

ULTRASONIC DOPPLER SONAR SENSOR SYSTEM FOR EXTRACTION OF WALK SIGNATURES

by

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Abstract

In this work, a portable low cost sensor system is designed for the extraction of walking signatures in humans using the principle of Ultrasonic Doppler Sonar (UDS). UDS involves the use of two ultrasonic transducers acting as a transmitter-receiver pair. The transmitter produces a continuous ultrasonic signal at a specific frequency to be broadcasted onto a moving target, while the receiver will perform a frequency shift on the reflected signal in relation to the movement of the target. The sensor system used in this work is comprised of a frequency generator that drives the transducer with a 40 kHz sine wave and a data acquisition device. Signal processing methods were implemented on the received data to extract and analyze the Doppler features of a human walk.

Data was initially collected using a function generator which produced the transmitted 40 kHz signal together with Measurement Computing WaveBook-516E data acquisition measurement hardware. To make the system portable, the design was simplified using the National Instruments USB-6216 Data Acquisition (DAQ) for both the transmitted signal and saving the received sampled data. The WaveView data acquisition software was used to control the WaveBook DAQ while a LabView program was written to interface with the NI USB-6216 hardware. The primary objective of implementing the sensor system is to automate the data collection without the use of a computer, which the use of NI data acquisition made possible, but the system parts were expensive and needed the use of a laptop to manage the process.

A microprocessor, together with an Analog to Digital Converter (ADC) and a Digital to Analog Converter (DAC), were tested for generating the driving transmit-

ting signal and the collection of the data. The TI C6748 digital signal processors on the Texas Instruments OMAP-L138 Development Kit was the chosen processor as it is a floating-/fixed-point DSP with up to 456 MHz clock speed, the access to standard interfaces on the development kit, and the availability of software development kits, drivers, and algorithm libraries for fast development.

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Abbreviations

AC	Alternating current
ADC	Analog to Digital Converter
BNC	Bayonet NeillConcelman
CCS	Code Composer Studio
CSV	Comma separated values
DAC	Digital to Analog Converter
DAQ	Data Acquisition System
DC	Direct current
DSP	Digital Signal Processor
FFT	Fast Fourier Transform
FM	Frequency Modulated
I(t)	In-phase signal
IDE	Integrated Development Environment
JTAG	Joint Test Action Group
kS/s	kilo samples per second
NI	National Instruments
PIR	Passive Infrared
Q(t)	Quadrature signal
RTOS	Real Time Operating System

SD	Secure Digital card
SDK	Software Development Kit
SPI	Serial Peripheral Interface
SRS	Stanford Research Systems
STFT	Short Time Fourier Transform
TI	Texas Instruments
UDS	Ultrasonic Doppler Sonar

1. Literature Survey

Ultrasonic Doppler Sonar (UDS) sensors have been used in a variety of applications such as in range finding [1], collision detection [2], object recognition [3], and human motion detection [4]. A continuous wave radar system for human gait recognition was done through the use of low cost microwave sensors and the use of an oscillator to transmit a stable continuous wave signal on to a moving object [5]. The received signal from the object corresponds with the Doppler frequency of the moving target. The reflected signal is then mixed with the transmitted signal to remove the carrier, converting into baseband which is digitalized using a data acquisition module and saved onto a laptop. This method was applied to a person walking towards and away from the sensor system as the moving target. The reflected signal from a person walking will be mainly from the legs, torso and the arm with a constant Doppler shift for a person walking at a constant velocity. A short-time Fast Fourier Transform (SFFT) was used to form spectrograms to extract the velocity component of the human motions which were used for gait recognition and differentiation of human motion from animal motion.

A similar approach using the same principles was used in [6], but used ultrasonic sensors to extract walking signatures in humans using different Doppler signature extraction methods. An UDS was constructed using two ultrasonic sensors with a resonance frequency of 40 kHz. A signal generator was used to transmit a 40 kHz sine wave on one of the sensors while the other was used as a receiver for the reflected signal from a human walking. The data was captured using a Data Acquisition (DAQ) hardware and stored onto a disk and MATLAB was used for analysis. Doppler

signature extractions methods that can be used for the ultrasonic Doppler sonar include direct demodulation, digital baseband demodulation, analog down-conversion of reflected signal and analog baseband demodulation.

Direct Demodulation of the reflected signal is a Fast Fourier Transform (FFT) method for analyzing the Doppler signatures of the human walking body components. The received signal is digitalized using the DAQ hardware at a sampling rate that satisfies the Nyquist criterion. FFT analysis of the sampled data and the spectrogram plot shows the Doppler signature of the subject. While this is a fast method in extraction of the Doppler signatures, it is inefficient in terms of storage as the sampling rate must be high enough to satisfy the Nyquist criterion, and it has a poor frequency resolution. Digital baseband demodulation of the reflected signal converts the received signal into baseband $I(t)$ and $Q(t)$ by multiplying it with the carrier signal and a shifted version of the carrier. It is low-pass filtered and the resulting components can be decimated before combining to form a complex Doppler signal. The down-sampling that can be done is an advantage over the direct demodulation method as it can be helpful in saving storage and the ability at working at lower frequencies. The spectrogram of the down-sampled data is processed to analyze the features at a better resolution.

A key component of the design of ultrasonic sonar sensor systems is data acquisition hardware used for either generating the transmitting signal, sampling the received reflected signal or both. The WaveBook DAQ module can be used for sampling of the received signal. It has eight data acquisition channels and can sample data up to 1 MHz [7]. It has to be interfaced with a software on a laptop than controls the sampling requirements. The WaveBook is also limited as it cannot generate signals which brings the need for a frequency generator in making the system, a disadvantage in designing a portable acquisition system as a different module or a frequency generator circuit has to be used to produce the transmitting signal. An-

other disadvantage is that the WaveBook will need a laptop to control the hardware and save the collected data individually which makes it impossible to automate the collection of the data. The received sampled data cannot be down-sampled before saving, thereby leading to inefficiency of storage.

The NI USB-6216 DAQ module has analog outputs together with sixteen channels analog inputs that can be used for sampling data up to 400 kS/s [8]. The analog outputs can be used for generating a transmitting signal to drive the transmitting transducer. A LabVIEW program was written to control the hardware, giving the flexibility of converting the received signal to baseband down-sampled $I(t)$ and $Q(t)$ before saving it to the computer. Down-sampling the baseband signal saves space for automated data collection that requires collection of data monitoring people at houses whenever they walk past the sensor. Although using the NI-USB 6116 makes for a more portable system it is still high in cost as the DAQ hardware is expensive and there is the need for using a laptop for every system.

The design of a portable low cost data acquisition system will use a microprocessor to interface with ADC chips for sampling of the received signal and a DAC chip to produce the transmitting signal. The TI OMAP-L138 chip contains an integrated floating-/fixed-point Digital Signal Processor (DSP) with up to 456 MHz with two Serial Peripheral Interfaces [9] which can be used to communicate with the ADC and DAC chips, and external memory interfaces that can be used to save the data on an SD card. The architecture of the chip enables real time signal processing algorithm to be run on the processor at a fast rate.

2. Operation of Ultrasonic Doppler System

2.1 Principle of Operation of the UDS

The principle of Ultrasonic Doppler Sonar relies on the transmission of a continuous wave ultrasound signal from a stationary source on to a moving target as well as the measurement of the Doppler frequency shift of scattered continuous wave by the moving target to obtain the velocity. The received signal from the moving target is frequency modulated (FM) as a result of the Doppler effect [10]. The vibration velocity of the target is directly proportional to the Doppler shift, a relationship that can be derived from the general Doppler Effect equations for a stationary source, and simplified as [11]

$$f_d(t) = \frac{2f_c v(t)}{c}, \quad (2.1)$$

where $f_d(t)$ is the Doppler shift frequency, $v(t)$ is the velocity of the moving target, f_c is the carrier frequency, and c is the speed of sound in air.

The source sends a continuous signal at a specific carrier frequency. This is represented in the form of an equation as:

$$g_c(t) = A \cos(2\pi f_c t). \quad (2.2)$$

The transmitted signal is reflected on the moving target, and the reflected signal from the moving target is measured by the receiving transducer collocated with the

transmitter. The received reflected signal will be Doppler shifted in the direction of the targets motion such that the signal will be shifted in phase. The received signal can be represented by the equation:

$$g(t) = B \cos(2\pi f_c t + \phi(t)). \quad (2.3)$$

where $\phi(t)$, is the instantaneous phase which can be represented mathematically as:

$$\phi(t) = \frac{4\pi}{\lambda} \int_{-\infty}^t v(\tau) d\tau + \phi_0, \quad (2.4)$$

where $v(t)$ is the velocity of the moving object with respect to time and λ is the wavelength of the sound.

While acoustic waves of any frequency can be used for the principle of ultrasonic Doppler based on theory, an ultrasonic frequency of 40 kHz is used because they are inaudible to humans, and also gives the advantage of using lower sample rates in sampling the received reflected signal. The lower sample rates leads to lower computational complexity for the data analysis.

2.2 IQ Demodulation

The extraction of the Doppler features from the received reflected signal are based on IQ demodulation, and computing the spectrogram of the complex Doppler signal formed from the base-band $I(t)$ and $Q(t)$ signals [6]. $I(t)$ and $Q(t)$ are obtained by multiplying the reflected signal by the carrier signal, and the shifted version of the carrier signal respectively and then passing the results through a low pass filter. These can be described mathematically as follows.

The reflected signal $g(t)$ is multiplied by the carrier signal ($g_c(t) = \cos(2\pi f_c t)$) as follows:

$$g(t) \times g_c(t) = \frac{1}{2} (\cos(4\pi f_c t + \phi) + \cos(\phi)), \quad (2.5)$$

and the reflected signal $g(t)$ is then multiplied by carrier signal shifted by $\pi/2$ ($g'_c(t) = \cos(2\pi f_c t - \pi/2) = \sin(2\pi f_c t)$)

$$g(t) \times g'_c(t) = \frac{1}{2}(\sin(4\pi f_c t + \phi) + \sin(\phi)). \quad (2.6)$$

The results from the multiplication are then low pass filtered to get rid of the doubles of the carrier frequency resulting in the base-band $I(t)$ and $Q(t)$ signals

$$I(t) = \cos(\phi) \quad (2.7)$$

and

$$Q(t) = \sin(\phi). \quad (2.8)$$

Since the carrier frequency is removed and the resulting frequency content of interest is less than 2 kHz, the $I(t)$ and $Q(t)$ signals can be decimated to a sampling frequency of at least 4 kHz to $I_{dec}(t)$ and $Q_{dec}(t)$ without losing information needed for feature extraction. The instantaneous phase $\phi(t)$ can be calculated by

$$\phi(t) = \tan^{-1} \left(\frac{Q_{dec}(t)}{I_{dec}(t)} \right). \quad (2.9)$$

The decimated base-band $I(t)$ and $Q(t)$ signals are combined to form the complex Doppler signal $S(t)$ as follows:

$$S(t) = I_{dec}(t) + iQ_{dec}(t). \quad (2.10)$$

2.3 Spectrograms

The Doppler-shifted frequencies of the moving target are extracted by computing the spectrogram of the complex Doppler signal $S(t)$. The spectrogram is computed using the short-time Fourier transform(STFT) method. In this method, the complex Doppler signal $S(t)$ is broken into blocks of length T points, of which the magnitude of the Fast Fourier Transform(FFT) of each block is calculated to obtain its frequency spectrum content. These blocks of data are called window size of the

spectrogram. The results obtained can be represented on a frequency-time plot, with the magnitude of the STFT output at each point represented by the hue of the color on a dB scale [6]. This can be represented mathematically as:

$$STFT(t, f) = \int S(t + T)w(T)\exp(-2i\pi fT)dT. \quad (2.11)$$

where, $w(T)$ is a sliding windowing function that collects the block of the data that is being analyzed.

The time resolution may be improved by making the blocks overlap, and we chose an overlap of fifty percent for spectrogram computation, which increases the time resolution. With decimated complex Doppler signal normally down-sampled to 5000 Hz for this work, a window size of 1024 points(0.2 s) is used together with the fifty percent overlap in computing the spectrograms.

