Comparison of Sensors (Digital Stethoscope and Contact Microphone) for Foetal Heart Sound Acquisition

Sharadhi U Bharadwaj, Dr.Manish Arora

Student (BMS College of Engineering), Basavangudi, Bangalore, sharadhiubharadwaj@gmail.com

ABSTRACT

Foetal Phonocardiography is a non-invasive method of measuring the foetal heart rate. Foetal Heart Rate is an important parameter to know the foetal well-being and any case of foetal distress during the antepartum or intrapartum period [2]. Foetal heart sounds for calculating the foetal heart rate is a valuable alternative to invasive and expensive procedures like Foetal Electrocardiograph (fECG). To obtain a gold standard for testing algorithms, Manual Measurement of Foetal Heart Rate from clinically obtained Foetal Heart Sound was carried out. Two sensors, Digital Stethoscope and Contact Microphone were also tested and compared for foetal heart sound acquisition. The comparison of the sensors was carried out by measuring the SNR of the data acquired by the sensors. The optimum force to be applied to the mother's womb by the sensors was also found by experimentation.

Keywords: Foetal Heart Rate, Optimum force, Signal to Noise Ratio

INTRODUCTION

The Normal Heart Rate range for a healthy foetus is 120 to 160 beats per minute. The foetus is said to be Tachycardic is the Foetal Heart Rate is above 160 beats per minute and Bradycardic if the Foetal Heart Rate is below 100 beats per minute [1].

Foetal phonocardiography (fPCG) is a passive recording of the foetal heart sounds from the maternal abdomen produced due to the mechanical activities of the foetal heart. The foetal heart sounds during the first and second trimester provide valuable information regarding foetal well-being, whereas, in the third trimester, foetal wellbeing is determined by the foetal heart rate (FHR). The other methods for measuring the FHR includes foetal Doppler, foetal electrocardiography(fECG) and foetal Magnetocardiography(fMCG). All these methods have been widely used to know the well-being of the foetus. Foetal electrocardiography (fECG) is the most accurate of the following methods to determine Foetal Heart Rate (FHR) but is an invasive method. fPCG is a passive measurement technique, thus no energy is passed to the foetus and is hence considered to be safe to the foetus [2].

A MATLAB routine was developed where the FHR from the clinically obtained foetal heart sounds was extracted.

The project focuses on recording heart sounds from the Electronic Stethoscope and the Contact Microphone simulated by the foetal simulator. The data recorded is then analysed offline and the Signal-to-Noise ratio of the data recorded by both the sensors is measured.

The report is divided into two sections, Section 1 and Section 2.

- Section 1 - Manual measurement of foetal heart rate from clinically obtained foetal heart sound.
- Section 2 - Comparison of Digital Stethoscope with Contact Microphone for foetal heart sound acquisition.

Section 1: Manual Measurement of Foetal Heart Rate from Clinically Obtained Foetal Heart Sounds

Clinically obtained foetal heart sounds were manually picked using a MATLAB routine where the entire dataset was divided into 4-second windows. The time between each heart sound was calculated and extrapolated to calculate the reference heart rate at every 4-second frame.

This manually annotated data would hence serve as a standard on which any further developed algorithms can be tested and trained.

Number of data recordings manually annotated – 25

Length of each recording – 10 minutes.

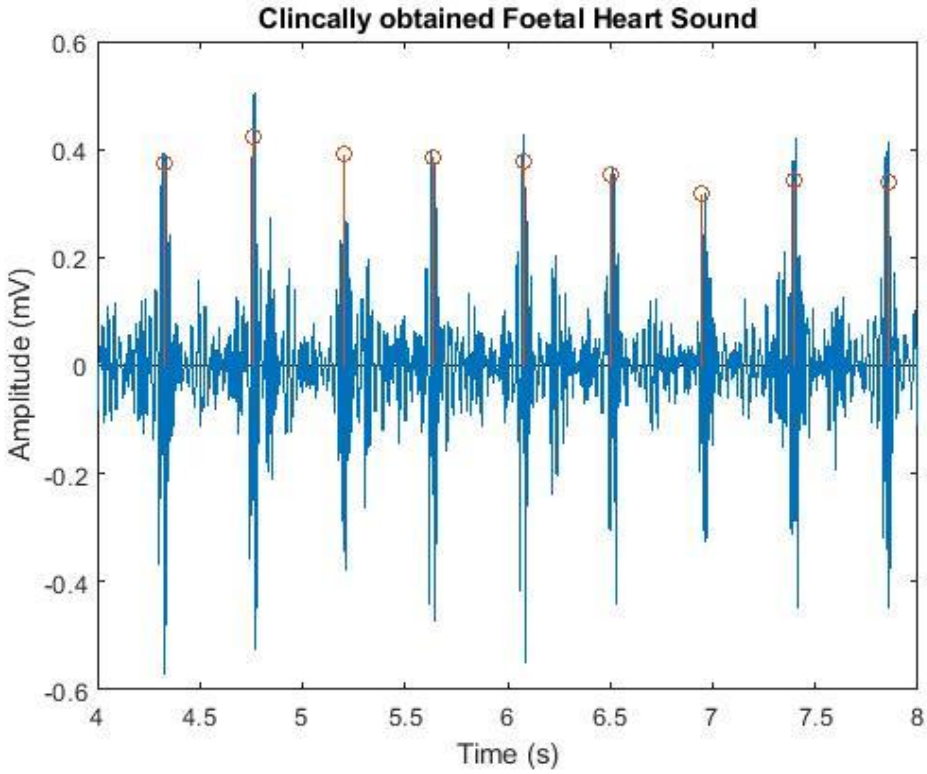

Figure 1: Clinically obtained Foetal Heart Sound showing the manual annotations.

At times, the heart sound signal in the data could not be identified due to various reasons like high ambient noise, motion artefact, etc. Such frames where the signal could not be identified had to be skipped for calculating the reference heart rate.

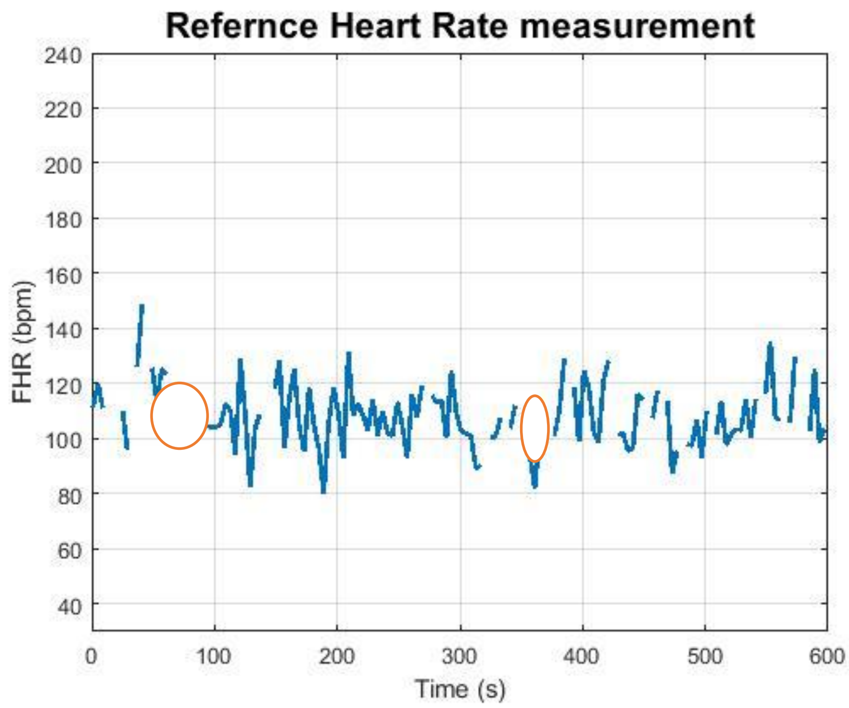

Figure 2: Example (1) of manually calculated Foetal Heart Rate from Foetal Heart Sounds. The red circled spots are the data frames where the heart sound peaks could not be identified.

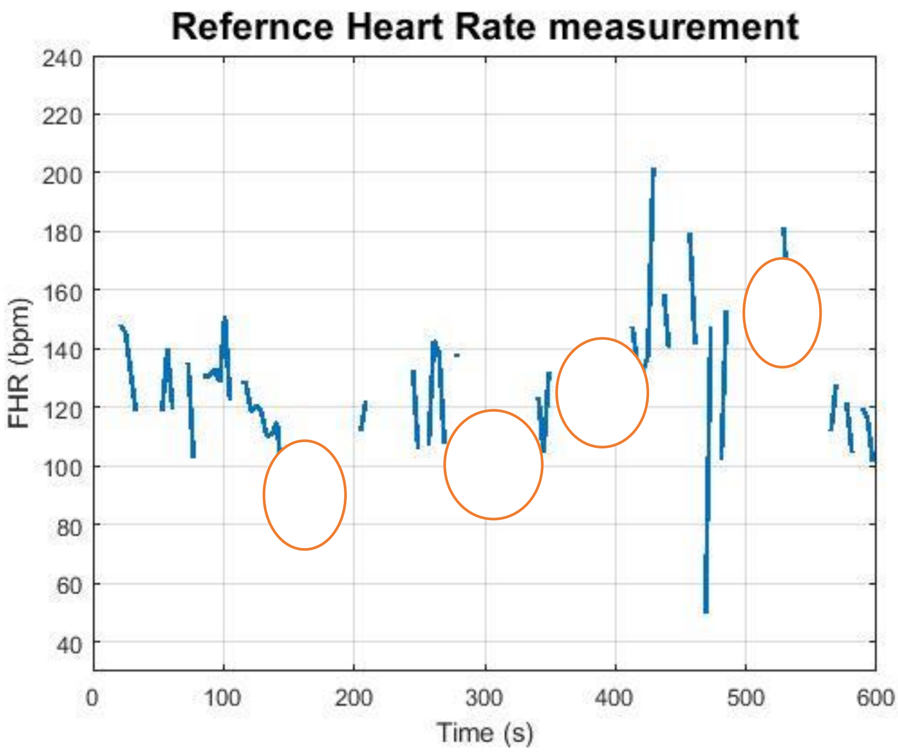

Figure 3: Example (2) of manually calculated Foetal Heart Rate from Foetal Heart Sounds. The red circled spots are the data frames where the heart sound peaks could not be identified.

