. Thus it is an effective input for finding the frequency response of the system.

The signals were digitized at 44100 samples per second with quantized in 16 bits. The sampling frequency was enough to cover all components without aliasing. Lengths of signals were equalized for analysis. To obtain the general frequency response of the system, a fast Fourier transform was performed on all 17 signals with 2220 frames and 50% overlap. Each window was multiplied by a Hamming-window. Spectral estimates of each frame were averaged in the frequency domain by taking RMS (Root Mean Squared). Then the 16 recorded FFT spectra were averaged once again by taking the RMS value and converted into decibels (dB).

To compare each point's frequency response, I took a fast Fourier transform on all 17 signals with 544 frames and 50% overlap. I took less number of frames than that of the first part for more smoothed out graphs. Again, I computed four RMS values corresponding to each position and converted into decibels (dB).

Experiment 2 – Distortion Analysis

The goal of this experiment is to find if there exist possible distortions in the output signals. To do so, I took vesicular breath sound and heartbeat sound samples as representations of continuous and discontinuous signals, respectively. Their outputs in both time domain and frequency domain were compared with their inputs. They should somewhat represent the input signal without too much errors. Signal processing part for spectral analysis were similar to that of Experiment 1 (2220 frames).

IV. RESULTS

Experiment 1 – Frequency Response

The general frequency response of white noise signal input is shown in Fig. 7. Blue is the original signal spectrum and red is the averaged recorded spectrum. These signals are represented in logarithmic axis.

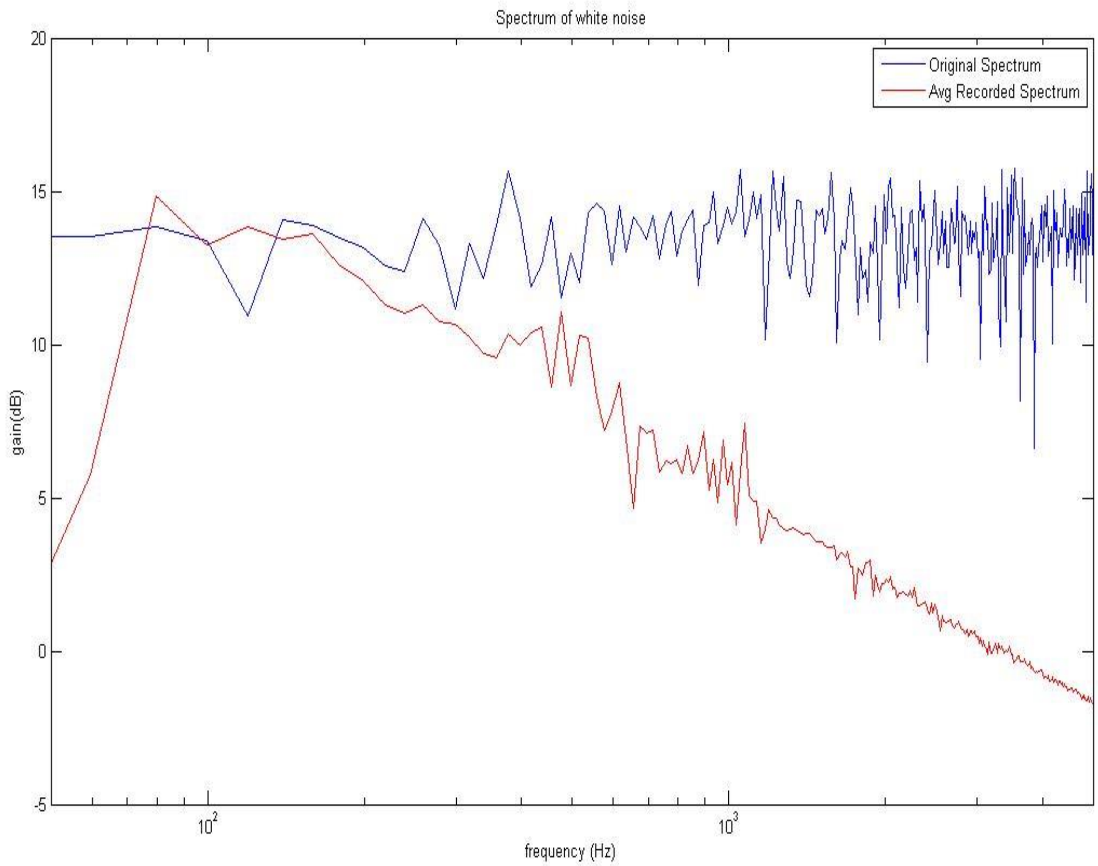


Fig. 7. Spectrum of White noise, Original vs. Average Recorded

The original signal shown in blue, has somewhat flat spectrum throughout the frequency. The average spectrum of 16 recorded signal in red shows an interesting result. The frequency peaks around 100 Hz, and decreases as it gets to higher frequency. Frequency over 2.5 kHz yields 0 dB gain. The frequency response between 200 Hz to 1,000 Hz, our main focus, has a positive response.

Each point's average frequency response of white noise signal input is shown in Fig. 8. Blue is the original signal spectrum, red - position 1, cyan-position 2, black-position 3, magenta-position 4.