3. Components of the UDS Sensor System

The UDS sensor system comprises of a signal generator, an ultrasonic transducer, amplifiers, a data acquisition system, a computer for data collection and FFT analysis to extract the Doppler features. The components are explained in detail below:

3.1 Ultrasonic Transducers

The ultrasonic transducer used in the UDS sensor system is the MATSUN/PAN EFR-RC40K. These are bi-directional and can be used for both transmitting and reception modes. The resonant frequency of the transducer is 40 kHz. While other ultrasonic frequencies will work well in the application, 40 kHz provides values that can lead to low sampling rate requirement, and will be inaudible to most humans and pets that could be in the house. The bandwidth of the transducer is 4 kHz at 6 dB, and directivity of 60° at -6 dB. The input driving voltage rating of the transducers is rated at a maximum of 20 V rms.

The higher the driving signal voltage supplied to the transmitting transducer, the further the range in detecting the moving target. The sensor system comprises of two of these transducers, mounted side by side in a plastic box, with one acting as the transmitter and the other as a receiver. BNC cables are used to make connections to the transducers. With a directivity of 60 at -6 dB, the cross talk between the two transducers is minimal at 40 kHz. Figure 3.1 below shows the transducers collocated

in a plastic box.



Figure 3.1: Ultrasonic transducers collocated in a plastic box

3.2 Signal Generator

The signal generator is needed for providing the driving signal to the transmitted signal. During the different design phases of the sensor system, different signal generators were used. The HP 8904A signal generator was the source of the driving signal at the initial stages for the design and testing of the sensor system. The maximum driving voltage that can be obtained from this was ± 10 V and experiments using this experiment used the maximum voltage to drive the transmitting transducer with a continuous sinusoidal wave at 40 kHz.

In making the sensor system more portable, the NI-USB 6216 data acquisition (DAQ) device was used to sample the driving signal for the transmitter. The USB 6216 DAQ has two analog output channels, eight differential and sixteen single ended analog input channels and an input and output voltage range of ± 10 V. A LabVIEW program was written to interface with the DAQ to transmit the signal and also sample the received signals. The advantage of using the NI USB 6216 is that it could provide

an analog output to drive the transmitter while also providing an Analog to Digital (ADC) channel to sample the received signal from the moving target. This simplified the design, and also made the sensor system portable. With additional input channels, the sensor system could also be automated and it was easier to synchronize the device for validation tests with other devices.

A Microcontroller and a Digital Signal Processor were interfaced with a Digital to Analog Converter (DAC) chip through the Serial Peripheral Interface to provide the driving signal. The use of these chips in the design will get to the ultimate goal of creating a low cost portable sensor system for the design. The DAC chips used have a resolution of 16 bits with a maximum sampling rate ranging from 250 kHz to 1 MHz which would be sufficient for the sensor system design. Tests for generating a clean driving signal showed that sampling must be done at least five times the frequency of the transmitting signal.

3.3 Pre-Amplifier

The Pre-Amplifier is used to amplify the receiving signal before it goes into the ADC for maximum use of the dynamic range. The pre-amplifier used for initial test of concepts were the Stanford Research Systems SR560 Low Noise Amplifier. With a $4 \text{ nV}/\sqrt{\text{Hz}}$ input noise and a bandwidth of 100 MHz, and a maximum output voltage of 10 Vpp, the SR560 satisfied the frequency range and desired noise level requirements needed for the received signals. The gain was set to a linear gain of 100 when doing experiments in the laboratory.

In making a portable version of the sensor system to use in houses for measurements, the amplifier used was the Analog Modules Model 351A-3 low noise amplifier. The dimensions of this amplifier were approximately 3 X 1.5 X 1 inches, portable enough to fit in a box to collect data at a house. The noise level of the amplifiers was

1 nV/ \sqrt{Hz} , with a bandwidth of 6.5 MHz and a maximum out voltage specification of 12 Vpp. The supply voltage needed for the amplifier was ± 15 V DC. The MinMax AC/DC power module was used to provide the voltage requirements for the amplifier.

3.4 Data Acquisition System

The WaveBook 516E DAQ hardware was used initially for data acquisition in the laboratory. It is an Ethernet based high speed data acquisition system with 16 differential input channels with a resolution of 16 bits, and a maximum sample rate of 1 MHz. It is interfaced with the WaveView software package that is used to set the channel properties, sample rate and duration of collecting data. The disadvantage of using the device was that it was expensive, not portable enough for setup at a house, the lack of a modification to automate the collection of data from a sensor, and the controlling software could not be modified to do further processing of the received signals before saving which results to a bigger file size as the sampling must meet Nyquist criterion of being atleast twice the input bandwidth. The WaveBook was used during initial test in the laboratory to collect data, and to compare the results of the sensor system to other known gait measurement systems.

In making the portable sensor system, the NI USB-6216 was used to serve as both the data acquisition device and the signal generator. A LabVIEW program was written to interface with the NI-USB 6216 to acquire the data, demodulate to base-band, and filter it before down sampling to a reduced sampling frequency. The file size was reduced by a factor of the down-sampling factor used of the original. A trigger system to start collection of data when motion is detected by the Passive Infrared Sensor (PIR sensor) was included in the design to automate data collection in a house.

Developing the sensor system to be fabricated on a circuit board requires the use of a processor that can process the demodulation, filtering of the data and sampling and saving the down sampled data on a disk while meeting real time constraints. The TI TMS320C6748 digital signal processor, with a clock rate of 456 MHz, two SPI interfaces with multiple chip selects, a multimedia card interface was chosen to be the processor to interface with the ADC and DAC chips necessary for the sensor system. The TI Code Composer Studio IDE was used for developing the C programs for the processor.

4. Demodulation Methods

The demodulation methods investigated to extract the Doppler features from the received signal were IQ Demodulation and Direct Demodulation. The two methods differed based on the sample rates required, and the demodulation techniques involved [6].

Direct Demodulated is a quick method of analyzing the features from the received signal. It is based on computing the spectrogram of the digitalized reflected signal. IQ demodulation is based on computing the spectrogram of the complex signal from the baseband $I(t)$ and $Q(t)$ signals as described in Section 1.2

4.1 Experimental Setup

The UDS sensor system was created by using the two ultrasonic transducers collocated in a plastic box, with one acting as the transmitter and the other as the receiver. The HP 3314A signal generator was used to drive the transmitter with a 40 kHz, 20 Vpp continuous sine wave. The moving target used was a pendulum with a length of 1 m, and located at a distance of 2m from the transducers. The reflected signal from the receiver was amplified using the SRS 560 pre-amplifier and then fed into one of the channels of the Wavebook DAQ. The transmit signal from the signal generator was teed off to another channel of the DAQ and the data were sampled at 100 kHz for 10 seconds, and saved for further analysis using MATLAB.

4.2 Data Analysis

For the Direct Demodulation method, the spectrogram of the received digitalized signal was computed to show the extracted Doppler features of the pendulum swing. The sample rate used for computing the spectrogram was 100 kHz, with the window size set to 8192 and the number of FFT points for each window set to twice window size. The resulting spectrogram is shown in Figure 4.1.

While performing IQ demodulation, the received digitalized signal was multiplied by the digitalized carrier signal and the shifted carrier signal. The products were then passed through a 2000 kHz low pass filter constructed in MATLAB to obtain the baseband $I(t)$ and $Q(t)$ signals which were combined to form the complex Doppler signal as described in Section 1. Since the frequency of interest is less than 2 kHz, the complex Doppler signal was decimated by a factor of twenty which reduced the sampling rate to 5000 Hz. The spectrogram of the decimated complex Doppler signal was computed, using a window size of 1024 points. Figure 4.2 shows the spectrogram obtained.

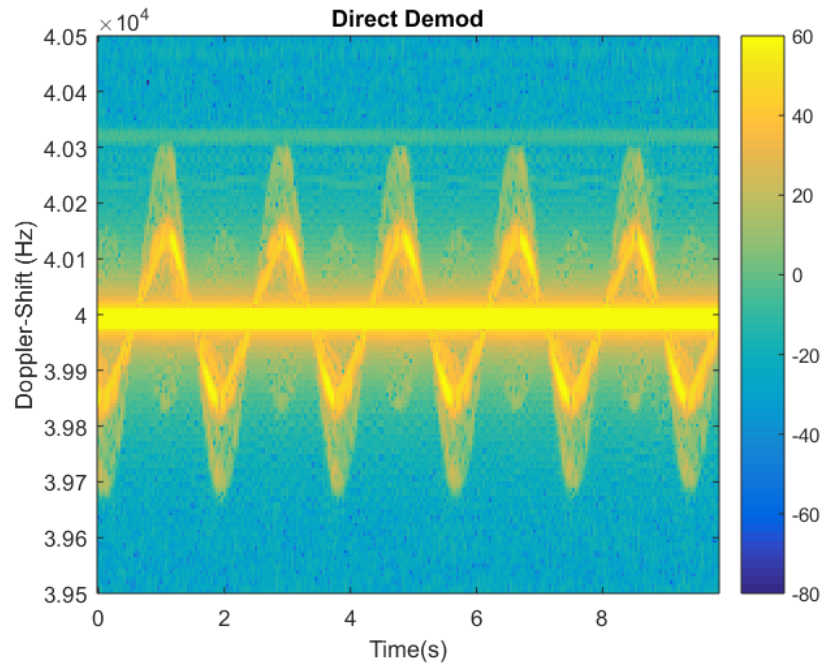


Figure 4.1: Spectrogram Obatined from Direct Demodulation

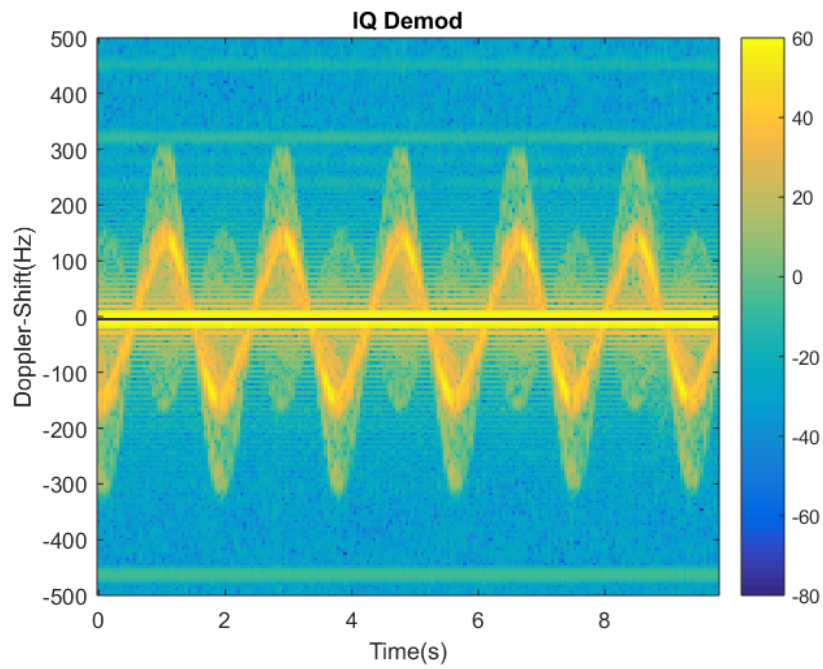


Figure 4.2: Spectrogram Obatined from IQ Demodulation

4.3 Results

The positive and negative Doppler shifted frequencies for the pendulum swing are the same in both figures from the center point. The spectrogram plot shown in Figure 4.1 is centered at 40 kHz due to the presence of the carrier while that of Figure 4.2 is centered at 0 Hz due to the IQ demodulation which got rid of the carrier. The maximum Doppler-shifted frequency with respect to the center is 166 Hz for both figures. The Doppler-shifted frequencies can be converted to velocity using the relationship established in equation 2.1 in the following manner:

$$v(t) = \frac{cf_d(t)}{2f_c} \quad (4.1)$$

Although direct demodulation is a quick method, the sample rates needed are high since the highest frequency component obtained is approximately 42 kHz, which means the sampling rate must be at least 84 kHz to meet Nyquist criterion. The frequency content of interest is less than 2 kHz but due to the presence of the carrier, the high sampling rate is a requirement. The high sampling rate also results in inefficiency in storing data for collecting multiple data sets at longer periods and a computational costly method in processing the spectrograms.