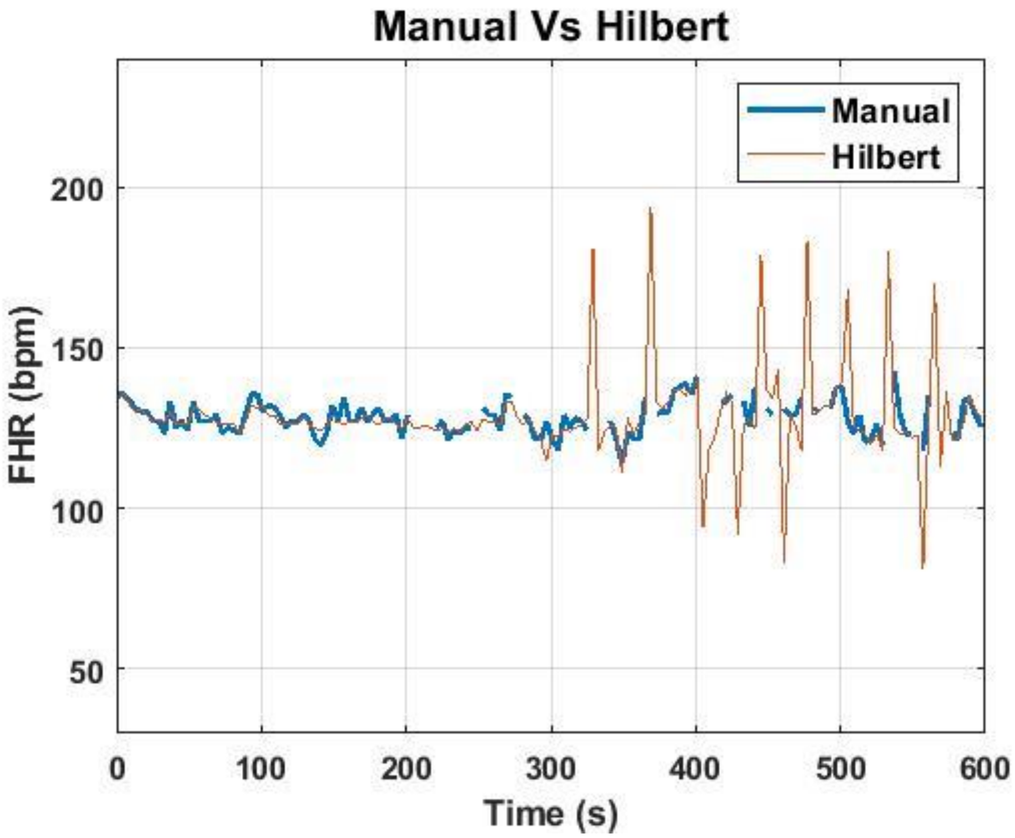

Figure 4: Graph showing the comparison of Foetal Heart Rate calculated manually and using Hilbert Algorithm.

Subject	Number of windows	Number of windows peaks not visible
1	150	65
2	150	17
3	150	25
4	150	53
5	150	61
6	150	29
7	150	36
8	150	15
9	54	3
10	150	26

Table 1: Number of data frames in the entire signal, where heart sounds were not identifiable.

The manually annotated data can also be used to compare the efficiency of different algorithms normally and at a lower Signal-to-Noise Ratio.

The number of data frames where the heart sound was not identifiable motivated us to look at other sensors which can be used for foetal heart sound acquisition. This also made us investigate the optimum force that needs to be applied to obtain higher SNR with respect to both the sensors.

Section 2: Comparison of Sensors (Digital Stethoscope and Contact Microphone) for Foetal Heart Sound Acquisition

The two sensors used for comparison of Foetal Heart Sound acquisition were the Contact Microphone and the Digital Stethoscope.

Contact Microphone:

The CM-01B contact microphone uses sensitive but robust PVDF piezo film combined with a low noise electronic preamplifier to provide a unique sound or vibration pick-up with buffered output. The design minimizes external acoustic noise while offering extremely high sensitivity to vibration applied to the central rubber pad. The CM-01B is ideal for detecting body sounds [6].

Figure 5: Contact Microphone (CM-01b (TE Connectivity))

Parameter	Min	Typ	Max	Units
Sensitivity		40		V/mm
Lower Limiting Frequency (-3 dB)		8		Hz
Upper Limiting Frequency (+3 dB)		2.2		kHz
Resonance Frequency		5		kHz
Spring Constant		20		N/m
Electronic Noise		1		mV_{pk-pk}
Supply Voltage	4	5	30	V-DC
Supply Current		0.1		mA
Operating Temperature	+5		+60	°C
Storage Temperature	-20		+85	°C

Table2: Performance Specifications of CM-01b (TE Connectivity)

Digital Stethoscope:

The SS30L Electronic Stethoscope will allow you to record and listen to heart sounds and Korotkoff sounds. The Electronic Stethoscope has a microphone built into the tubing that connects to the

MP36/36R/35/45 data acquisition unit. The microphone will record the sounds heard through the stethoscope and simultaneously display them [7].

Specifications-

- Stethoscope length from Y to contact point: 57 cm
- Stethoscope length from Y to ears: 21 cm
- Microphone Bandwidth: 20-300 Hz
- Microphone Cable Length: 2 meters

Figure 6: Electronic Stethoscope
(SS30L (Biopac))

A Foetal Acoustic Simulator is used to test both the sensors. The Foetal Acoustic Simulator simulates the S1 and S2 heart sounds of the foetus. The S1 heart sound corresponds to the closure of the mitral valves and the S2 heart sound corresponds to the closing of aortic and pulmonary valves. The simulator can also simulate the S1 and S2 sounds of the mother's heart and other internal sounds of the mother but is not used here for the testing of the sensors [2].

The central frequency of the simulated S1 heart sound is 25Hz and that of the S2 heart sound is 50Hz. The recordings from the sensor are also associated with external ambient noise/vibrations and the electronic noise from the sensor itself and the other electronic components connected to the system. A Biopac (MP36) System is used to record the data from both the sensors at different forces to conclude the optimum force range to record foetal heart sounds of them [2].

Multiple trials were conducted to conclude the optimum force range to be applied on the Contact Microphone (17 trials) and Digital Stethoscope (15 trials).

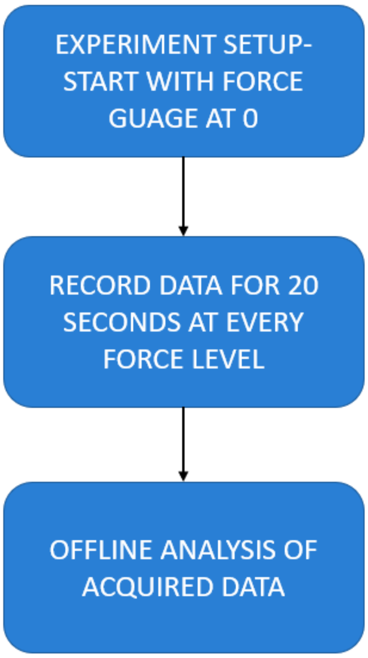

Figure 7: Flow chart of the method followed in the experiment

List of Components Used for the Experiment Setup [Fig 8]:

- Laptop
- Sensors (Contact Microphone/ Digital Stethoscope)
- Biopac (MP36) system – Battery powered
- Audio Amplifier – AC Powered
- Surface Speaker – Connected to Audio Amplifier
- Foetal Acoustic Simulator
- Football bladder – Simulates mother's abdomen

A force gauge was used to measure the force being applied to the bladder. The displacement was incremented at fixed steps which would increase the force applied. A recording at every displacement/force was taken for 20 seconds and the Displacement vs Force graphs were plotted. Power Spectral Density (PSD) of the recorded data was plotted to further understand the characteristics of the sensors and analyse the data in the frequency domain. The typical Displacement vs Force graphs for Contact Microphone and Digital Stethoscope is shown in Fig.10 and Fig.11 respectively. Foam was added below the whole experiment setup at the later stages to reduce the vibrations reaching the sensors. The foam was approximately 6cm is height [Fig 9].

The experiment was conducted keeping the FHR (Foetal Heart Rate) a constant at 130bpm. The trials were carried out both at PC volume 14 and 30. At the PC Volume 14, the RMS voltage of the signal entering the Surface Speaker is 0.12V and that at PC Volume 30 is 0.36V. The number of trials taken at volume 14 was 10 for the Contact Microphone and 8 for Digital Stethoscope and those at volume 30 were 7 for both Contact Microphone and Digital Stethoscope.

A MATLAB routine was written to calculate the peak to peak amplitude of the 5 peaks in a recording at each force which was then averaged to find the average peak-peak amplitude at every force. The Force vs Average Peak-Peak Amplitude graph obtained at volume 30 is shown in Fig 12 and 13 for Contact Microphone and Digital Stethoscope respectively. It was observed that the trend remained similar at the PC Volumes 14 and 30 but the peak to peak amplitude obtained at PC Volume 14 is lower compared to when the Volume was kept at 30. Volume 14 was chosen since it simulated the clinical settings.

Figure 8: Experiment Setup

Figure 9: Experiment Setup using a foam (~6cm height) at the base of the setup to reduce the vibrations reaching the sensor.