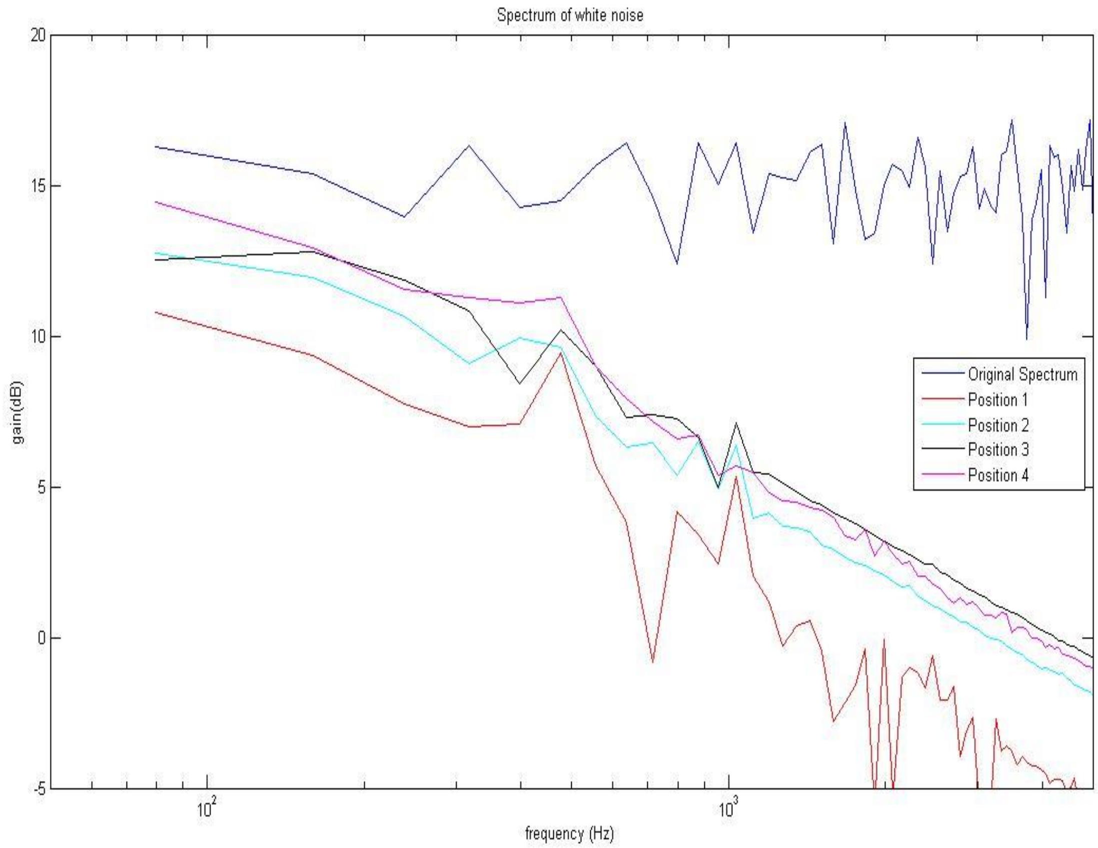


Fig. 8. Spectrum of White noise, Original vs. Average Recorded on Four Positions

All four positions show positive gain between 200 Hz to 1,000 Hz. Position 1 has the lowest and most unstable frequency response. Position 2 has low but relatively stable frequency response. Position 3 has a high and most stable frequency response. Position 4 has the highest and relatively stable frequency response. By observing the response from white-noise, any positions other than 1 would be useful. Position 3 or 4 would be optimal.

Experiment 2 – Distortion Observation

(1) Vesicular Breath Sound – Time Domain

The top signal in Fig. 9. represents the original vesicular breath sound in the time-domain. The below two signals represent two randomly selected recorded vesicular breath sounds.