The frequency resolution for the IQ demodulation is better than Direct Demodulation due to a reduced window size and FFT sample size. While the initial sample rate for collection of data remain the same in both methods, with IQ demodulation, the baseband $I(t)$ and $Q(t)$ signals can be decimated to a reduced sample rate. The reduced sample rate leads to efficiency in storage when large sets of data collection are needed.

The ultimate goal of the UDS sensor system is to monitor the gait of a person at a house which will result in collection and processing of large sets of data, the IQ demodulation method is used rather than Direct Demodulation method. The

generation of the decimated $I(t)$ and $Q(t)$ baseband signals will be included in the data acquisition software to be used in subsequent designs.

5. Validation of UDS Sensor System

The validation of the UDS sensor system was done by comparing it with Radar system used for measuring Doppler shift. The radar system was used in fall-risk assessment of seniors by measuring their walking speeds and other gait properties over a period of time [12]. The radar system was constructed using Pulse-Doppler range control radars which periodically transmit a 5.8 GHz pulse. The transmitted and received signals for each time period are mixed and then low pass filtered to get the base-band signal which contains the Doppler shifted frequencies. The base-band signal is then sampled using the DATAQ DI-710 data acquisition system at 960 Hz.

5.1 Experimental Setup

A pendulum was used as the moving target for comparison of the two different sensor systems. The transducers were placed at distances of 1m, 2m and 4m away from each of the transducers. At each distance away from the transducers, the pendulum was given an angular displacement of 10cm, and 40cm and the data was sampled at 100 kHz for the UDS sensor system and at 960 Hz for the radar system for a sampling time of 10 seconds.

5.2 Data Analysis

IQ demodulation method was used to extract the Doppler features of the pendulum swing for the UDS sensor system. The Doppler shifted frequencies of the pen-

dulum swing were obtained by computing the spectrogram of the complex Doppler signal formed from the decimated $I(t)$ and $Q(t)$ signals as explained in Chapter 1. The data for the radar system was sampled at base-band and the spectrogram was computed directly to extract the frequency shifts of the pendulum swing. The two sensor systems have different carrier frequencies which affect the Doppler shifted frequencies returned by the spectrogram.

The velocity of the moving target (pendulum) was obtained using the Doppler shift frequency and velocity relation stated in equation 2.1. The carrier frequency of the UDS sensor system used was 40 kHz while that of the radar system was 5.8 GHz. The speed of sound used for the UDS sensor system was 343 m/s while the speed of light was used for the radar system was 2.99×10^8 m/s.

5.3 Results

Figures 5.1 and 5.2 show the spectrogram plot of the velocity-time graph for the pendulum at a distance of 1 m away from the sensors and an angular displacement of 10cm. Figures 5.3 and 5.4 show the spectrogram plot of the velocity-time graph for the pendulum at a distance of 2 m away from the sensors and an angular displacement of 20 cm. Figures 5.5 and 5.6 show the spectrogram plot of the velocity-time graph for the pendulum at a distance of 4 m away from the sensors and an angular displacement of 10 cm.

The velocity for the same angular displacement was approximately the same for both sensor systems at the same distance and at different distances away from the sensor systems. The maximum velocity of the pendulum swing for a displacement of 10 cm from the center was approximately 0.67 m/s for both sensors and at distances 1 m and 4 m away. For a displacement of 40 cm from the center, the maximum velocity was approximately 1.2 m/s for both sensors at a distance 2 m away from

the sensors. The Radar sensor system, cannot differentiate between motion from and motion towards the sensor as it is pulse based. The UDS sensor system being continuous wave, could differentiate positive and negative motion. The resolution of the UDS sensor system was better than that of the radar system, however the intensity of the signals for the UDS sensors system reduce with distance away from the sensor due to wavelength of sound and the size of the target used.

The UDS sensor system was comparable to the Radar system for measuring the velocity of moving targets at small distances away from the sensor. Since the application of the sensor system will be in a house to measure about ten steps of walking data, the UDS sonar system will be sufficient in measuring the gait features from human walks.