RESULT

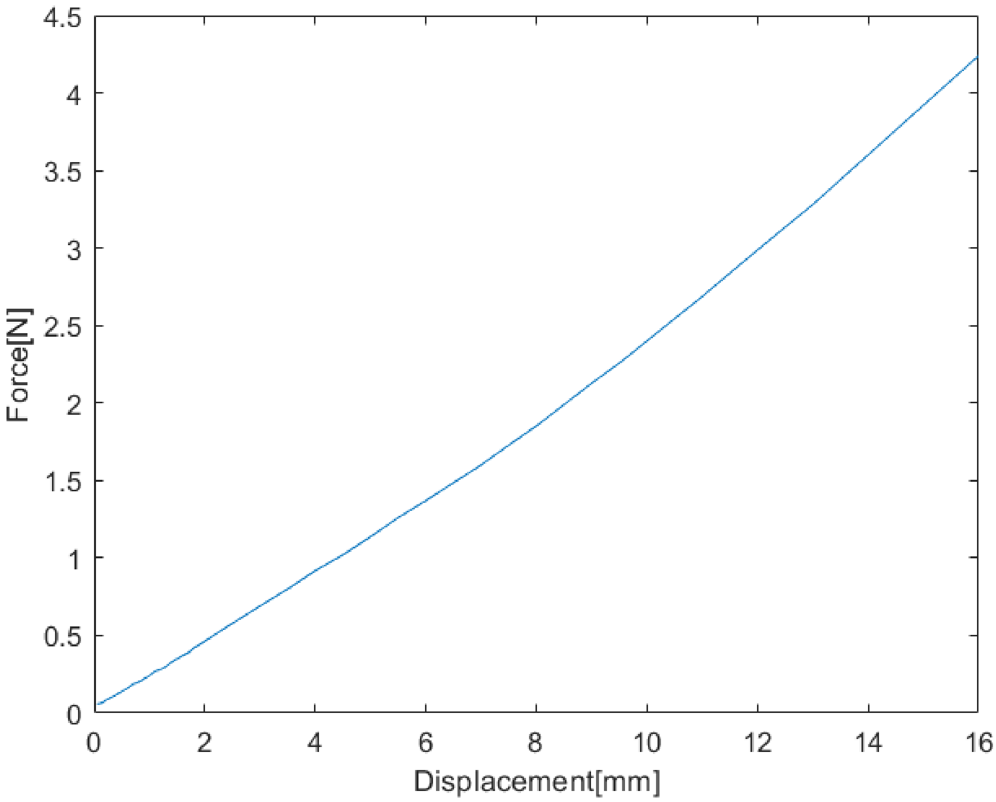

Figure 10: Typical Displacement(mm) vs Force(N) graph for Contact Microphone

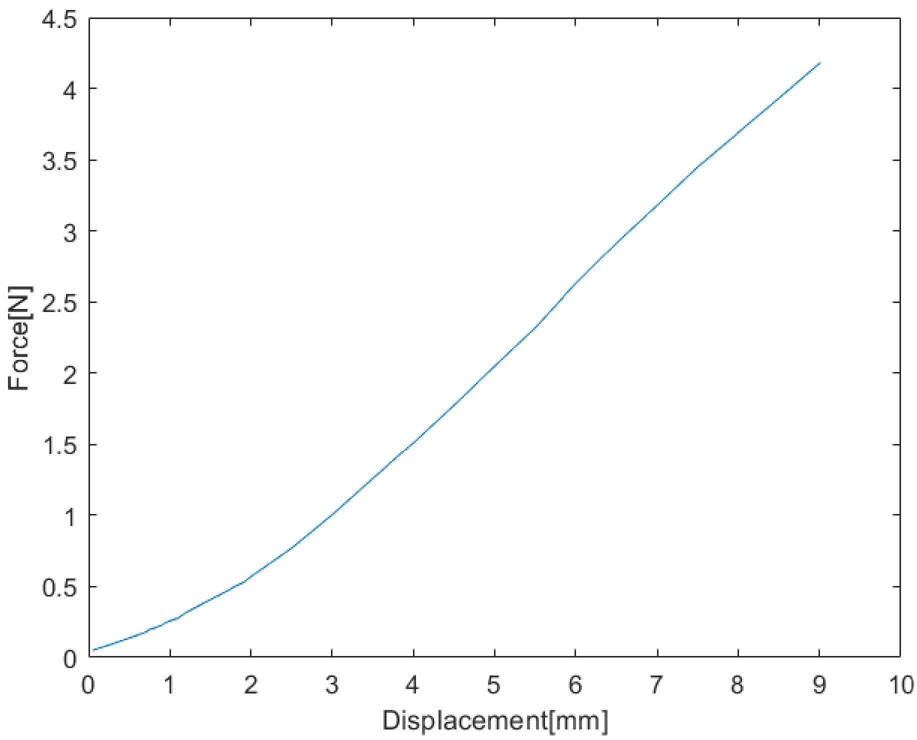

Figure 11: Typical Displacement(mm) vs Force(N) graph for Digital Stethoscope

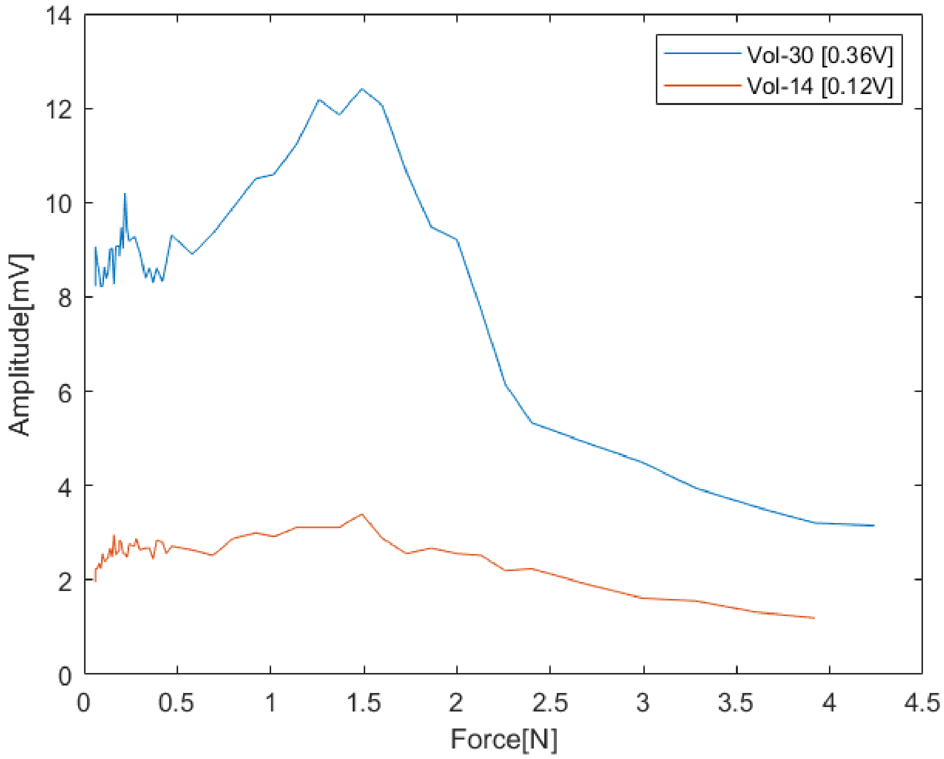

Figure 12: Force(N) vs Amplitude(mV) graph for Contact Microphone

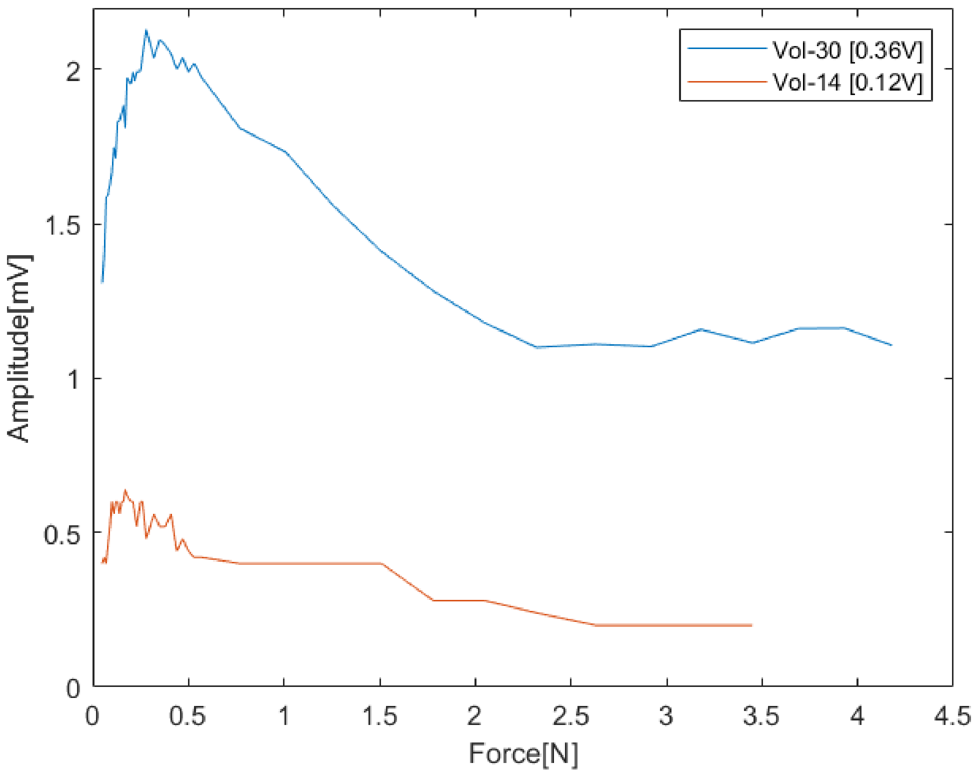

Figure 13: Force(N) vs Amplitude(mV) graphs for Digital Stethoscope

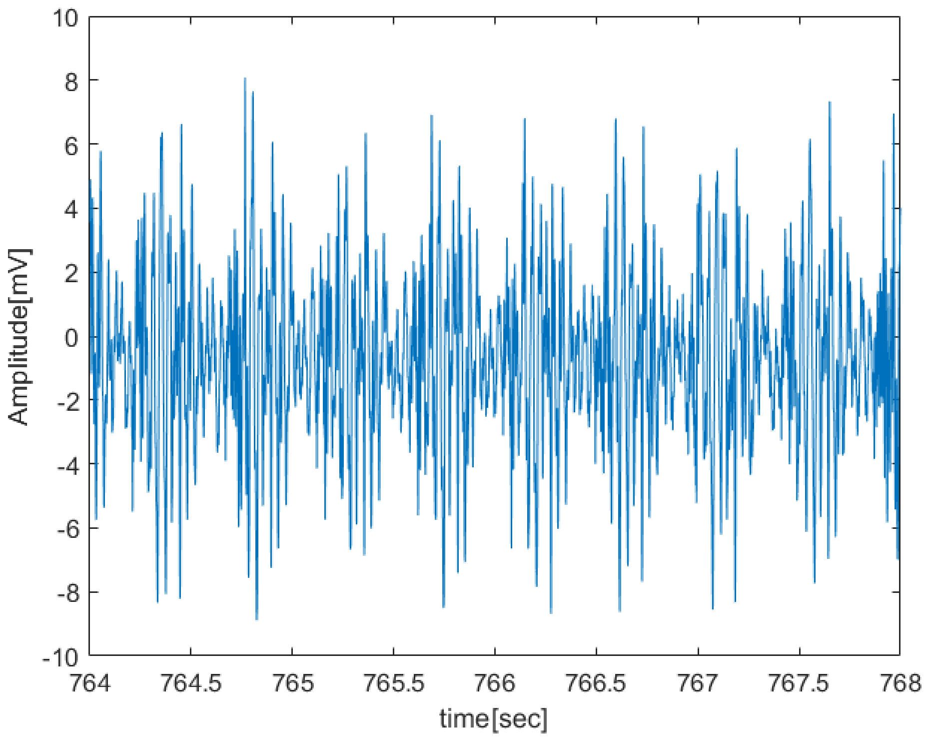

Figure 14: Raw signal obtained from Contact Microphone
(FHR=130 bpm, PC Vol = 30, Force = 1.5N)