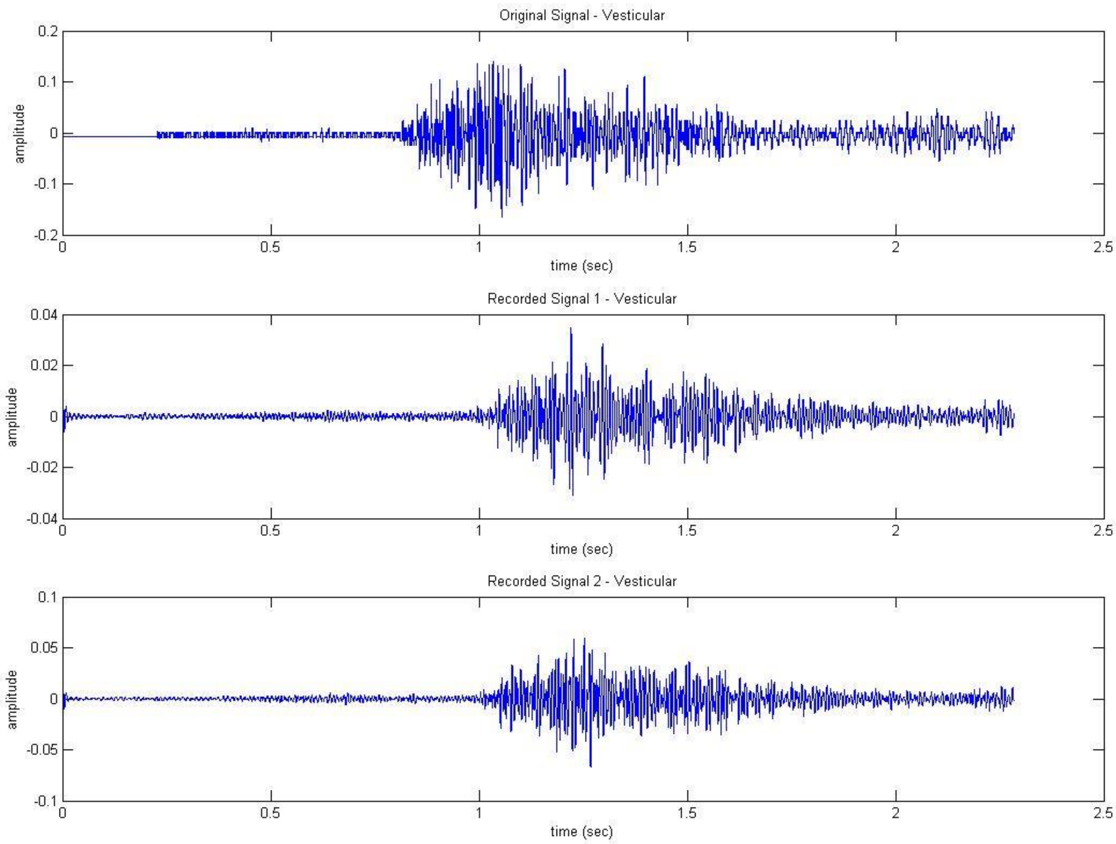


Fig. 9. Time-domain representation of Original vs. 2 Randomly Selected Recorded signals

There is about 0.3 seconds of delay due to the recording process. Notice that the original signal has about five times the amplitude of that of Recorded signal 1, and about three times the amplitude of that of Recorded signal 2. Recorded signal 1 is taken from Position 3, and recorded signal 2 is taken from Position 4. Signals recorded at Position 4 seems to have generally larger and more accurate gain than any other positions. If signals were taken to match the amplitude of the original signal, distortions occurred in very high frequency values. However, when taken at the level of a loud lung sound, the output signal seems to be undistorted. Therefore it is suggested that Position 4 be considered the best location for comparing different transducers.

(2) Vesicular Breath Sound – Frequency Domain

The frequency response of vesicular breath sound is shown in Fig. 10. Blue is the original signal spectrum, and red is the average spectrum of recorded signals.

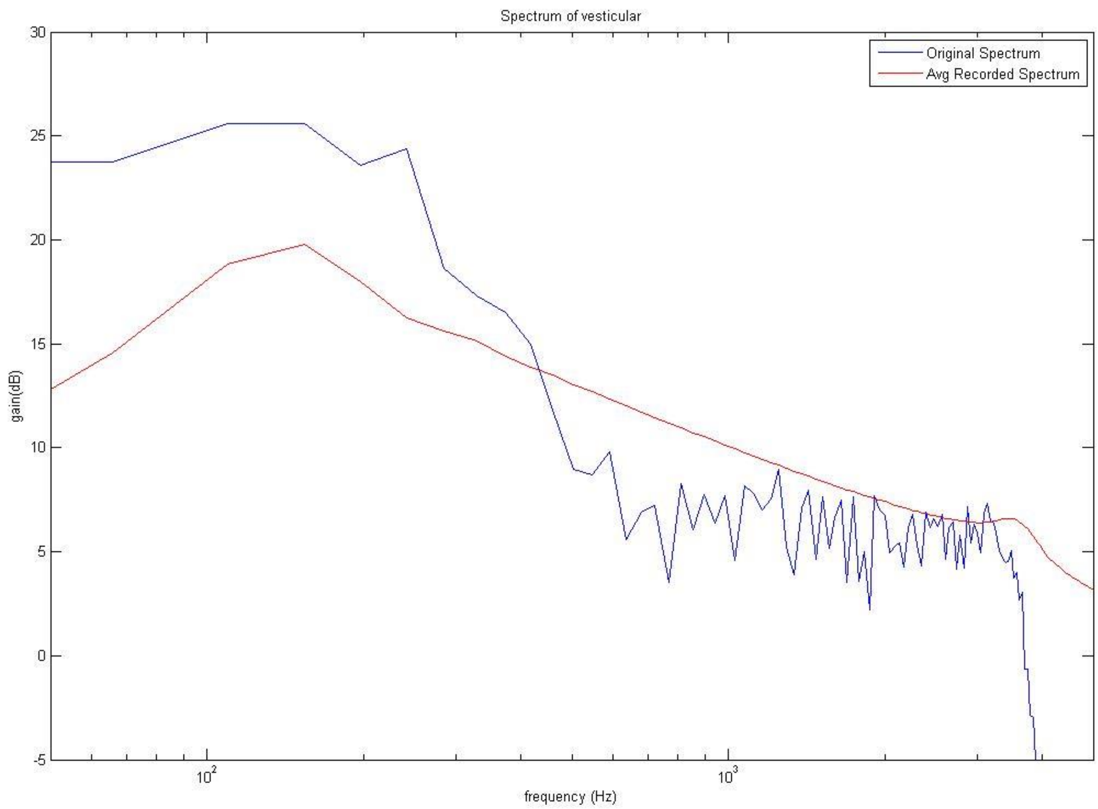


Fig. 10. Spectrum of Vesicular, Original vs. Average Recorded

The frequency response did not show any noticeable anomalies. The recorded spectrum generally mimics the behavior of the original spectrum. The original spectrum shows stronger low frequencies and more rapid fall between 200 Hz to 800 Hz. The recorded spectrum, however, seems more smoothed. It has weaker low frequencies and less rapid fall between 200 Hz to 800 Hz.