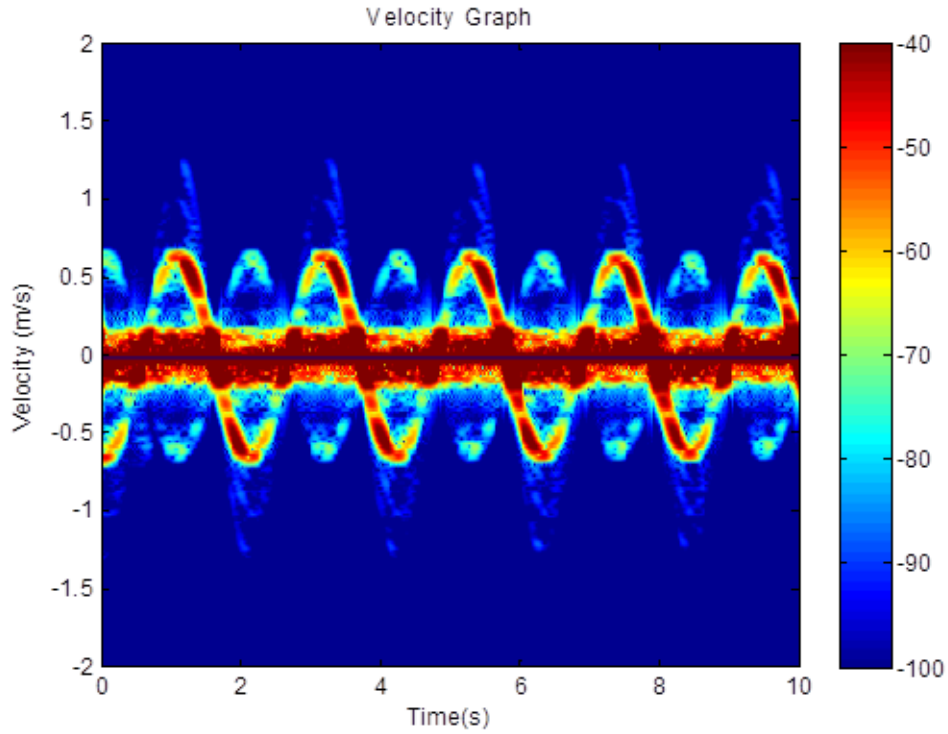


Figure 5.1: Pendulum at 1 m away and 10 cm displacement-UDS Sensor

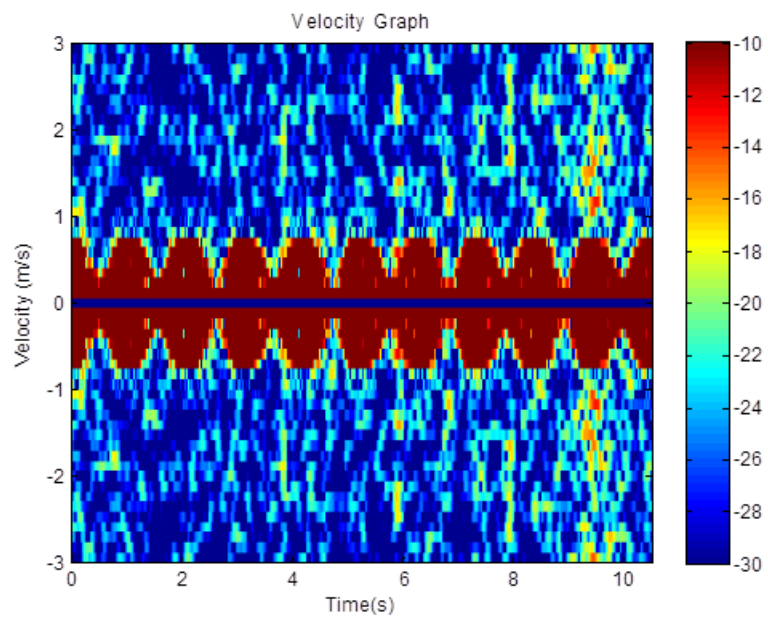


Figure 5.2: Pendulum at 1 m away and 10 cm displacement-Radar Sensor

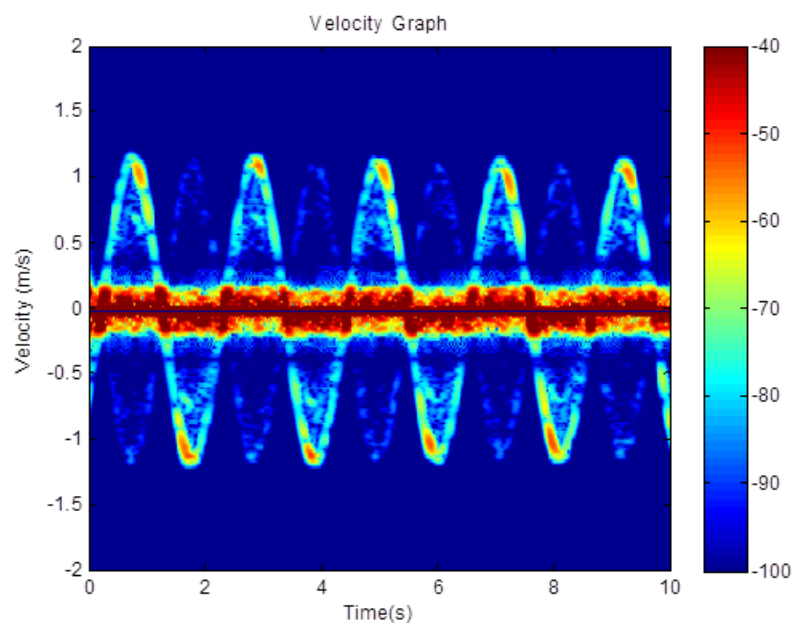


Figure 5.3: Pendulum at 2 m away and 40 cm displacement-UDS Sensor

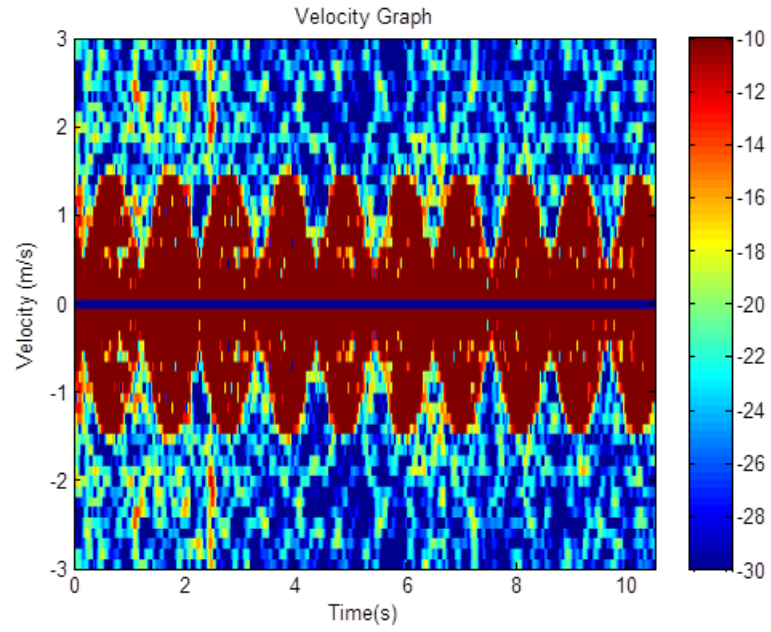


Figure 5.4: Pendulum at 2 m away and 40 cm displacement-Radar Sensor

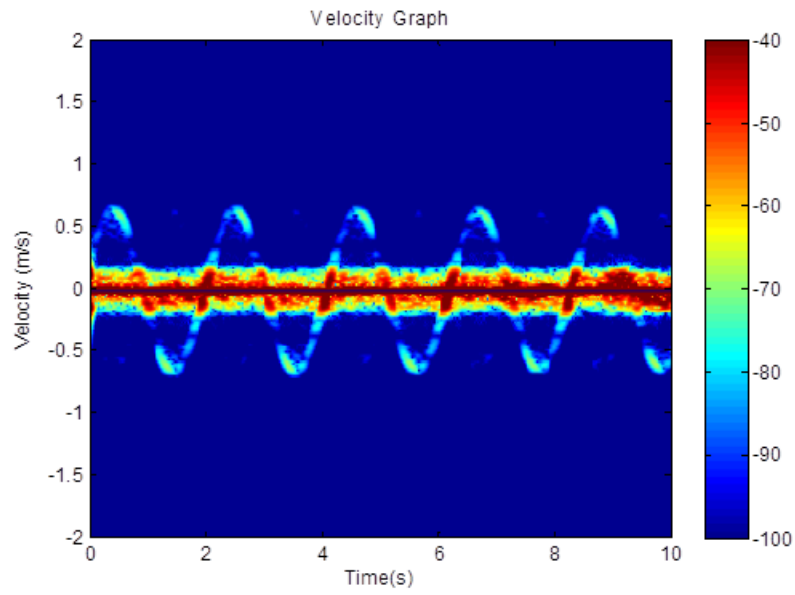


Figure 5.5: Pendulum at 4 m away and 10 cm displacement-UDS Sensor

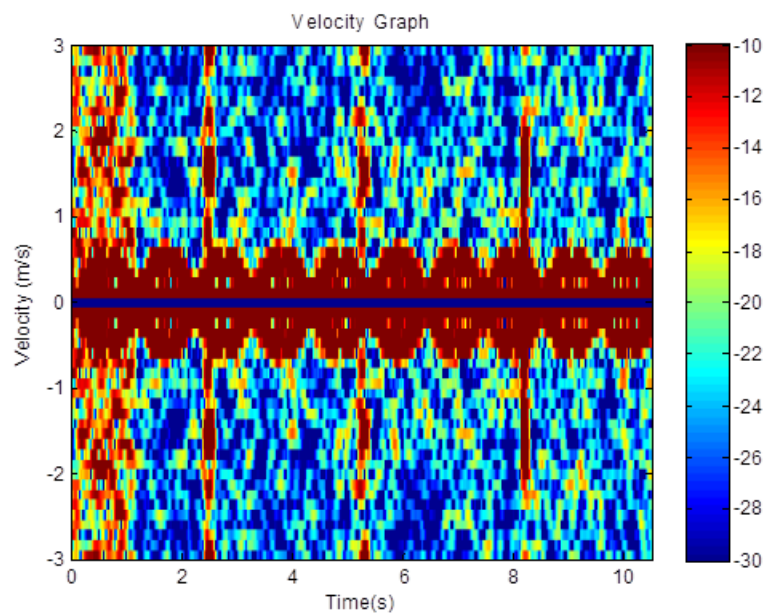


Figure 5.6: Pendulum at 4 m away and 10 cm displacement-Radar Sensor

6. Automatic UDS Sensor System

The automatic collection of walk data in houses will need a portable sensor system, that would be triggered to collect walk data by a sensor when it detects human motion. A sensor box measuring 10.5 in X 7.5 in X 4 in was used to contain the components of the UDS sensor system with the transducers supported on a tripod stand.

6.1 Hardware Components

The hardware components of the system comprised of a Passive Infrared Sensor, MATSUN/PAN EFR-RC40K ultrasonic transducers, NI-USB 6216 data acquisition system, Analog Module Model 351A-3 Amplifier, MINMAX ABF-04D15 AC/DC Power Module.

6.1.1 Passive Infrared Sensor

The Passive Infrared (PIR) Sensor was used to detect human motion that would trigger the sensor system to start the collection of data, and also to note the amount of time that the human motion was in front of the sensor. The PIR Sensor requires a supply voltage of 3.3/5 V, a detecting range up to 9 meters, and a detection angle of 120°. The output of the sensor is a continuous digital high signal when movement is detected.

The NI USB-6216 DAQ was used to provide the dc voltage supply of 5 V to the PIR sensor, and use the output as a trigger for the start of data collection.

6.1.2 MATSUN/PAN EFR-RC40K transducers

Two MATSUN/PAN EFR-RC40K transducers were collocated in a plastic box to be the transmitter and receiver. The transducers have a resonance at 40 kHz, a maximum supply voltage rating of 10 Vrms, a bandwidth of 4 kHz and a directivity of 60° at -6 dB.

The transmitter was driven by a 40 kHz sine wave with an amplitude of 10 V which was produced by the NI USB-6216 DAQ through one of its analog output channels. The signal from the receiver was fed into the amplifier before being sampled by the data acquisition device.

6.1.3 Analog Modules Model 351A-3 Amplifier

The pre-amplifier used for the box was a non-inverting Analog Modules Model 351A-3 low noise amplifier. It has an input impedance of 4.7 k Ω , a bandwidth from DC upto 3.5 MHz, requires a supply voltage of ± 15 V DC at 28 mA, and provides an output voltage of up to 16 Vpp into a 1 k Ω load. The gain setting is adjustable to up to 80 dB.

The MINMAX ABF-04D15 AC/DC Power Module was used to provide the ± 15 V DC power supply. The gain was set to 48 dB since the expected input to the amplifier is ± 32 mV and an output voltage range of ± 4 V was desired for the ADC setting used. Connections to the amplifier were done using lead wires with BNC connections.

6.1.4 MINMAX ABF-04D15 AC/DC Power Module

The MINMAX ABF-04D15 AC/DC Power Module was used to provide power supply for the amplifier. It requires a universal input voltage range of 85-264 VAC

through two input terminals AC(Neutral) and AC(Live), and has three output terminals which provide +15 V, -15 V, and the Common reference. The power module is enclosed in a case size of 1.44 X 1.06 X 0.67 inches, portable enough for the application needs. The AC supply voltage would be provide from wall sockets through an AC power chord.

6.1.5 NI USB-6216 DAQ Device

The NI USB-6216 DAQ was used as a power supply for the PIR sensor through one of the 5 V DC output signals, the signal generator for the transmitter and the data acquisition device to sample the received signal. The analog output channel has a DAC resolution of 16 bits and a maximum update rate of 250 kilo samples per second (kS/s) and an output range of ± 10 V. The analog input channel has an input range settings of ± 10 , ± 5 , ± 1 , and ± 0.2 V, an ADC resolution of 16 bits, and a maximum sample rate 400 kS/s.

A 10 V amplitude 40 kHz sine wave was produced to drive the transmitter through the DAC output channels. The signal was sampled at 250 kS/s to provide a clean driving signal. The input ADC channel was set to sample the received signal at 100 kS/s, and the digital input channel was set to sample at 1 kS/s to trigger the start of data collection on a digital high signal from the PIR sensor.

6.2 LabVIEW Software Program

A LabVIEW program was used to control the NI USB-6216 DAQ to generate the transmitted signal, digitize the received signal, trigger the start of the data collection. The demodulated IQ down-sampled data collected is then saved in a CSV file.

The NI-DAQmx function *Create Channel* was used to create an output channel with range settings of ± 10 V to generate the transmitting signal and an input

channel with range setting of ± 5 V to sample the received amplified signal. The *Function Generator* function was used for generating the 40 kHz sinusoidal transmitting signal with an amplitude of 10 V. The sampling period and mode settings for both the input and output channels were set using the DAQmx *Timing* function. The DAQmx *Write* function on the analog output channel starts the generation of the continuous transmitting signal when the trigger signal goes high to signal the start of the acquisition, while the DAQ *Read* function on the input channel starts the sampling of the received signal, at a rate of 100 kS/s.

In real time, and in groups of 2500 samples, the received digitalized signal was multiplied with the transmitting signal to get I(t) signal, and multiplied with the Hilbert transform of the transmit signal to get the Q(t) signal. The resulting I(t) and Q(t) signals are then passed into a low pass Chebyshev filter which was designed to the appropriate sample rate with a cutoff frequency of 2 kHz. The outputs from the filter containing only base-band signal were decimated by a factor of 20 and then saved onto a CSV file. A graphical representation of the collection of data by the UDS sensor system is shown in figure 6.1

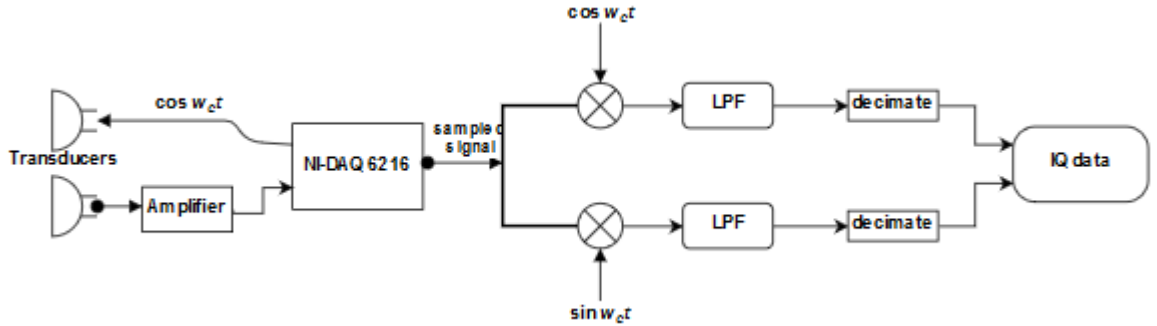


Figure 6.1: Graphical Representation of UDS sensor system

6.3 System Test

The sensor system built was tested in the laboratory with a simple pendulum constructed from a string and a spherical ball. The pendulum was placed about 2 m away from the transducers. The pendulum was swing into motion and data was collected for ten seconds.

The decimated I and Q base-band data which was collected by the UDS sensor system was then analyzed with a matlab code to compute the spectrogram. The spectrogram plot shown in Figure 6.2 shows the Doppler features of the pendulum motion. The Doppler frequency shifts that can be changed to velocity using equation 4.1 can be seen changing with time. The same principle will be applied to extracting the features in human walk in the next chapter.

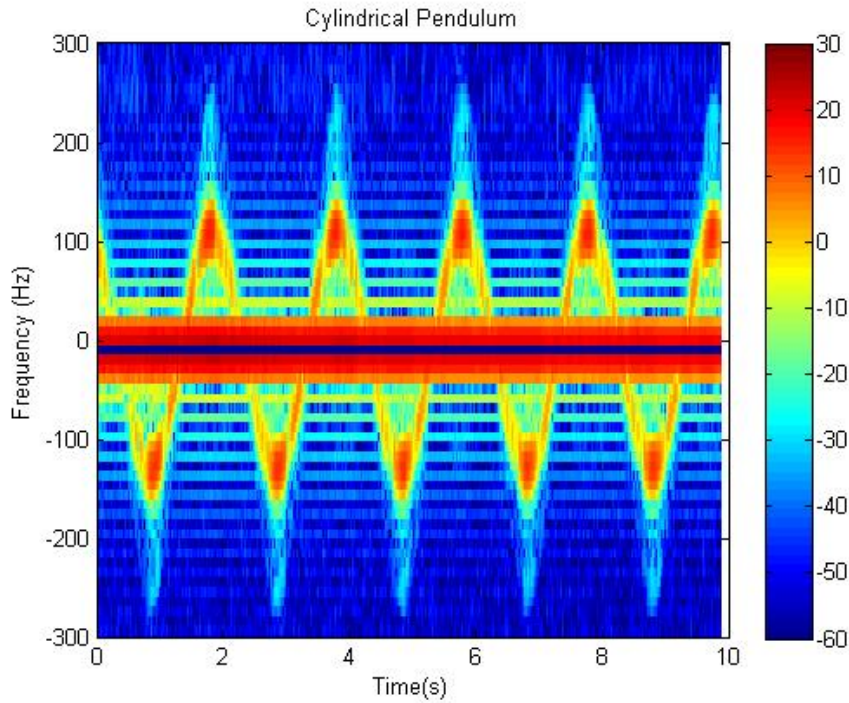


Figure 6.2: Spectrogram of pendulum swing

7. Experimental Tests On Gait Features

The UDS sensor system was used for collection of human walk data, and analysis of the doppler features of the walk was completed by computing the spectrograms. In this section, we describe the sets of experiments done to show the effect that the location of the sensor, feet noise, clothing materials, shoes, swinging arms, multi-path doppler frequencies had on the Doppler signature extracted from the spectrograms.