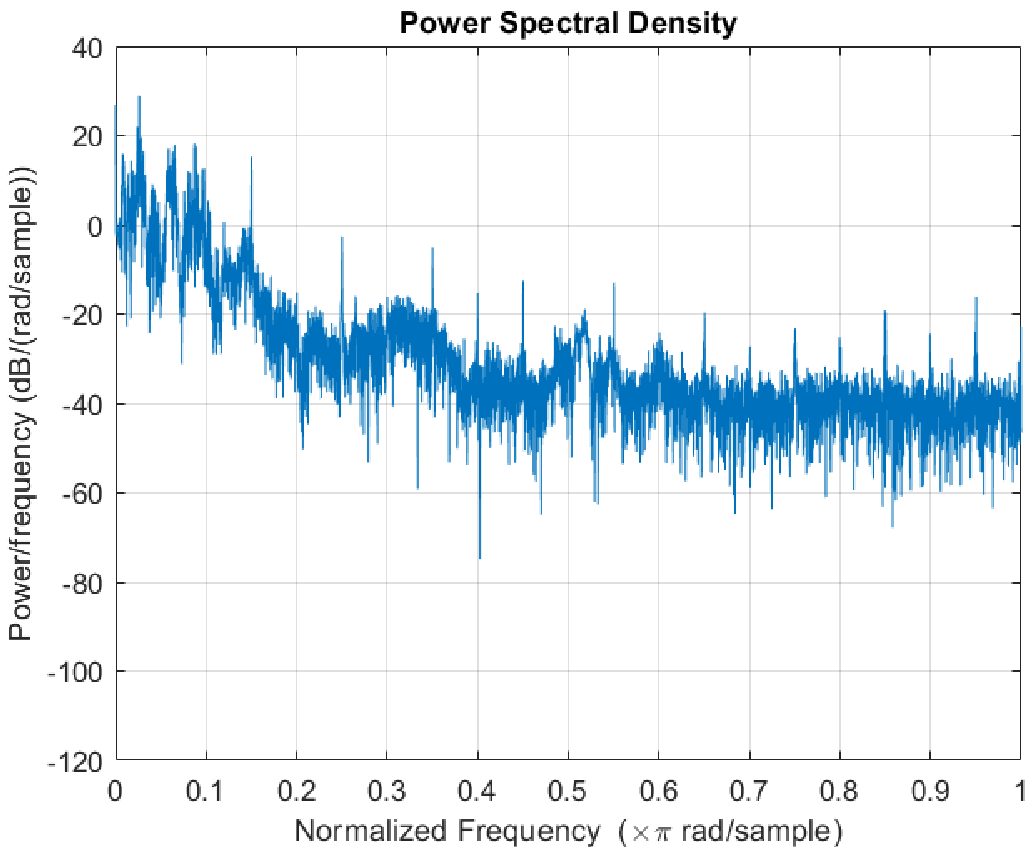

Figure 15: PSD of the raw signal obtained by Contact Microphone

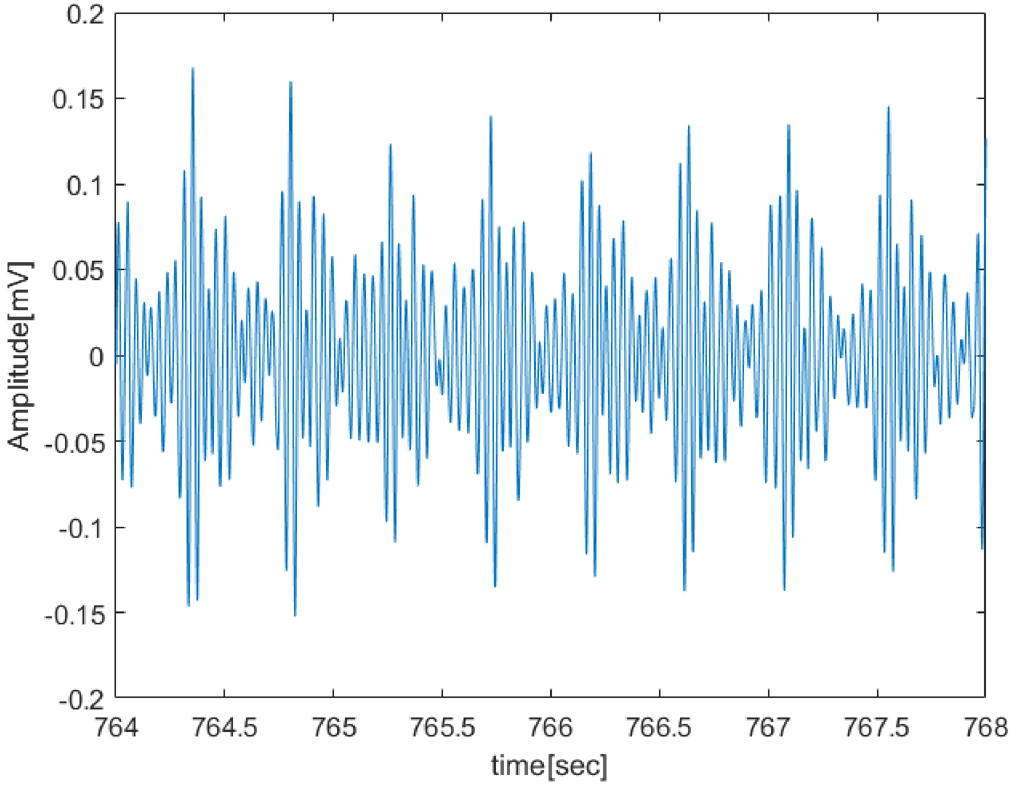

Figure 16: Filtered signal obtained from Contact Microphone

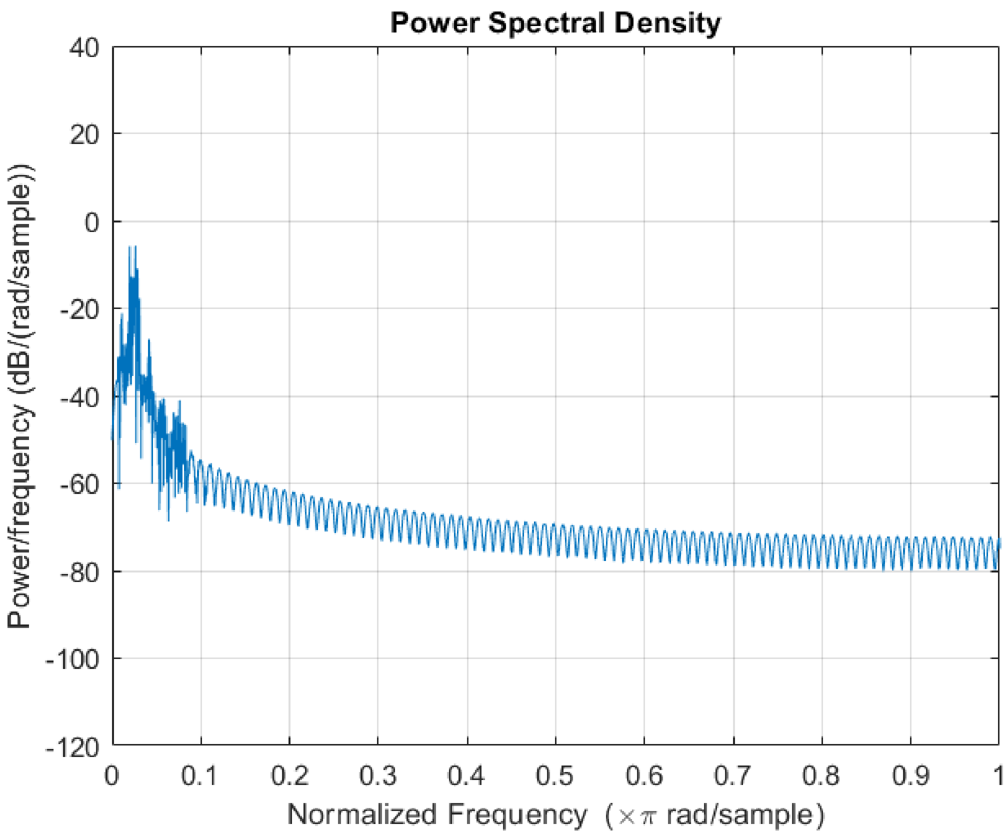

Figure 17: PSD of the filtered signal obtained from Contact Microphone

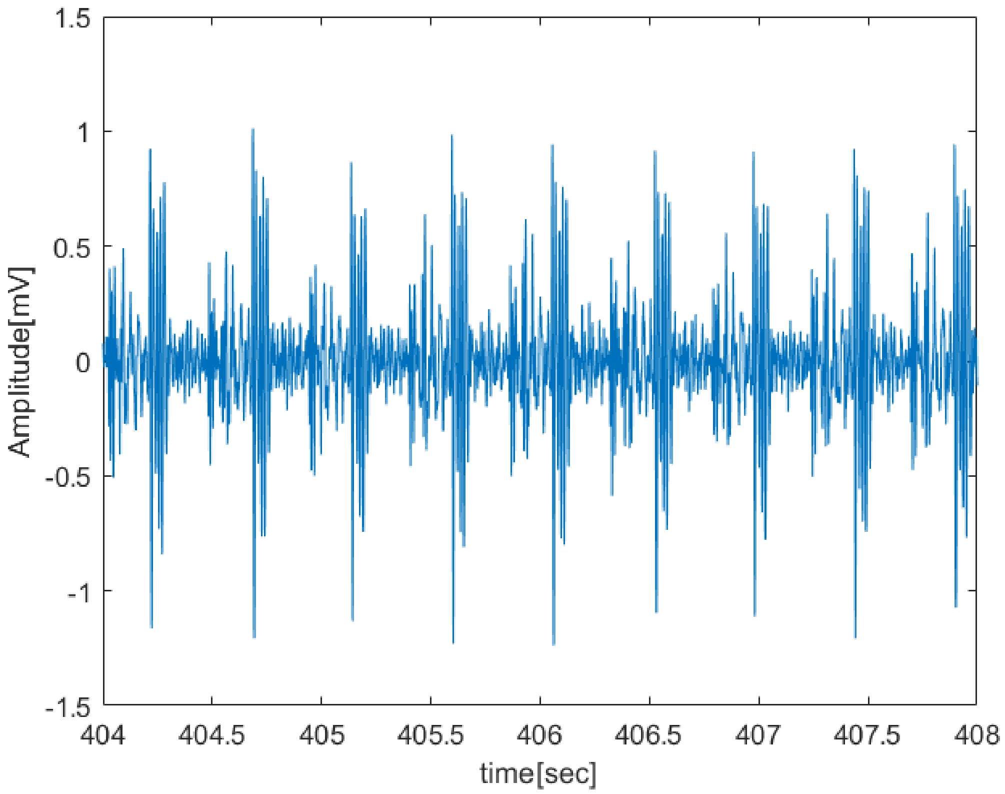

Figure 18: Raw signal obtained from Digital Stethoscope
(FHR =130 bpm, PC Vol =30, Force = 0.28N)