(3) Heartbeat sound – Time Domain

The top signal in Fig. 11. represents the original normal split heartbeat sound in the time-domain. The below two signals represent two randomly selected recorded normal split heartbeat sounds.

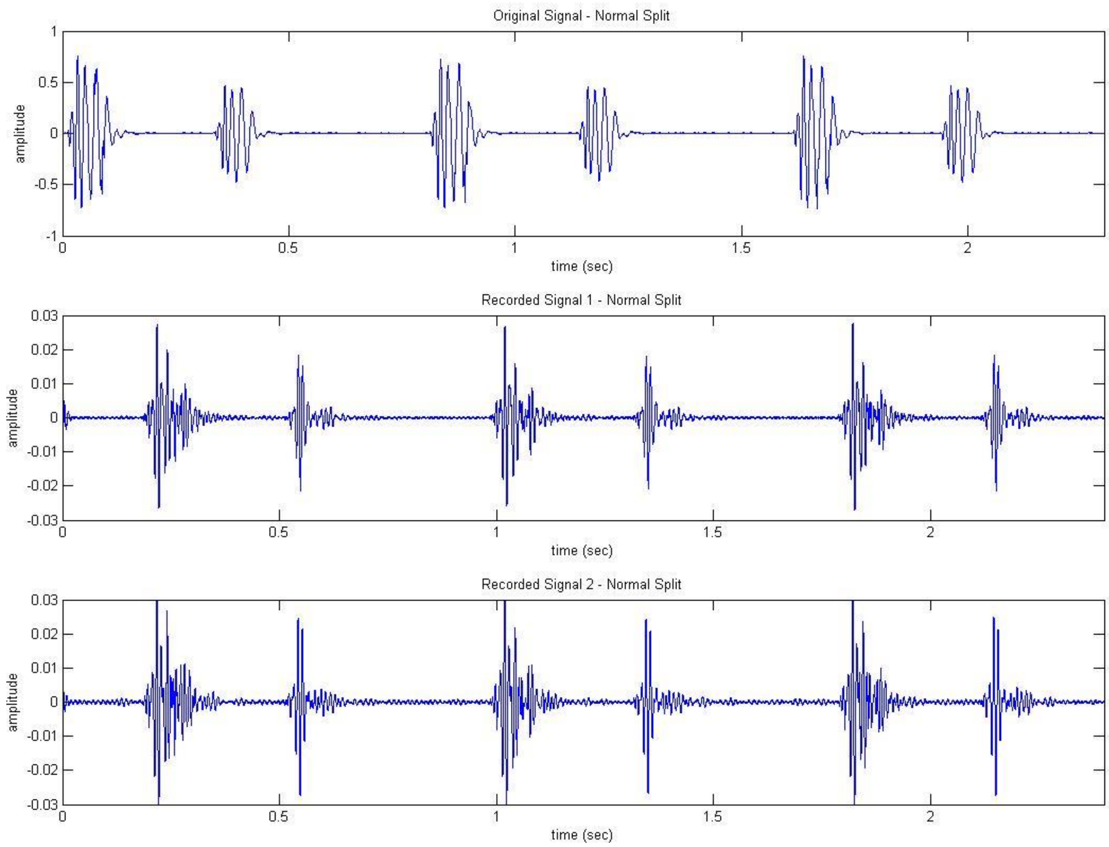


Fig. 11. Time-domain representation of Original vs. 2 Randomly Selected Recorded signals

As a whole, the recorded heartbeat output generally mimics the input signal. However, discontinuous sounds seem to yield relatively more distortions than continuous sounds. A sudden leap seems to cause the viscoelastic material to bounce back and forth rapidly. This is a problem for some measurements, but as long as the protocol is followed, comparing transducers with this system is still valid.

(4) Heartbeat sound – Frequency Domain

The frequency response of heartbeat sound is shown in Fig. 12. Blue is the original signal spectrum, and red is the average spectrum of recorded signals.