7.1 Doppler Features of a Normal Walk

The UDS sensor system was used to collect data for a normal walk, the natural walk of a subject. The transducers were placed on a tripod and adjusted to be at the same height as the waist of the subject walking. The subject walk data was collected for ten seconds for walking away and towards the transducer. The test was carried in the corridor of a house, with enough room to collect ten steps of walk data.

The data collected was analyzed using matlab to compute the spectrograms. The spectrogram plot shown in figure 7.1 shows the subject walking away from the transducer. The positive Doppler shifted frequencies shown indicate the leg velocity, and movement away from the transducer, while the negative Doppler shifted frequencies are a result of feet noise, hand swings, negative motion of one of the legs as the other moves forward, and reflections from multi-path Doppler. In theory positive Doppler shifted frequencies for the leg indicate movement towards the transducers and negative Doppler shifted frequencies for the leg indicate movement away from

the transducers, however the results were flipped during analysis as subsequent test results shown will be for movement away from the transducer only. The intensity reduces as the subject moves away in distance away from the transducer, however the features show an increase of leg velocity at the start from the first two steps to an almost constant leg velocity and then a reduction of the leg velocities as the subject stops. The spikes on each leg motion are also the result of feet noise, and multi-path but they have a lower intensity level. The spectrogram plot of the subject walking towards the sensor is shown in figure 7.2 showing almost a similar but opposite Doppler signature due to movement towards the transducers.

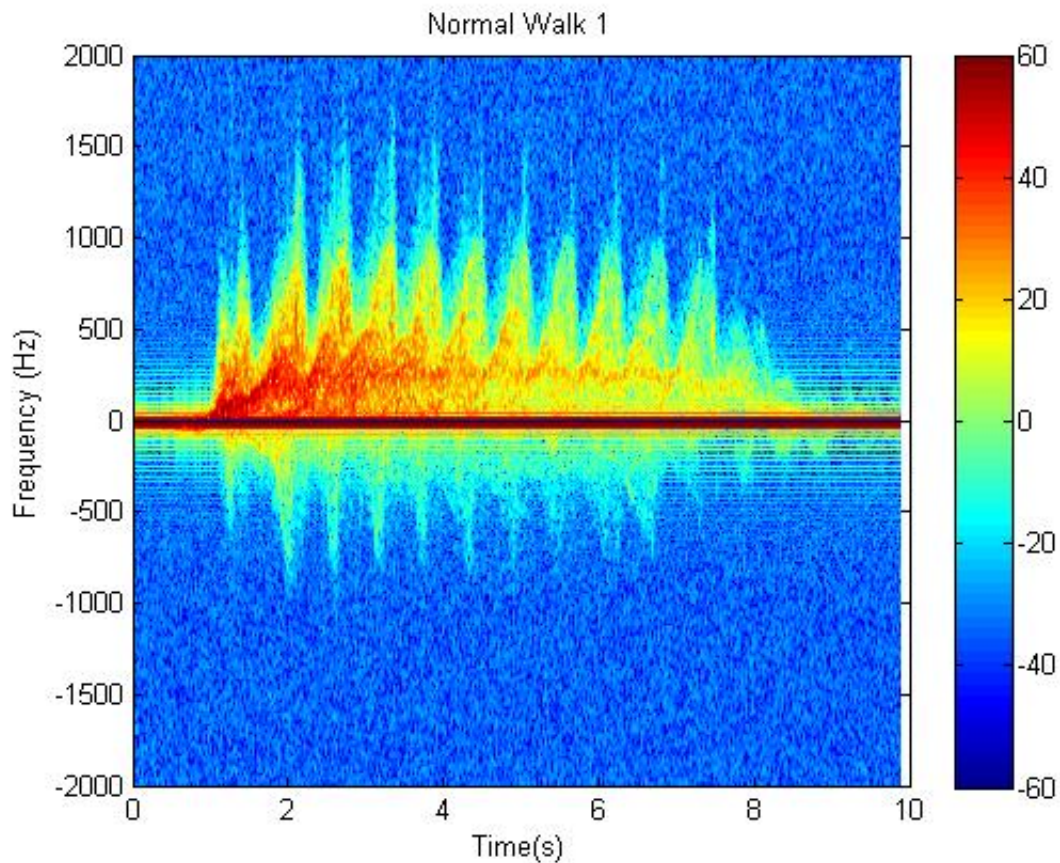


Figure 7.1: Subject walking away from transducer

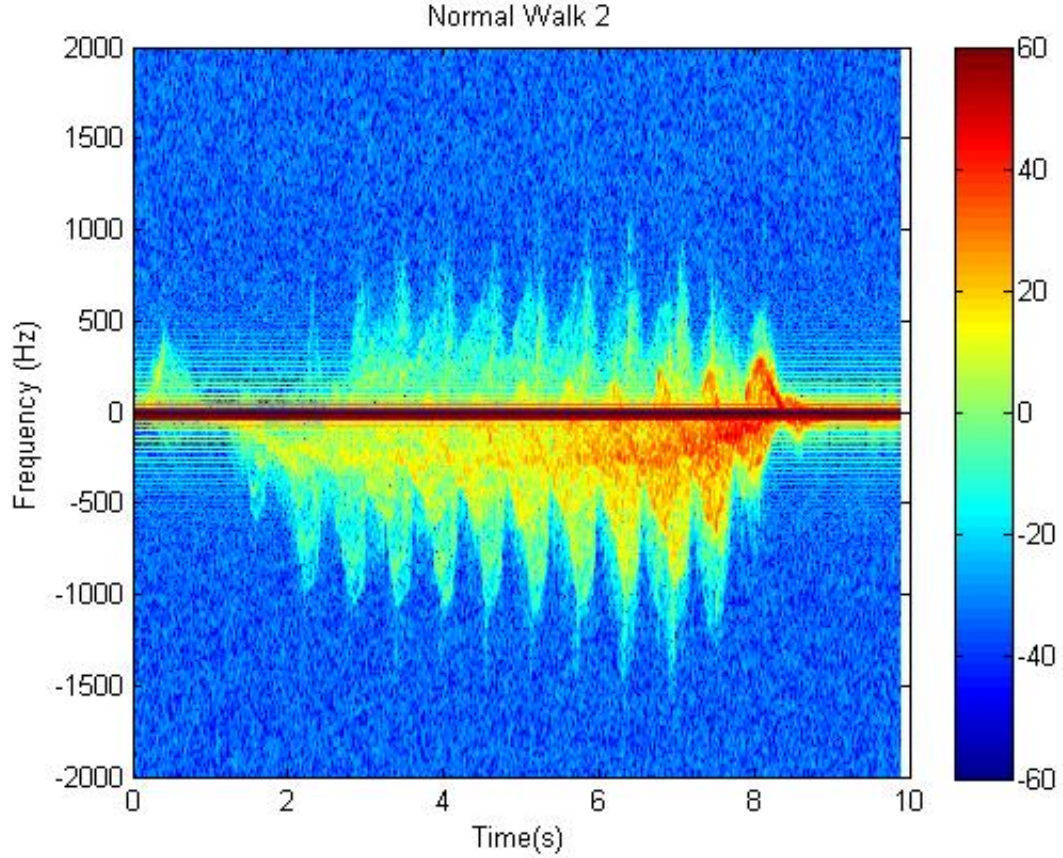


Figure 7.2: Subject walking towards transducer

7.2 Effects of Location of Sensors

The effects of the location of the collocated ultrasonic transducers on the Doppler signature of a walk was examined by placing the transducers at the heights of the feet, the knee and the waist. The ultrasonic transducers used are rated with a directivity of 60° at -6dB , which is one of the reasons for the signal attenuation as the subject moves away from the transducer.

The experimental tests were done in a corridor long enough for getting ten walking steps. The sensors were placed at three different positions, the knee, the feet and the waist of the subject walking. The UDS sensor system was used to collect the

data for ten seconds with the subject walking away and towards the sensors.

The resulting I and Q data saved was then analysed using MATLAB to get the spectrograms. Figures 7.3, 7.4 and 7.5 show the spectrogram plots of the subject walking away from the sensors located at feet, ankle and waist respectively. The Doppler signatures from the plots are almost identical and there is not much visible difference in the features of the walks, which is due to the fact that legs is big enough to reflect back transmitted signals at the three positions the transducers are placed. The intensity however decreases in all three as the subject moves away from the transducer, which is due to attenuation as a result of the directivity of the transducers and a reduction of the reflected signal strength due to distance.