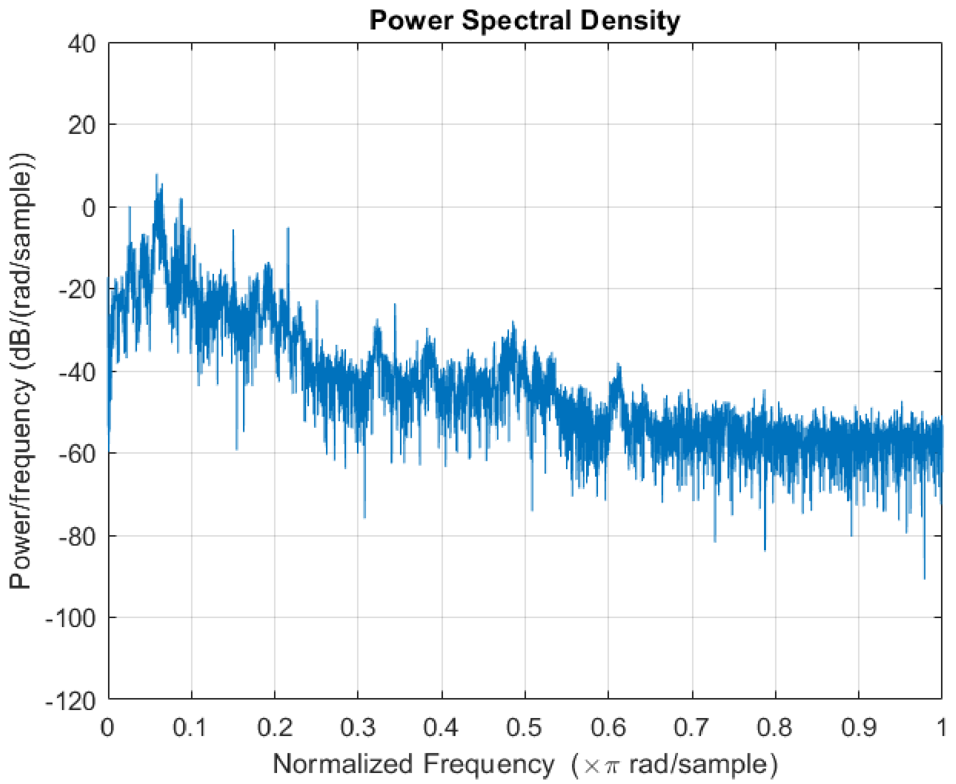

Figure 19: PSD obtained of raw signal from Digital Stethoscope

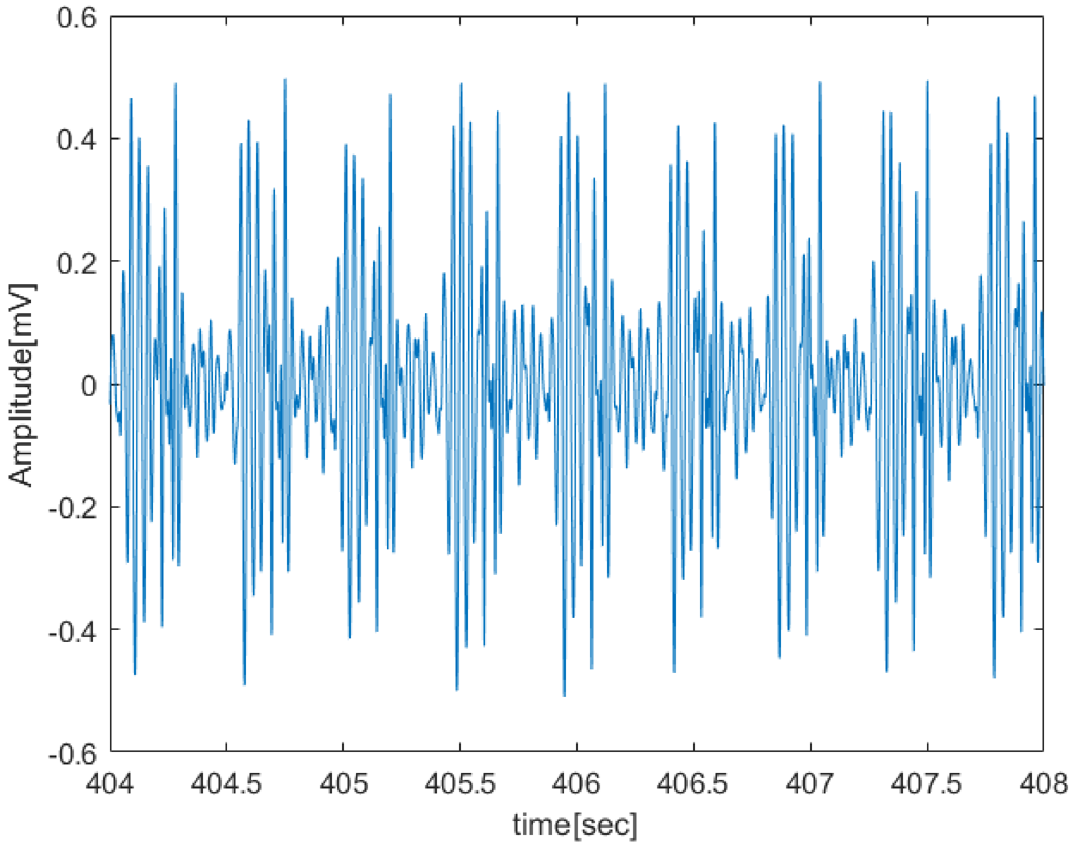

Figure 20: Filtered signal obtained from Digital Stethoscope

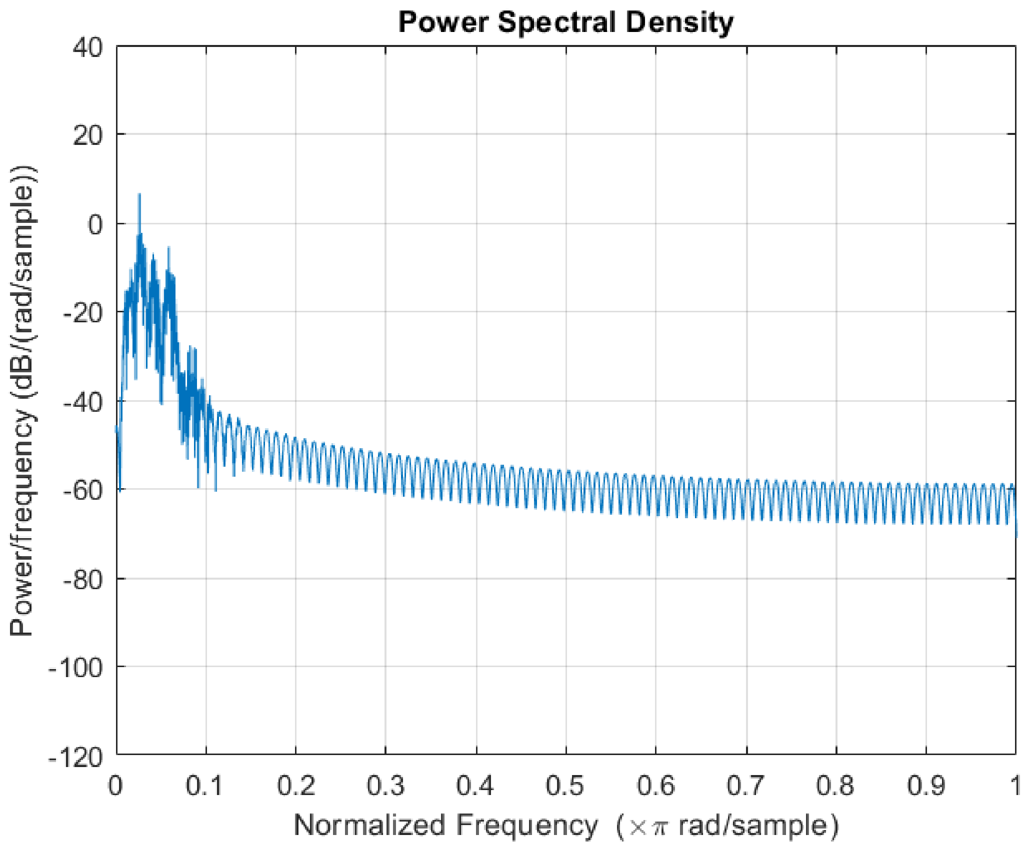

Figure 21: PSD obtained of filtered signal from Digital Stethoscope

The RMS of the noise part of the data and the RMS of the required signal of the data was calculated which was then used for the measurement of the Signal-Noise Ratio (SNR). The SNR was measured for the whole signal which includes the data recorded at every force and for the 20-second data at the optimum force. The SNR was also calculated for both the raw signal and the filtered signal (Filtering was done offline) [Table 3]. A 4^{th} order Butterworth bandpass filter with a lower cut-off frequency of 10Hz and higher cut-off frequency of 40Hz was used to filter the obtained data. The periodogram of the filtered signal was also plotted.

$$SNR = 20*\log((rms\_signal)/(rms\_noise))$$

Average SNR (dB)		
	Volume 14	Volume 30
Digital Stethoscope - Raw Signal	10.824	12.533
Contact Microphone - Raw Signal	0.4224	7.7242
Contact Microphone - Filtered Signal	4.7323	10.2578
SNR at optimum Force (dB)		
	Volume 14	Volume 30
Digital Stethoscope - Raw Signal	12.5304	14.229
Contact Microphone - Raw Signal	1.963	8.528
Contact Microphone - Filtered Signal	6.1495	10.385

Table 3: SNR measured for the whole signal which includes data recorded at every force and for the data at the optimum force for both the Volumes 14 and 30.

The noises caused by different components in the setup was collected to understand the sensor characteristics [Fig. 22,24,26,28,30]. The periodogram of the noise caused by the sensor and all the components in the experimental setup was plotted to understand the frequency domain of the electronic noise [Fig 23, 25, 27, 29, 31]. The RMS values of the recorded electronic noise were calculated [Table 4].