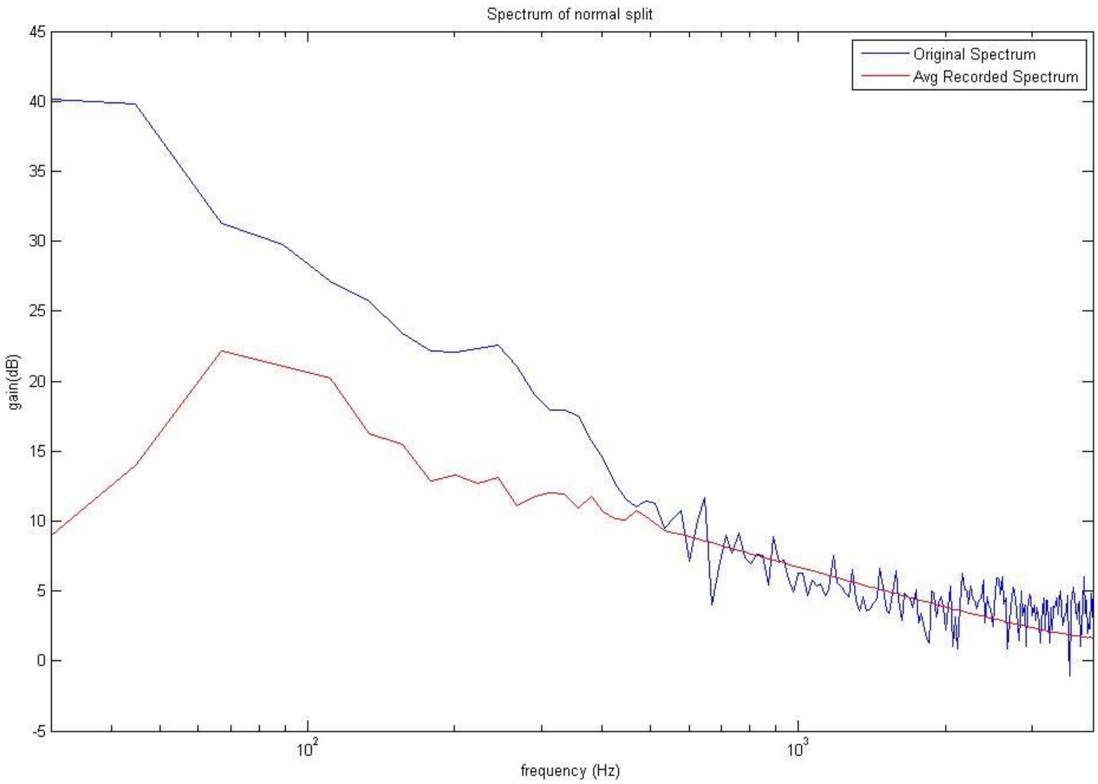


Fig. 12. Spectrum of Normal Split, Original vs. Average Recorded

The original signal has a very high level in the low frequencies. There is about 30 dB difference between 30 Hz to 500 Hz. Our recorded result shows that there is about 15 dB difference in gain between the similar frequency range. After 500 Hz, the spectrum gains are almost equal. This may be the reason to the distortion observed in the time-domain. There seems to be excessive frequency components between the essential peaks in the recorded signal. Relatively weaker gain in the lower frequencies than the high frequencies is the reason. Additional filtering can reduce the above differences.

V. Exemplary Testing

I implemented this system to analyze the overall performance and to obtain the spectrum of the transfer function of an electronic stethoscope [10], Thinklabs ds32a. It has two modes, Bell and Diaphragm as shown in

Fig. 13. Thinklabs Electronic Stethoscope ds32a.

Fig. 13. According to its manual, Bell mode has an amplification in low frequencies, while Diaphragm reduces it. I measured in the three signals that were used in Experiment 1 and 2 in the same way as they were previously conducted; 16 signals, 44,100 Hz sampling frequency, 16 bits quantization.

To analyze the overall performance, I plotted the spectra of input, condenser microphone output, Bell output, and Diaphragm output. Output recorded by condenser microphone is the reference point. Thus comparisons are made to that. To obtain the transfer functions, I divided the each mode's spectrum by the reference spectrum.