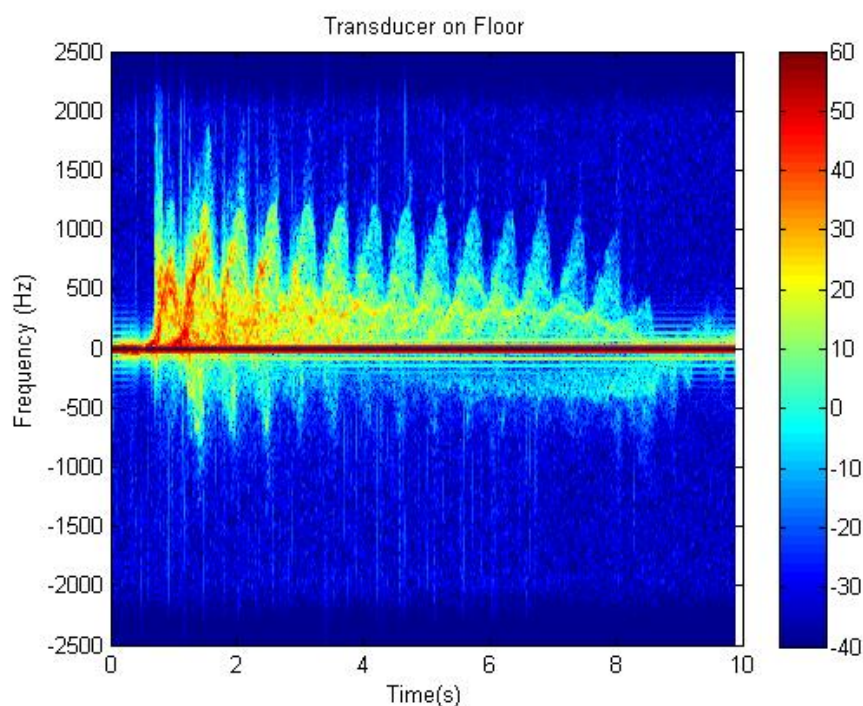


Figure 7.3: Sensors at feet level

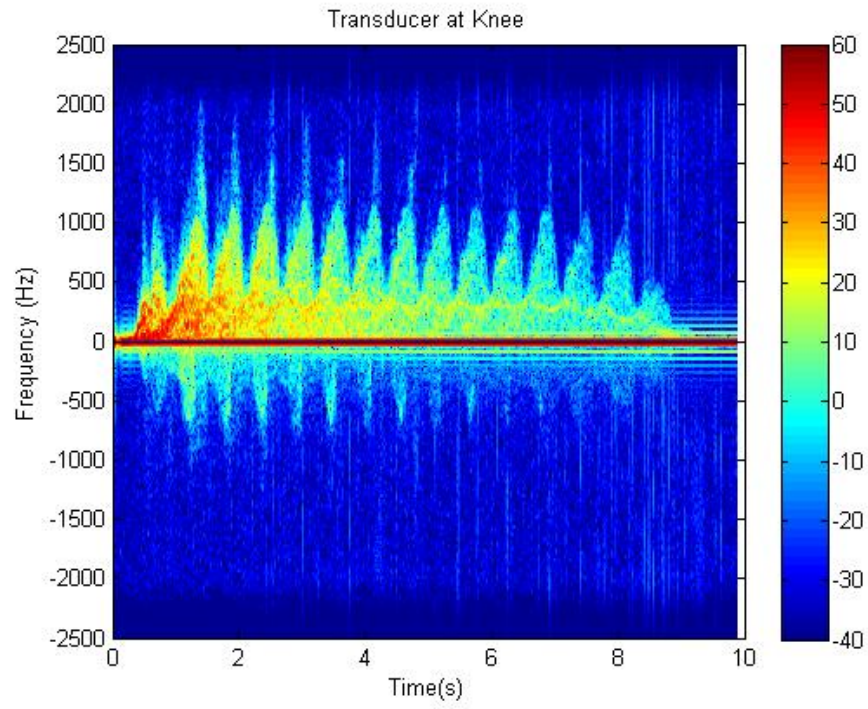


Figure 7.4: Sensors at knee level

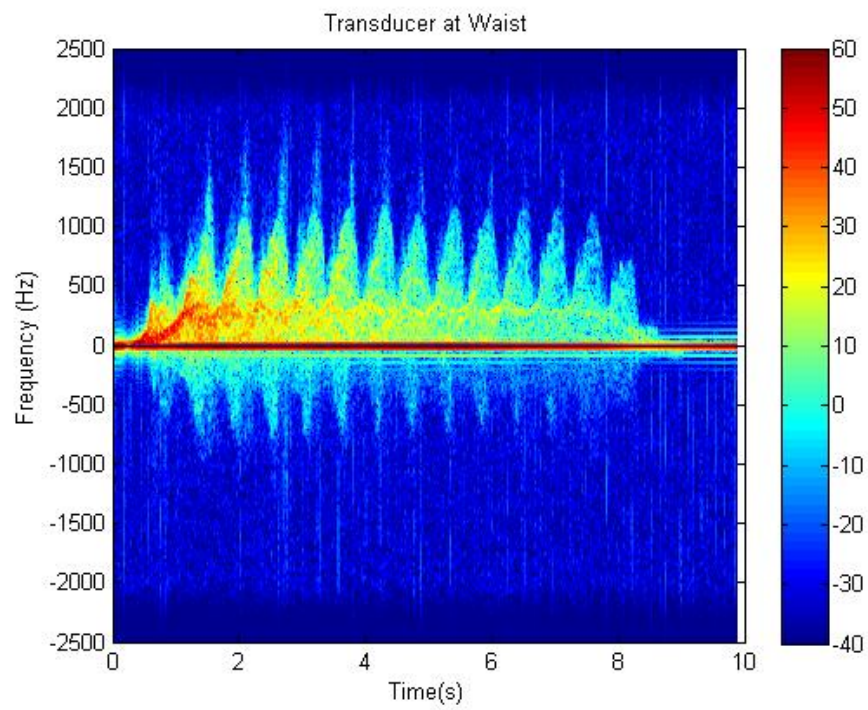


Figure 7.5: Sensors at waist level

7.3 Effects of Feet Noise

The effects of the feet noise generated in the Doppler signature as a subject walks were investigated. These experiments were done in three steps, the Doppler signature of a toe slap was examined to understand its shape and the Doppler shifted frequencies it generated, then a comparison of the Doppler signatures of a subject walking using shoes and then with socks.

The experimental setup for examining toe slap was done by placing the sensors about three steps away from the subject. The subject facing the transducer swung one of his legs making contact with the ground as he swung towards the transducer, then pulled back without making contact with the ground. This was repeated three times and the data was collected for ten seconds. Figure 7.6 shows the spectrogram plot of this data. The Doppler signatures obtained show the Doppler shifted frequencies of the leg swing, but with low intensity shows high Doppler shifted frequencies when contact is made with the ground. These high frequency spikes are seen in the Doppler signatures of the walks done.

The Doppler signatures of a subject walking using shoes and socks was compared to see the effects of contacts with the ground. The subject walked away and towards the transducer that was located at a height level of the waist. The data were collected for ten seconds for each walk. The experiments were done in the corridor of a house, with enough room for ten walk steps. The spectrogram plots of the walks are shown in figures 7.7 and 7.8.

The Doppler signature of the subject walking in shoes away from the sensors is shown in figure 7.7. As the subject walks, the shoes make contact with the ground comparable to the toe slap examined earlier. The broad high Doppler shifted frequency spikes can be seen in the plot in every leg motion as the subject walks away,

reducing with distance. This is compared to the Doppler signature of the subject walking away from the transducer in socks shown in figure 7.8. The socks have less friction when they make contact with the ground as the subject walks resulting in narrower high Doppler shifted frequency spikes on the leg velocities.

The three figures 7.6, 7.7 and 7.8 explain one of the features in the Doppler signatures of a subject walking. The main interest in the Doppler signatures is the leg velocities of the subject walking and differentiating this from the shifted frequencies generated from other motions is important.

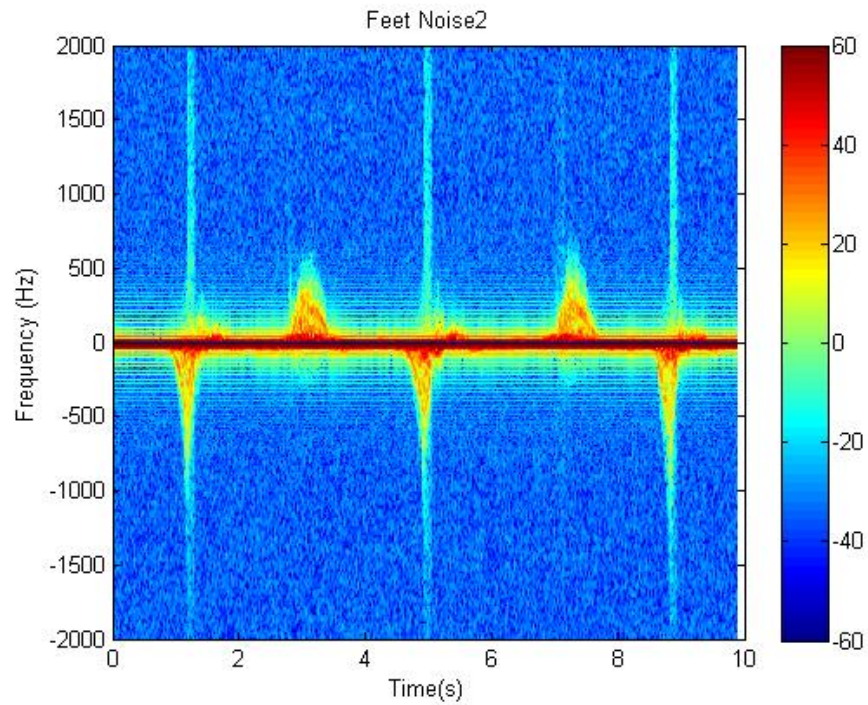


Figure 7.6: Leg Swing with ground contact

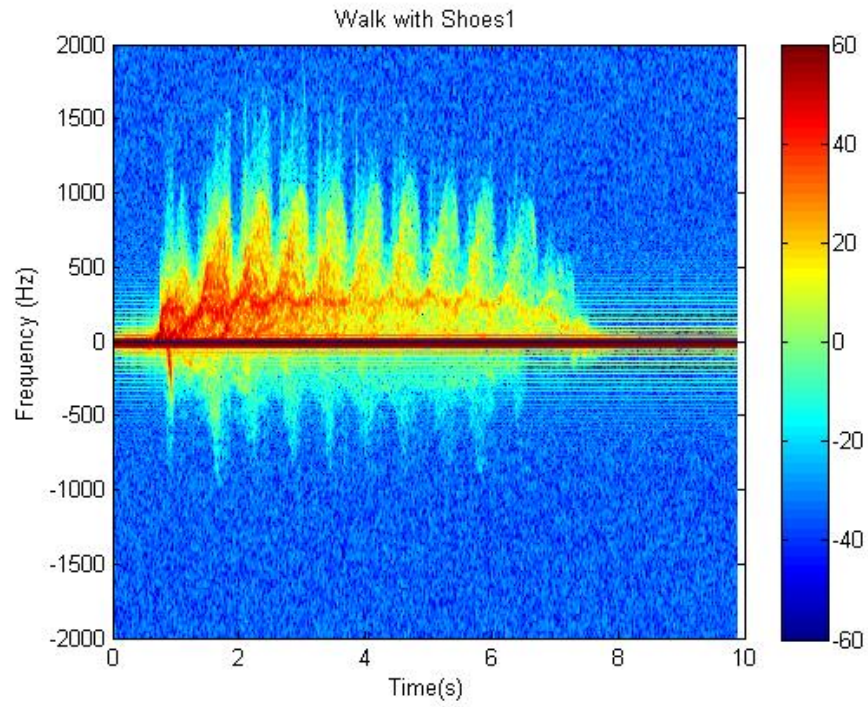


Figure 7.7: Subject walking with shoes

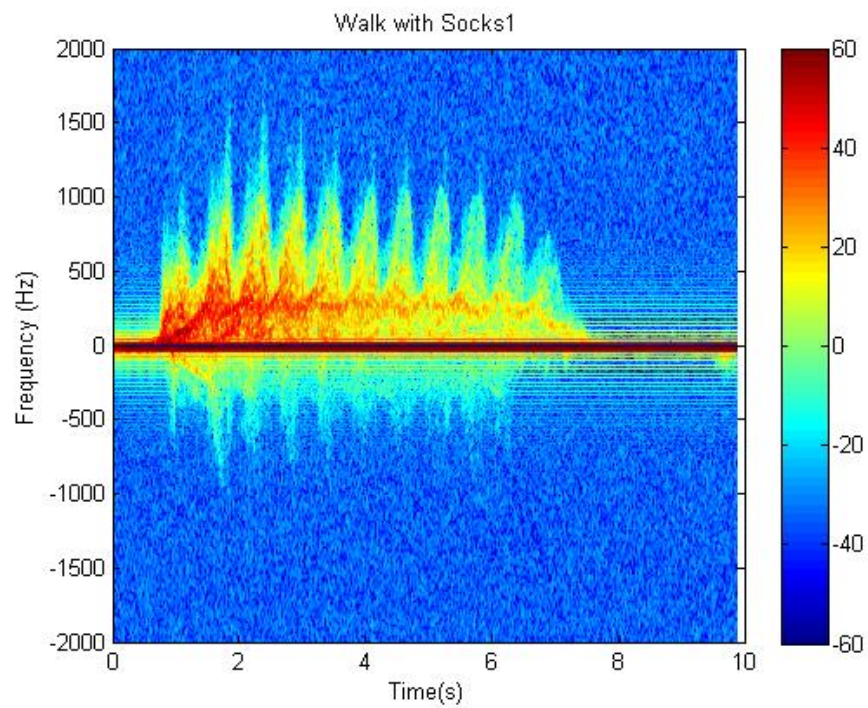


Figure 7.8: Subject walking with socks

7.4 Effects of Swinging Arms

The arms normally swing back and forth during walks, and this motion would be reflected in the Doppler signature collected from walks. To understand the nature of this motion, experiments were done to determine the Doppler signature of the arms in motion by a subject standing, and also with a subject walking with a single hand in the pocket and with both hands in the pocket to stop the arm motion.

The experimental setup for arm swings was done with the subject standing in the corridor of a house at different positions away from the sensor. The subject swung one of the arms at a distance of three, six, and nine footsteps away from the transducer. The data was collected for ten seconds and the spectrograms were computed. Figures 7.9, 7.10 and 7.11 show the spectrogram plots of the subject swinging the right arm at a distance of three, six and nine footsteps away from the transducer. All three figures show maximum Doppler-shifted frequencies that are lesser than the ones noted for the legs when walking. The frequencies from the hand during a walk are expected to be lower than these since the subject swung the hands at a faster rate while standing still. The shifted frequencies in the same direction of a walk will be embedded in the leg velocity signature, however the opposite motion will be visible since the negative motion of the leg in a walk is minimal compared with the arm swing. The intensity of the swings also reduces with increased distance away from the transducer, a result of the directivity of the transducers and the reduced signal strength due to distance.