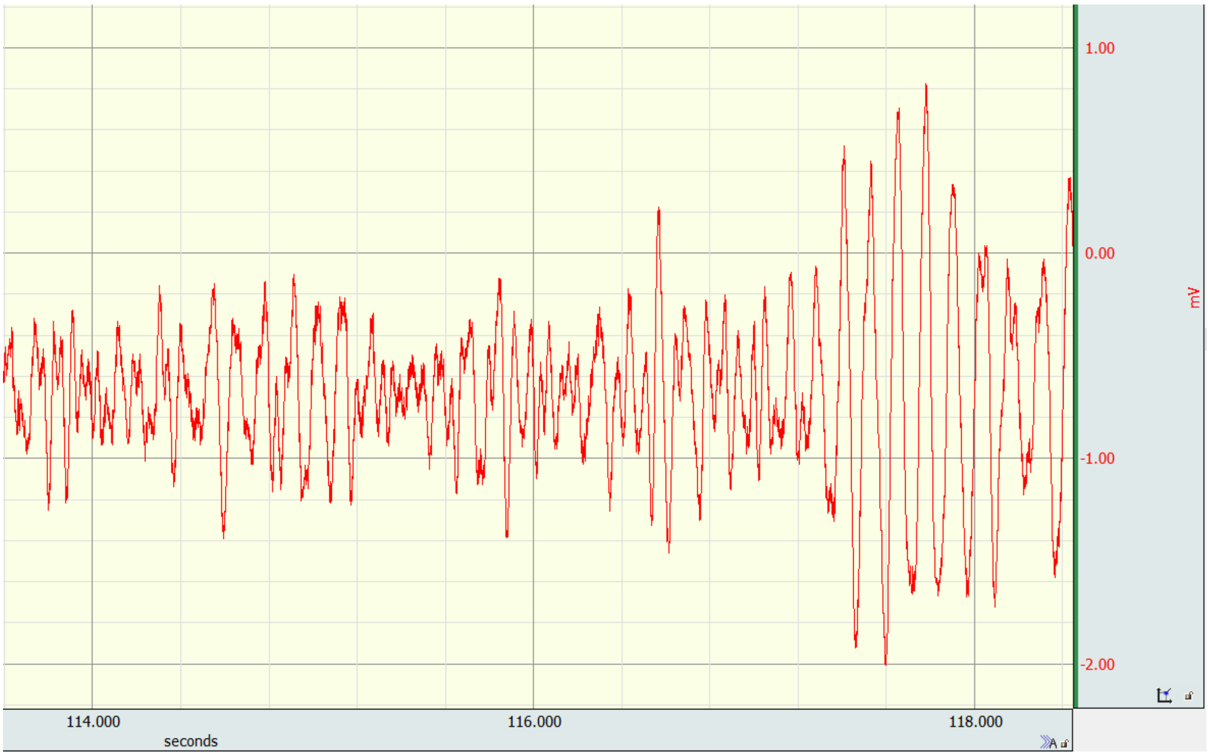

Figure 22: Electronic Noise of Contact Microphone.

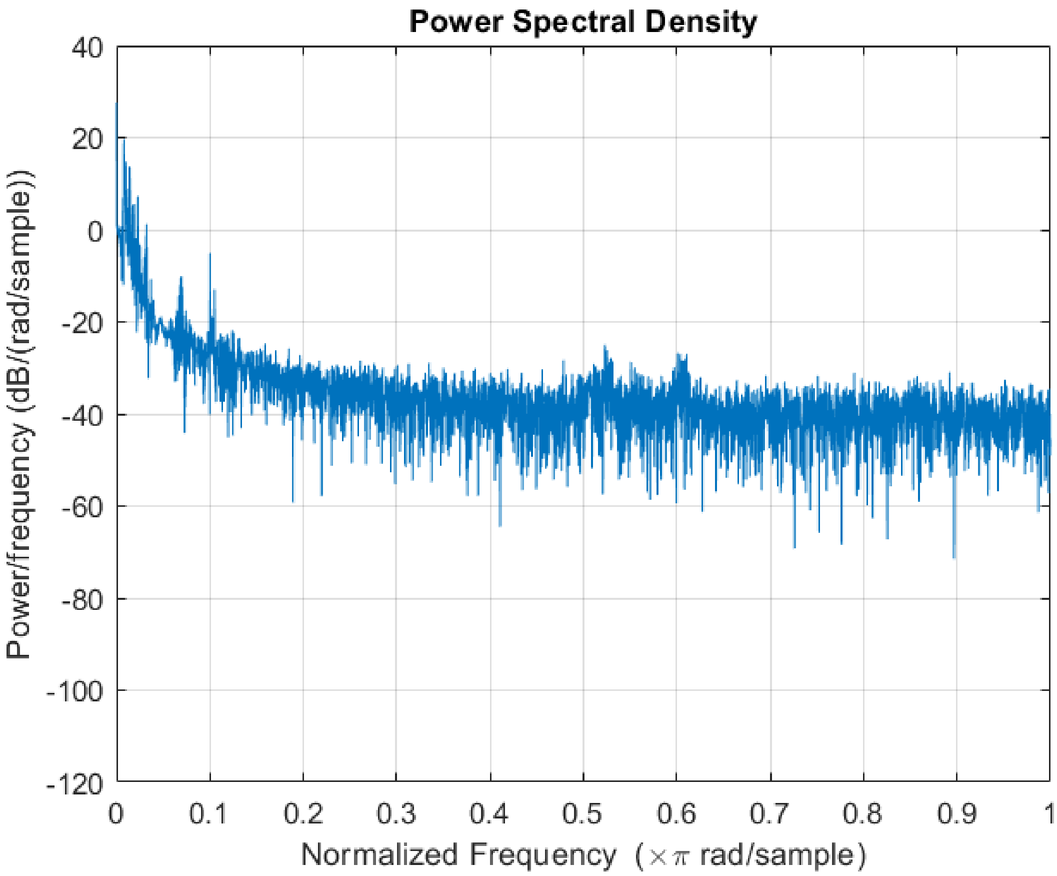

Figure 23: PSD of Electronic Noise of Contact Microphone

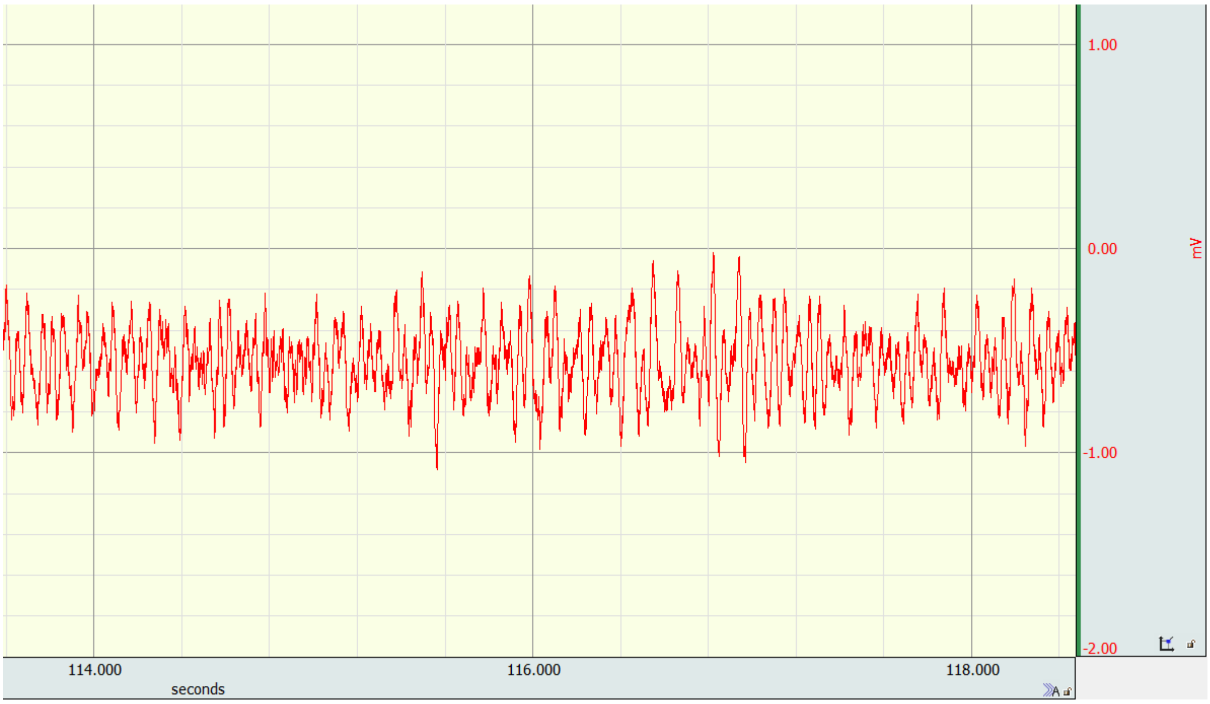

Figure 24: Electronic Noise Recorded of Contact Microphone after adding a foam below the setup to reduce vibrations reaching the sensor

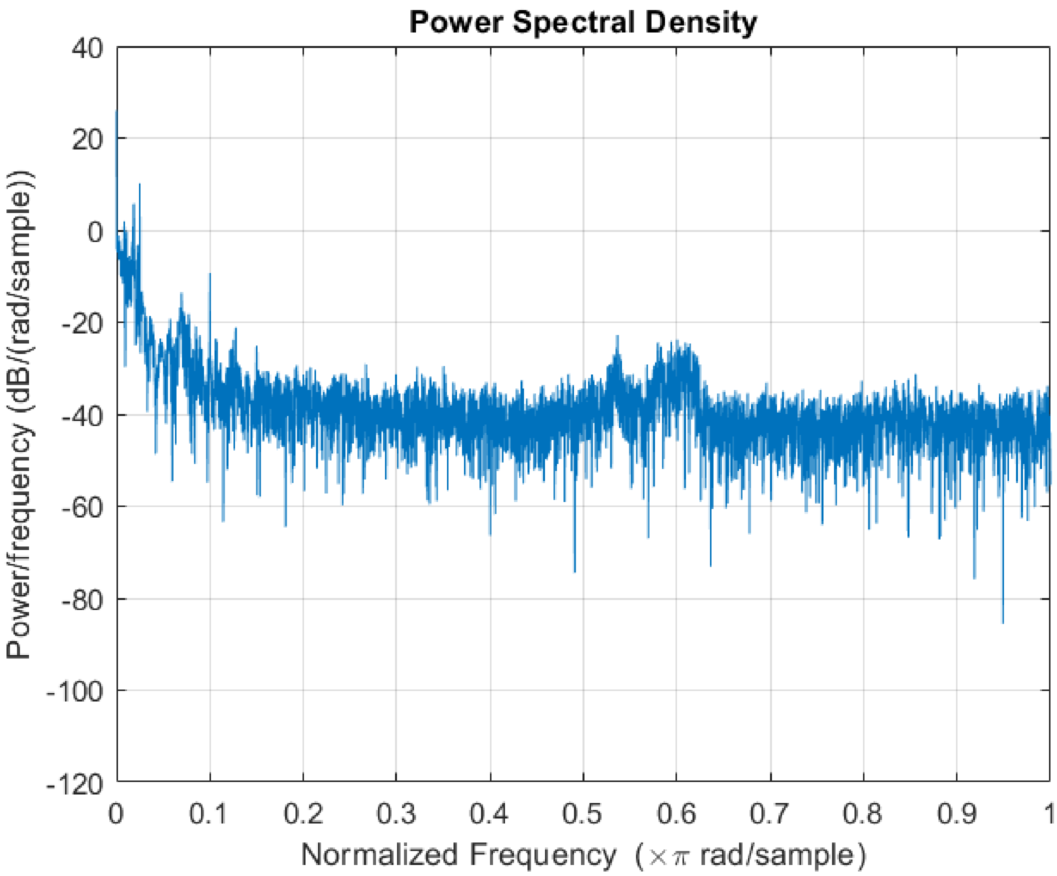

Figure 25: PSD – Electronic Noise of Contact Microphone after inserting a foam layer below the setup