(1) Spectra and Transfer Functions of White Noise Input

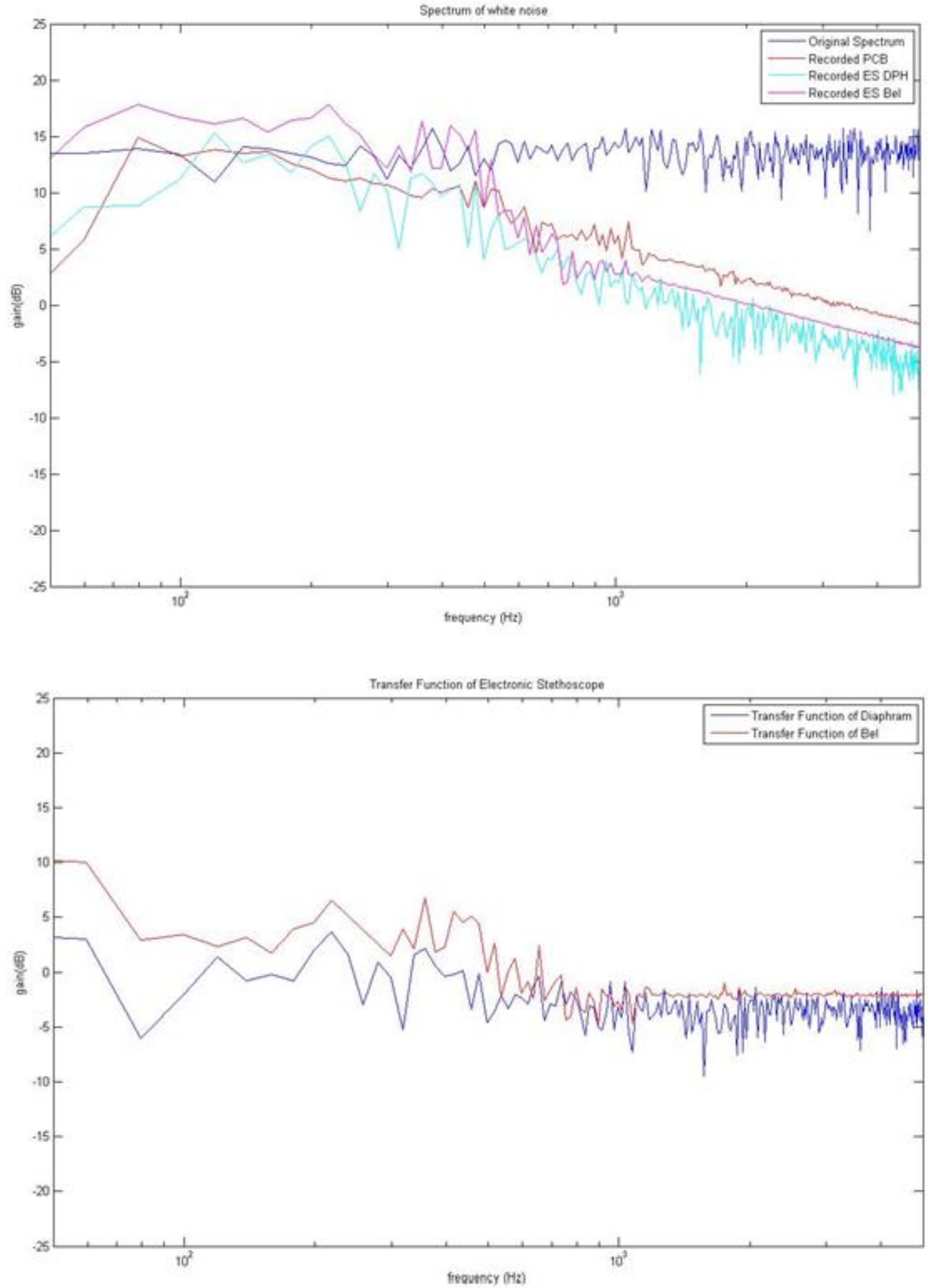


Fig. 14. Spectra and Transfer Functions of White Noise Input

Original spectrum is in blue, reference spectrum in red, Diaphragm mode in cyan, and Bell mode in magenta. For transfer functions, Diaphragm is in red, and Bell is in blue.