The effects of arm swings on the Doppler signature from walks was also examined by a subject walking away from the transducer with one of the hands and then both hands in the pocket to prevent arm swings when walking. The transducers were located at the waist level of the subject and data was collected for ten seconds in the corridor of a house as the subject walked. The spectrogram plots for the subject

walking with both hands in the pockets is shown in figure 7.12. Comparing this to figure 7.1 which shows the Doppler signature for a normal walk, it can be seen that the presence of opposite Doppler shifted frequencies to the leg velocities are lower when the arm swings are controlled. Figure 7.13 shows the spectrogram plot of the subject moving away from the transducer with one of the hands in the pocket. There is the presence of opposite Doppler shifted frequencies to the leg velocities but still not much pronounced as a normal walk when both arms swing.

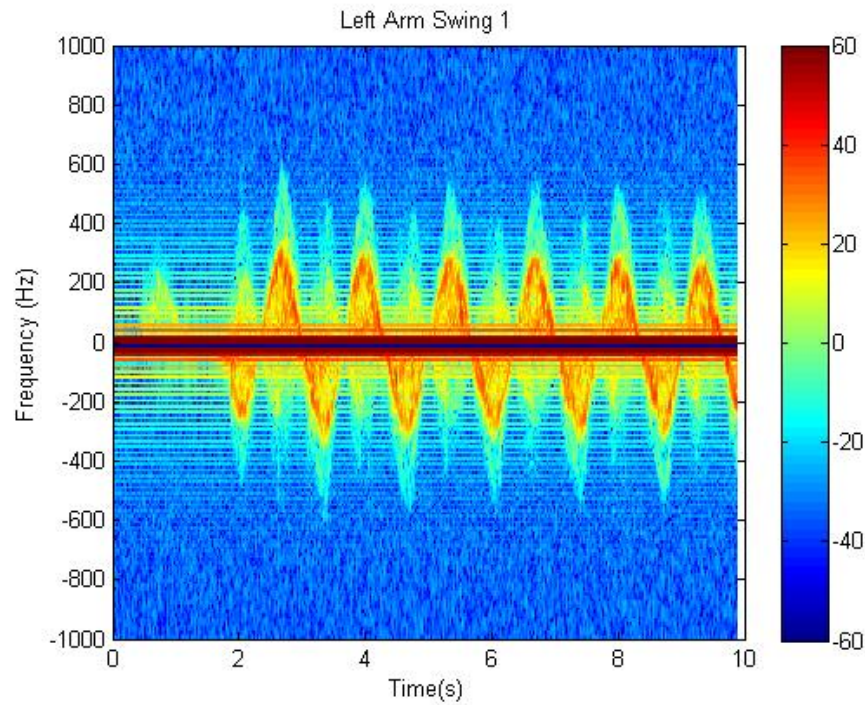


Figure 7.9: Arm swing three footsteps away

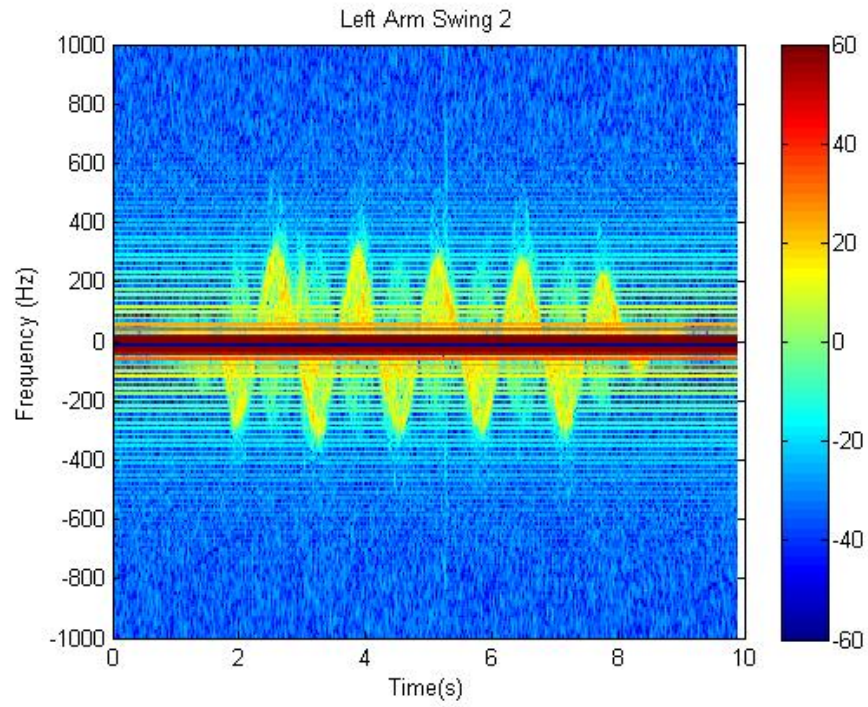


Figure 7.10: Arm swing six footsteps away

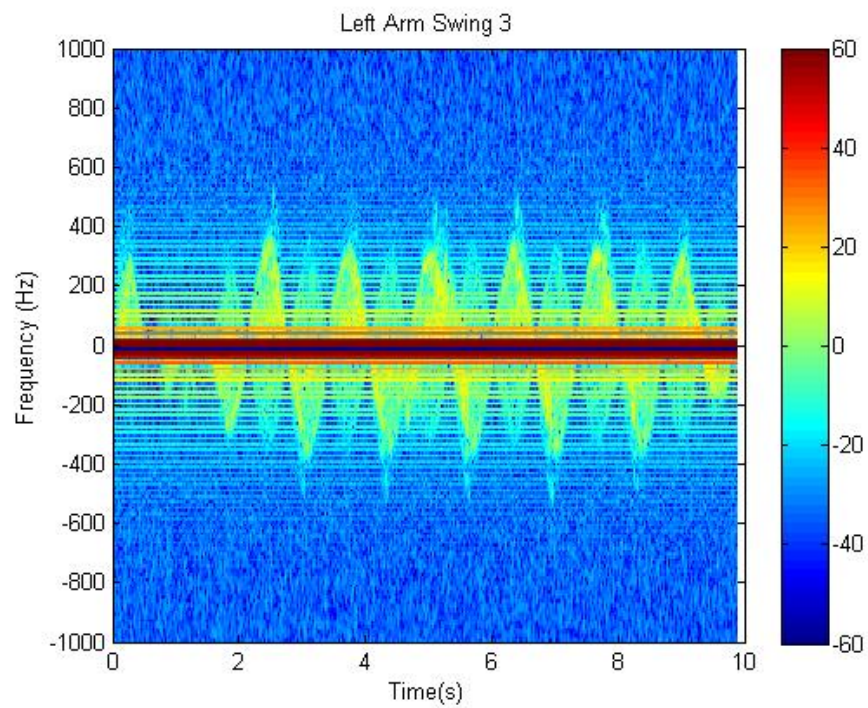


Figure 7.11: Arm swing nine footsteps away

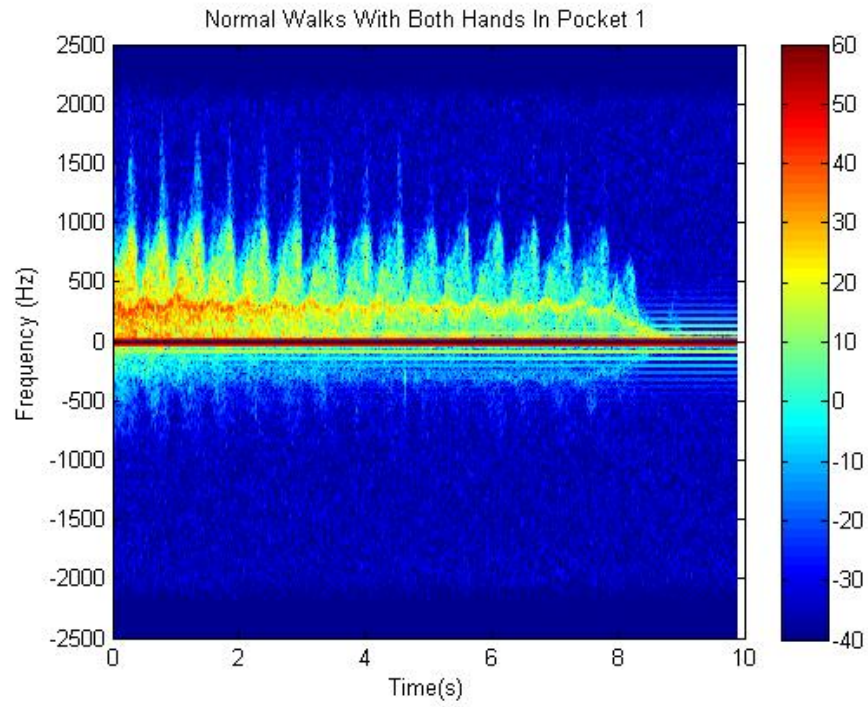


Figure 7.12: Subject walking with both hands inside

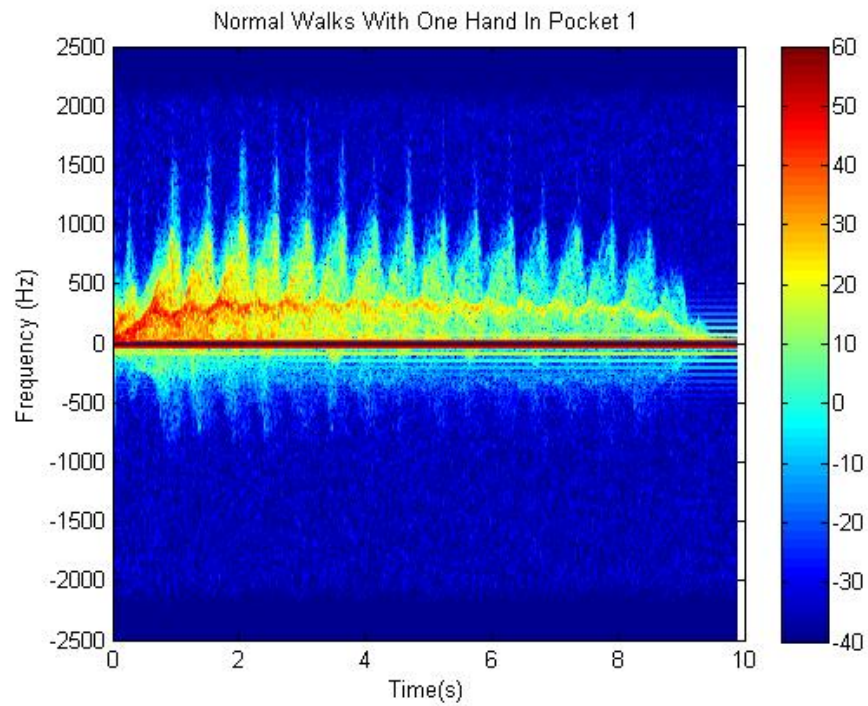


Figure 7.13: Subject walking with one hand inside

7.5 Multipath Doppler Effect

Multipath Doppler is the result of reflected signals coming to the receiver in more than a single path. This phenomenon occurs when the reflected signals from the moving object bounces off stationary objects in the room, resulting in ghost signals twice as large than the original. If the stationary objects are behind the sensor system, the multipath results in ghost signals that are the negative of the reflected signals. In the UDS sensor system, the transducers are collocated in a plastic box, which is stationary and a source of the multipath Doppler. The walls also in the rooms are also another source of multipath Doppler.

The effects of the multipath Doppler were tested both in the laboratory and in an anechoic chamber. In the laboratory a simple pendulum was created and data sets were collected putting foam behind the sensors to absorb the ultrasonic signals thereby reducing the multipath that results negative reflected signals. The simple pendulum was swung and data was collected for ten seconds without any foam behind the sensors. The experiment was repeated with placing foam behind the sensors and then repeated with a stationary pendulum.