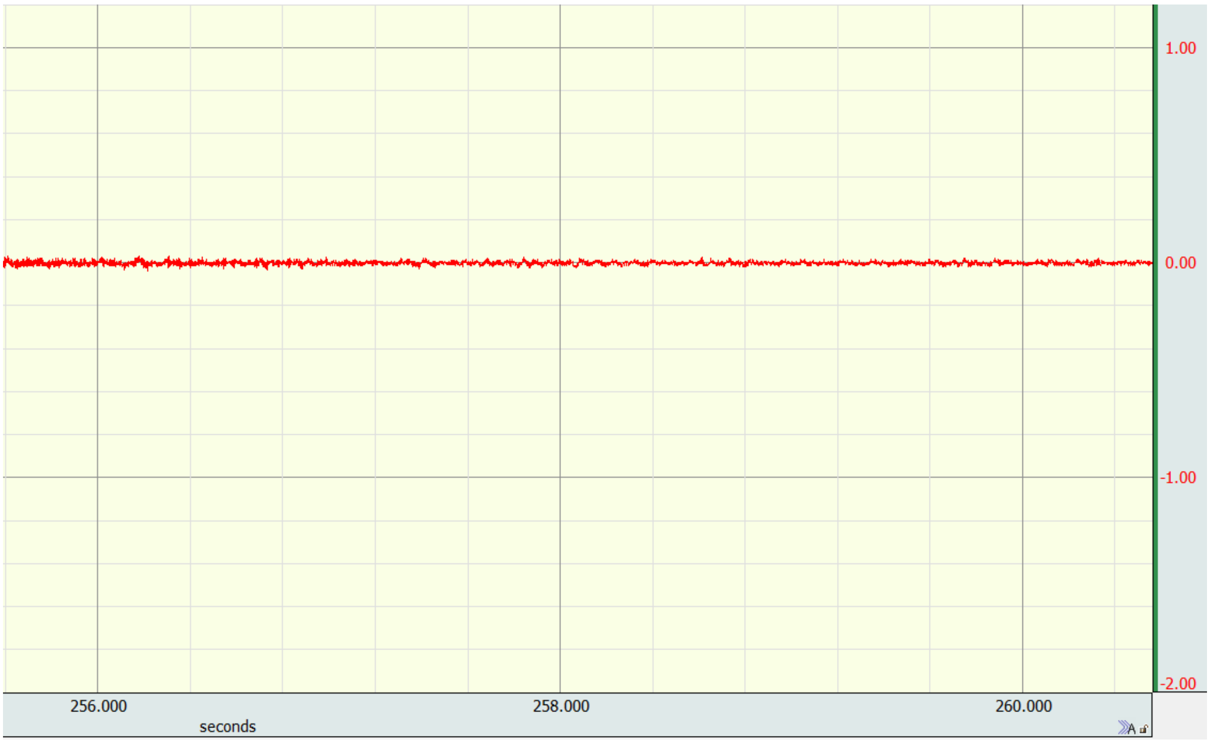

Figure 26: Electronic noise recorded of Digital Stethoscope

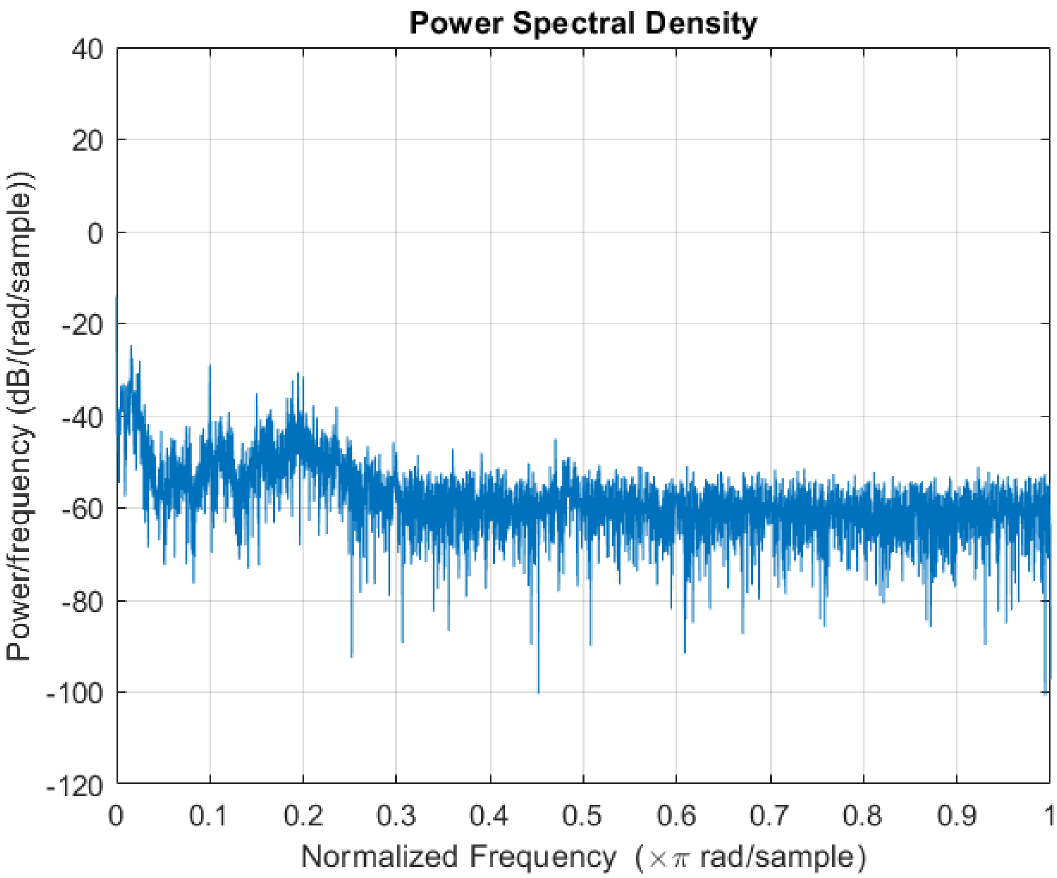

Figure 27: PSD of Electronic Noise of Digital Stethoscope

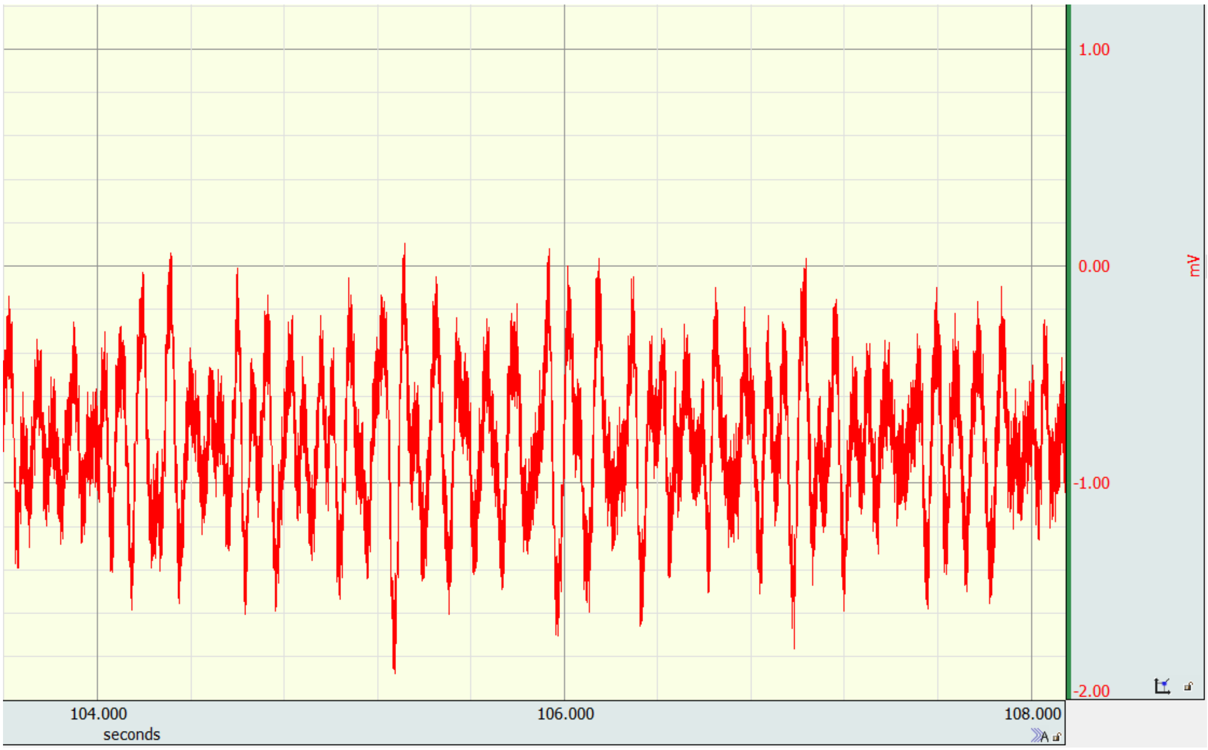

Figure 28: Noise contributed by all the components in the Contact Microphone Experiment Setup

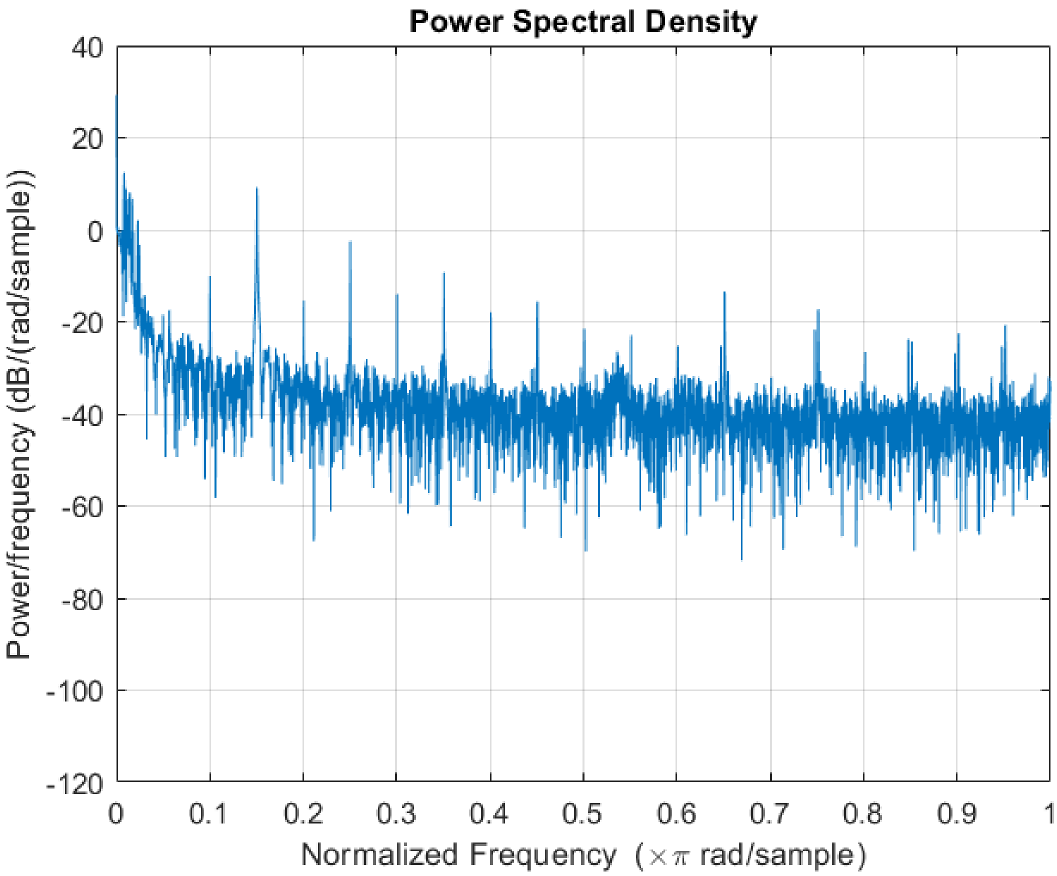

Figure 29: PSD of Noise contributed by all components in Contact Microphone Experiment Setup