(2) Spectra and Transfer Functions of Vesicular Breath Sound

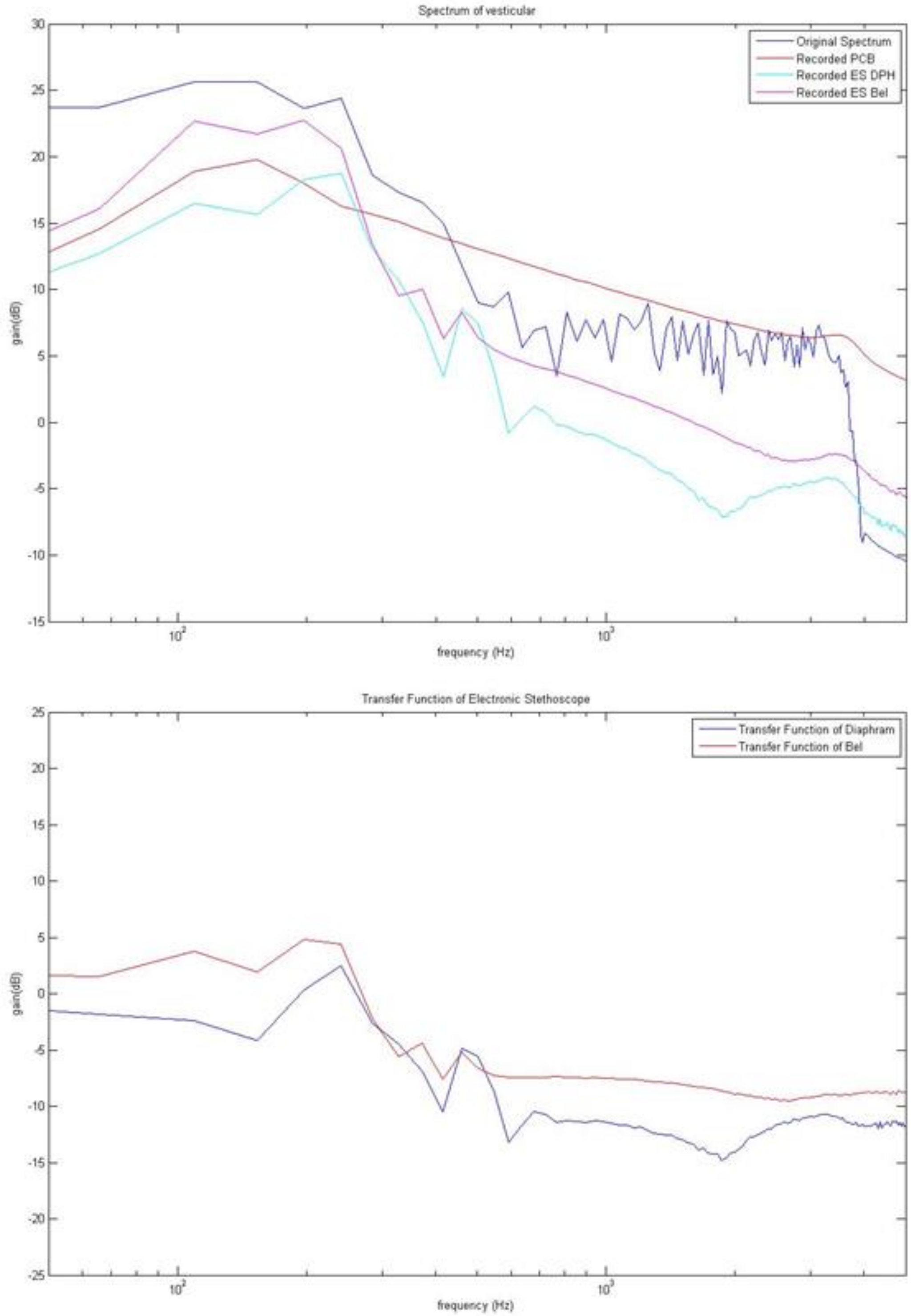
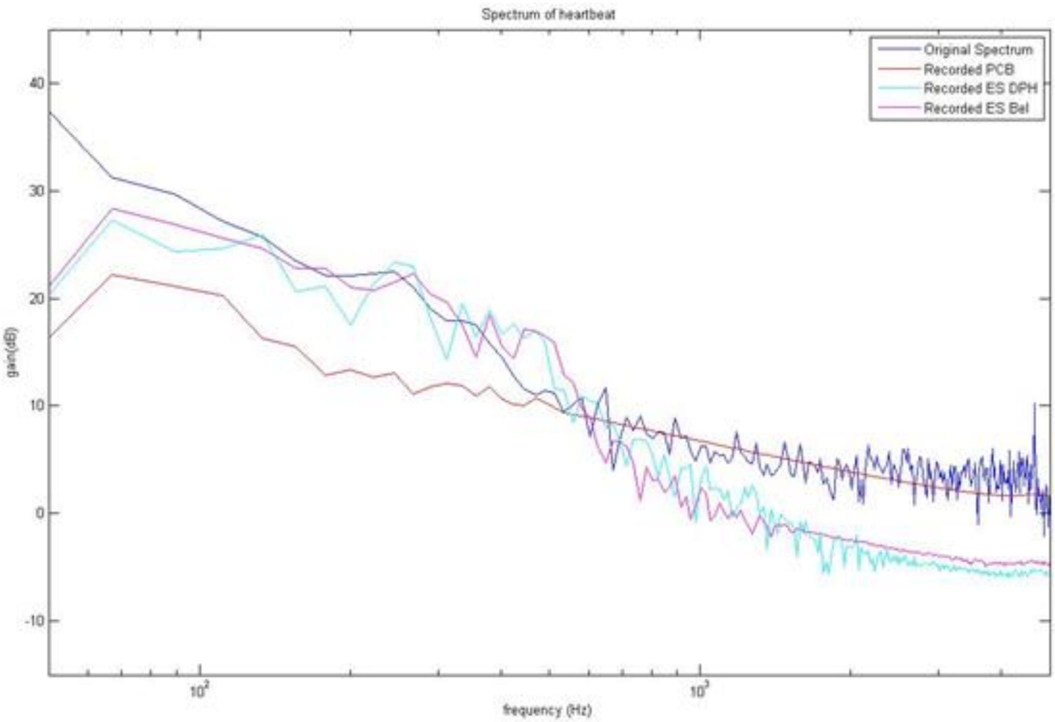


Fig. 15. Spectra and Transfer Functions of Vesicular Breath Sound

Original spectrum is in blue, reference spectrum in red, Diaphragm mode in cyan, and Bell mode in magenta. For transfer functions, Diaphragm is in red, and Bell is in blue.