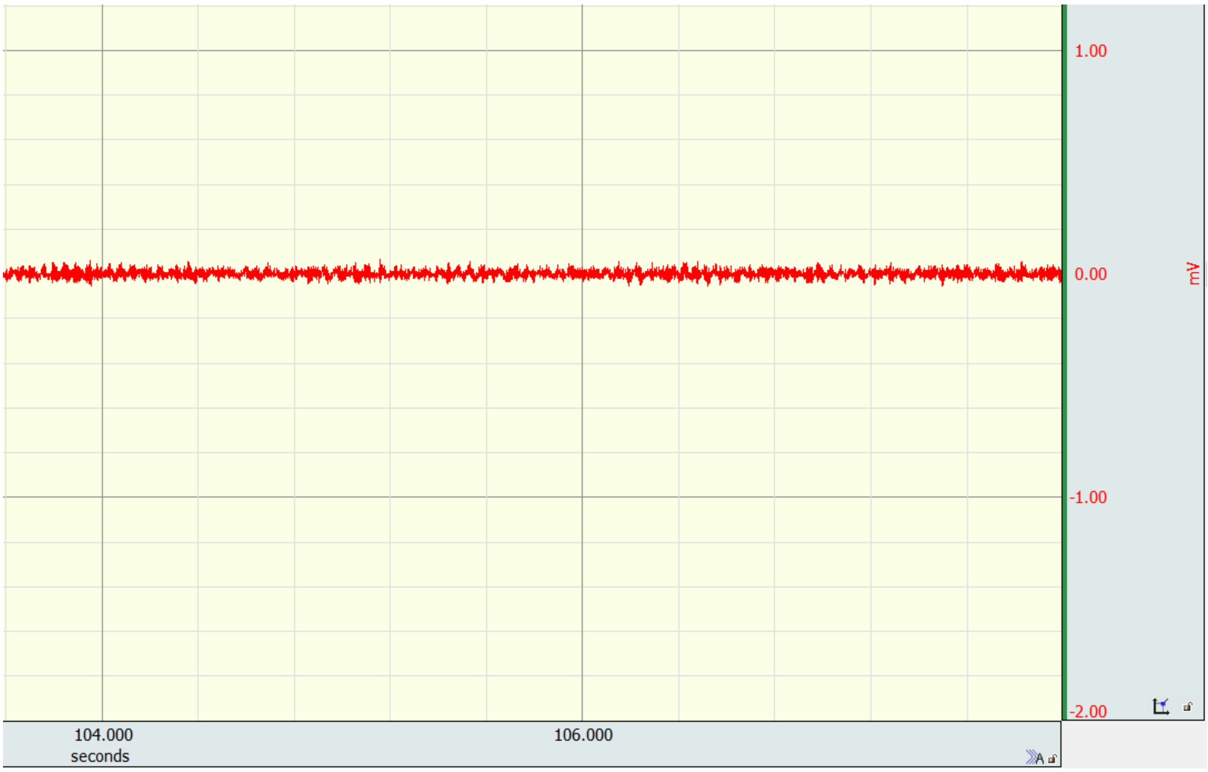

Figure 30: Noise contributed by all the components in the setup (Digital Stethoscope)

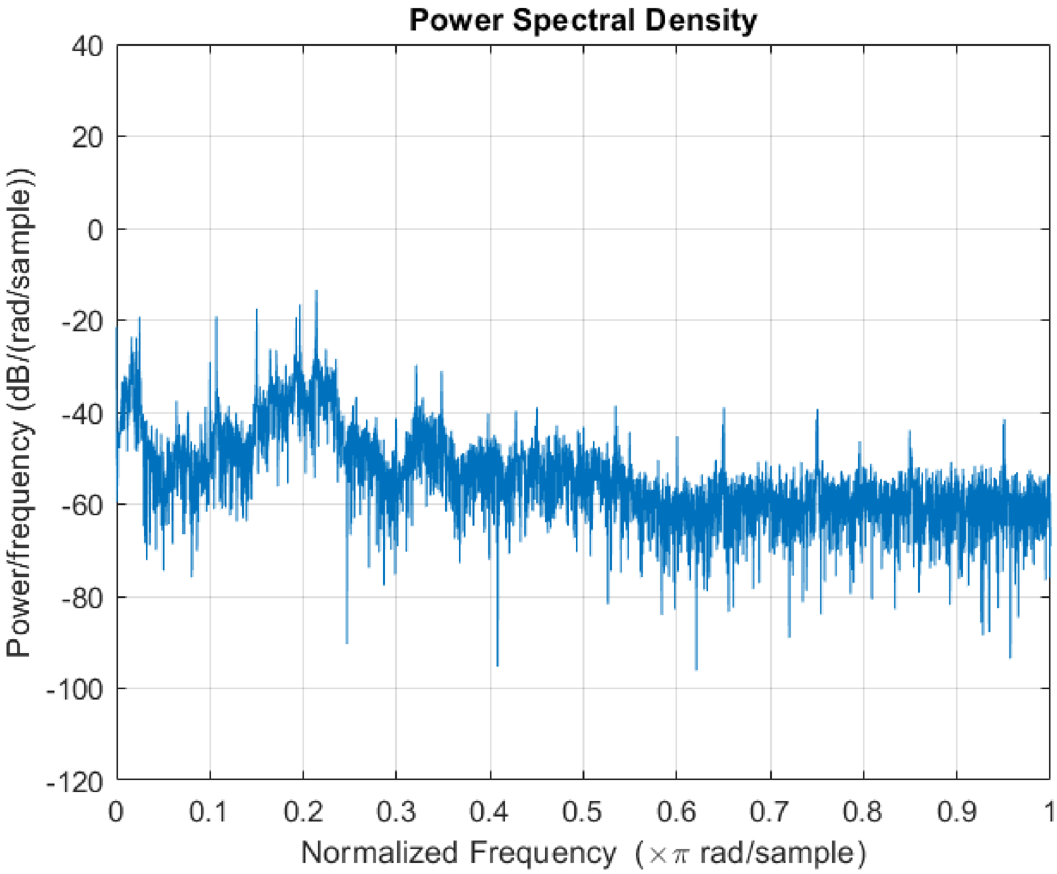

Figure 31: PSD of noise contributed by all components in the Digital Stethoscope Experiment Setup

The first case (Case 1) of experiments where the electronic noise was recorded had:

- Audio Amplifier – OFF (not connected to AC supply)
- Speaker not connected to Audio Amplifier
- Without foam
- Heart Sounds not playing

The second case (Case 2) of experiments:

- Audio Amplifier connected.
- Speaker Connected
- Heart Sounds not playing.

The third case (Case 3) had a setup similar to Case 1 with an addition of a foam layer.

RMS of electronic noise of Contact Microphone– Trial 1 (Case 1)	1.8986mV
RMS of electronic noise of Contact Microphone– Trial 2 (Case 1)	0.9742mV
RMS of electronic noise of Contact Microphone– Trial 3 (Case 1)	0.9671mV
RMS of electronic noise of Contact Microphone (Case 3)	0.8978mV
RMS of electronic noise of Contact Microphone (Case 2)	0.9982mV
RMS of electronic noise of Digital Stethoscope – Trial 1 (Case 1)	0.0184mV
RMS of electronic noise of Digital Stethoscope – Trial 2 (Case 1)	0.0198mV
RMS of electronic noise of Digital Stethoscope (Case 2)	0.0245mV

Table 4: RMS Values of electronic noise recorded of both the sensors

INFERENCE

The experiment was conducted for multiple trials for both Digital Stethoscope and Contact Microphone.

The optimum range for Contact Microphone is 1.5N to 2N and the optimum force range to be applied on the Digital Stethoscope is 0.2N to 0.6N.

The SNR at low ambient noise is higher for Digital Stethoscope than Contact Microphone.

FUTURE WORK

- To record at various ambient noise levels to know the efficiency of the sensors at higher noise levels.
- Compare the algorithms at a lower SNR.
- To integrate and test other microphones with Biopac.

OBSERVATIONS

- Both the sensors, Contact Microphone and Digital Stethoscope is sensitive to motion artefact.
- Contact Microphone is sensitive to vibrations whereas Digital Stethoscope is sensitive to ambient noise.

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EXPERIMENT PROTOCOL

Purpose:
To find a better device to detect foetal heart sound (Contact Microphone, Stethoscope).

Materials:
- Contact microphone
- Digital Stethoscope
- Biopac
- Audio Amplifier
- Force meter
- Heart sound simulator system

Precautions:
- The PC Volume and ambient noise level along with the fetal heart rate at every trail must be noted down.
- Ensure the spike-buster is not connected to the UPS.
- Note down if the fan and/or the 3D printer is on and also if the laptop is on the same table or another table.

Method:
- Ensure the Surface speaker is right above the contact microphone or the digital stethoscope.
- Record the fetal heart sound using biopac from the simulator incrementing the displacement by 0.05mm until 1mm (0.05, 0.1, 0.15,..., 1.0)
- Each recording is taken for 20 seconds.
- Then take 10 recordings, incrementing the displacement by 0.1mm (1, 1.1, 1.2,…, 2), for 20 seconds at each displacement.
- The next set of recordings are taken incrementing the displacement by 0.5mm until the displacement reaches 10mm.
- 5 more recordings by incrementing the displacement by 1mm.
- The experiment must be stopped anytime the force exceeds 4N.

Control:
Taking a 1minute recording at 0 PC Volume.

Interpretation:
- Calculate average amplitude taking any 5 peaks in the 20-second window
- Plot Displacement vs Force graph
- Plot Force vs Amplitude graph
- Plot Power Spectral Density (PSD) of the data recorded at the optimum force level.