(3) Spectra and Transfer Functions of Heartbeat



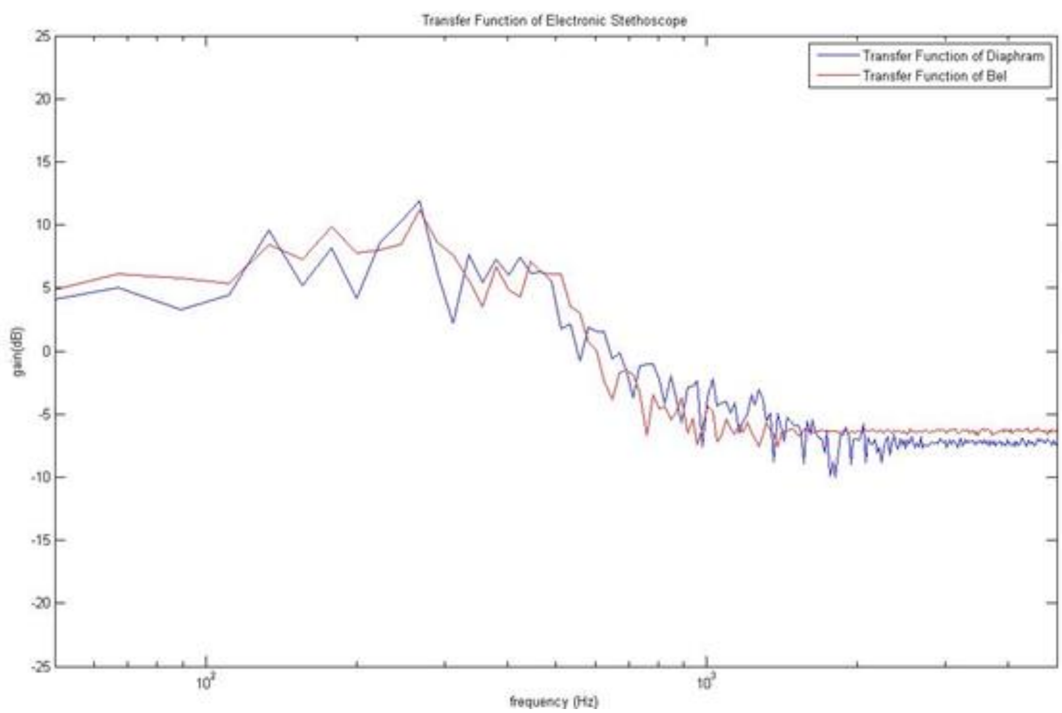


Fig. 16. Spectra and Transfer Functions of Heartbeat Sound

Original spectrum is in blue, reference spectrum in red, Diaphragm mode in cyan, and Bell mode in magenta. For transfer functions, Diaphragm is in red, and Bell is in blue.

From white-noise and vesicular breath sound input, I observed that Diaphragm mode of the electronic stethoscope showed lesser gain than the reference output while Bell mode showed more gain in the low frequencies. However after 600 Hz for white noise input, and 300 Hz for vesicular breath sound input, Bell mode gain decreased sharply under the reference gain. This clearly tells me that there exists an extra boost in the low frequencies for Bell mode. The plots of transfer functions allow me to visualize this clearly as 0 dB is the reference point. From heartbeat sound input, I observed that both Diaphragm and Bell modes showed almost identical results.

From this result, the following decisions can be made when using this stethoscope. To focus on very low frequencies of a signal (50 Hz ~ 300 Hz), I would use Bell Mode of the stethoscope. To focus on higher frequencies, (or to not be affected by the very low frequencies), I would use Diaphragm Mode of the stethoscope.

V. CONCLUSION

From Experiment 1, I observed that the overall frequency response of the system obtained using white noise input effectively covers the frequency range of crucial lung sounds. It shows quality gain in the region of 100 Hz to 1,000 Hz. Frequency responses from Experiment 2, vesicular breath sound and heartbeat, support this result. For both discontinuous and continuous signals, there exists no attenuation in the general lug sound range. Some crackles and wheezes may fall into higher frequencies, so they may require an equalizer to clearly show the output signal.

From Experiment 2, I observed that there is little distortion for continuous signals such as vesicular breath sound, but relatively more noticeable distortion for discontinuous signals. The distortions occur in frequencies where low-pass filter cannot eliminate. This may be alleviated by putting more acoustic cottons around.

From exemplary testing, I observed that using the condenser microphone as the reference point of outputs is an effective way of calibrating measurements. Transfer functions of white noise input, vesicular breath sounds, and heartbeat sounds, came out to be stable and similar. Thus this is another result that shows that this system can be used to figure out the behaviors of different transducers.

Overall, this system effectively represents a human chest in its design and analysis. The loudspeaker is capable of taking any kinds of audio signals, and surrounding ballistic gel is an excellent material of mimicking muscle tissue and skin. Its analysis shows that it has its strengths in its stable frequency response in the very important frequency range, in small amount of distortion in continuous signals, which most respiratory sounds are categorized at.

I believe that this simulator has its possibilities beyond its main purpose of comparing transducers. It can be used to find out the filter difference between an electronic stethoscope and a mechanical stethoscope. It can be used as a vibration tester for skin adhesive materials. It can be employed in a noisy environment to find out the signal to noise ratio of different kinds of transducers.

ACKNOWLEDGEMENTS

I would like to thank Dr. James E. West, for being my advisor, motivator, and mentor. As a student who has major interests in the field of acoustics, I could not have found a better advisor. Entering his lab in my sophomore year, I did not know how to practice my interests. But throughout the years, I could learn invaluable lessons by experience not only on how to technically perform in research, but also on how to enjoy it. Also I would like to thank Professor Mounya Elhilali for her lessons and help in audio signal processing.

REFERENCES

[1] Lung sound library. [Online]. Available: http://www.easyauscultation.com/

[2] Harvey, The Cardiopulmonary Patient Simulator. http://www.laerdal.com/us/harvey

[3] Simulaids – Training Aids for Emergency, Medical and Rescue Personnel. http://www.simulaids.com/ps.htm

[4] S. Kraman, G. Pressler, H. Pasterkamp, and G. Wodicka, (2006 Aug) "Design, Construction, and Evaluation of a BioAcoustic Transducer Testing (BATT) System for Respiratory Sounds", in *IEEE Transactions on Biomedical Engineering,* Vol. 53, NO. 8.

[5] Jawbone Jambox Loudspeaker specification. Available: https://jawbone.com/speakers/jambox/specs

[6] Clearballistics http://clearballistics.com/

[7] PCB Piezotronics microphone Model 426E01. Available: http://www.pcb.com/

[8] Audacity 2.0.5. Available: http://audacity.sourceforge.net/

[9] MATLAB. Available: http://www.mathworks.com

[10] Thinklabs Electronic Stethoscope. Available: http://www.thinklabsmedical.com/