Figure 7.14 shows the spectrogram plot of the pendulum motion without the use of foam behind the sensors. The ghost signals of the reflected signals causing both the opposite, and twice Doppler shifted frequencies of the swing can be seen. The spectrogram plot of the pendulum swing with the use of foam behind the sensors is shown in figure 7.15. The use of foam behind the sensors results in the attenuation of the ghost reflected signals opposite to the swing but the faded doubling of the shifted frequencies still remains. This is due to the presence of other stationary objects present in the room in front of the sensors that the reflected signals bounce on creating an alternate path to the receiver. The spectrogram plot of the stationary pendulum is shown in figure 7.16. There was no other motion in the room and

the intensity visible around the zero mark shows the reflections of the the carrier frequencies of stationary objects and low motion objects in the room. The highest intensity is always around this mark in all the spectrogram plots.

Tests were carried out in the anechooid chamber for the analysis of the multipath Doppler. The anechooid chamber at the National Center for Physical Acoustics on the University campus was used for this test. A foam was made to cover the plastic box that contained the transducers since it will be the stationary object that could cause multipath in the chamber. A simple pendulum was created and swung, with the collection of data for ten seconds, first without the foam, and then with the foam on the the box. The spectrogram plot without the foam is shown in the 7.17. The negative reflected signals are almost absent but there is still the presence of the faded double shifted frequencies. The use of foam reduces this effect as can be seen in figure 7.18 which shows the spectrogram plot with the use of foam on the plastic box.

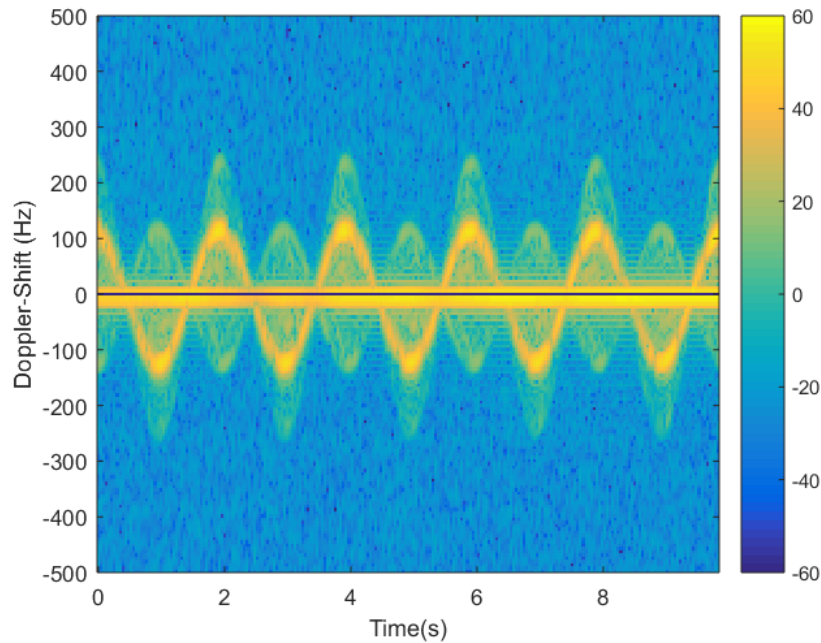


Figure 7.14: Pendulum swing in lab without foam

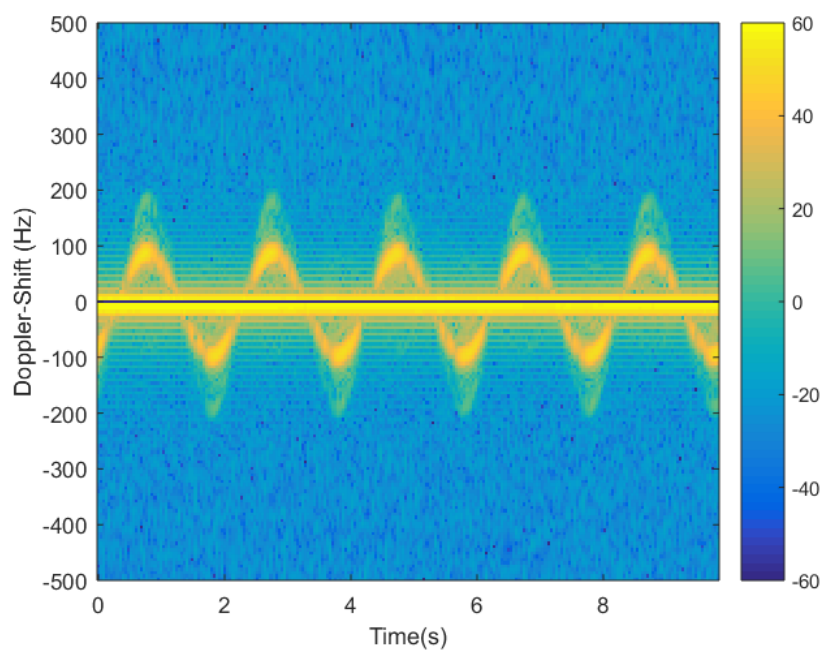


Figure 7.15: Pendulum swing in lab with foam

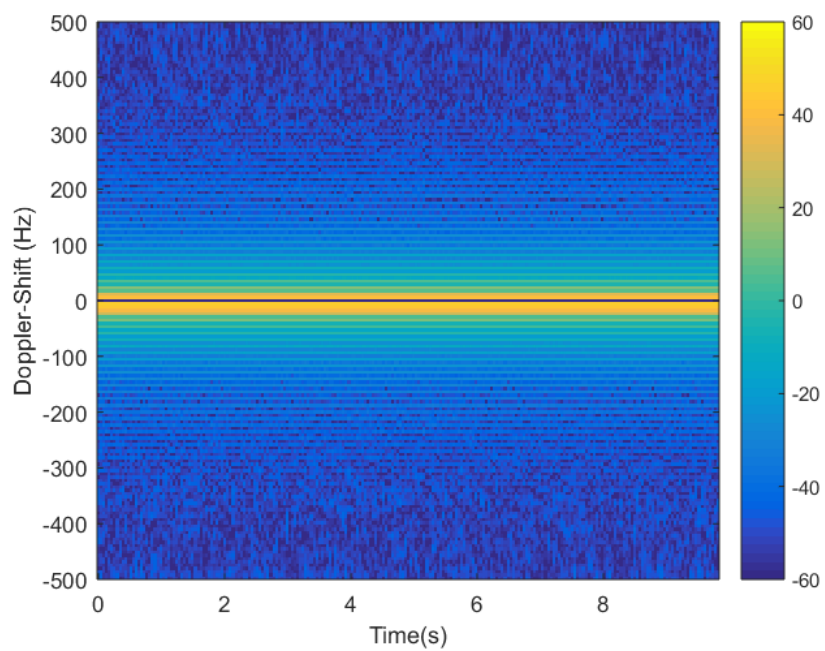


Figure 7.16: Stationary Pendulum

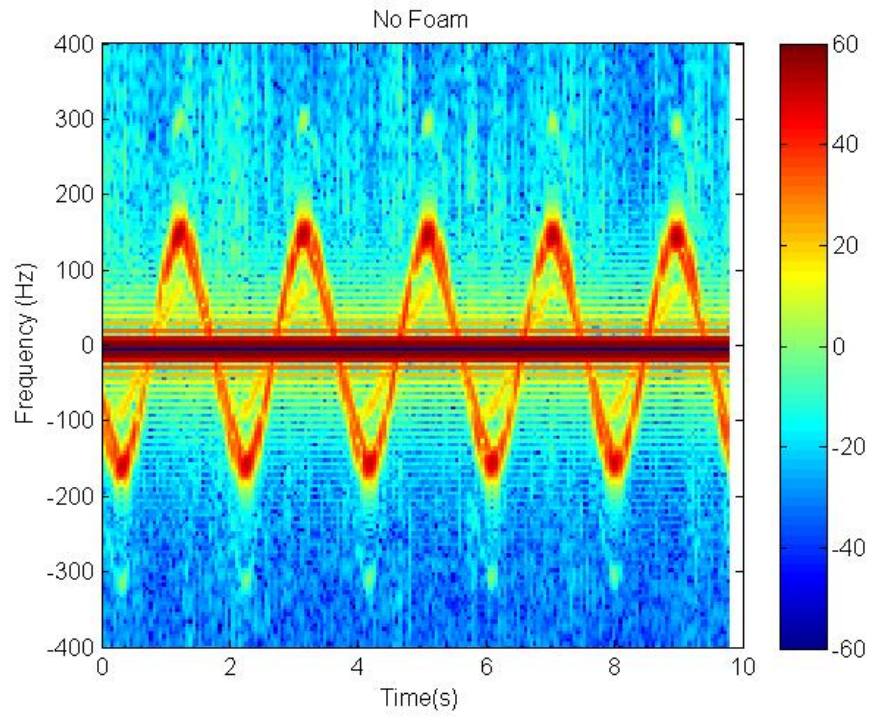


Figure 7.17: Pendulum swing in Anechoid Chamber without foam

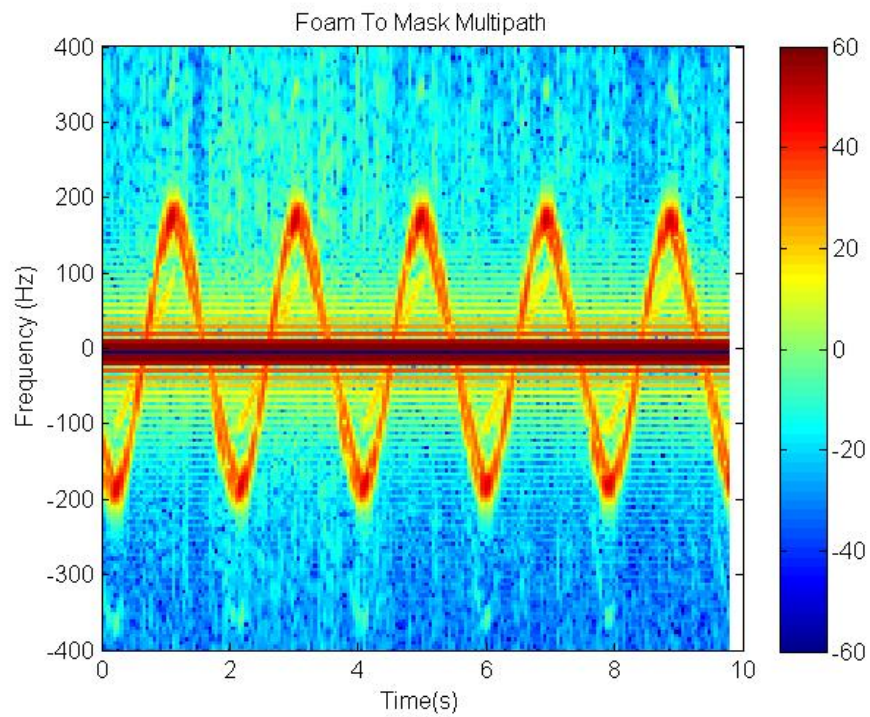


Figure 7.18: Pendulum swing in Anechoid Chamber with foam

8. Using Microprocessors to Make a Data Acquisition System

The UDS sensor system designed simplified the collection of data in houses and provided a portable equipment set for automatic data collection. However it still needed the use of a laptop to control the data acquisition hardware that provided the transmitting signal, and digitized the receiving signal before processing and saving into IQ format. The use of a microprocessor and ADC and DAC chips can simplify the design by eliminating the use of a laptop, making the device more portable, and reducing the cost of the sensor system.

The ADC and DAC chips would be interfaced with a capable processor using the SPI protocol, to digitize the received signal and to provide the transmitting signal. The processor chosen is the TI C6748, a fixed/floating point digital signal processor with a clock speed of 456 MHz. The DSP has two Serial Peripheral Interfaces that can be used for communication with the ADC and DAC, and an external memory interface to save data to an SD card. The TI OMAP-L138 development board which contains the C6748 processor was used to test the DSP because of the availability of drivers, software kits and algorithm libraries that will be needed for fast development. The Spectrum Digital XDS200 JTAG was the debug probe (emulator) used for debugging programs on the processor. Figure 8.1 shows the OMAP-L138 Development board with the XDS200 JTAG probe connected to it.

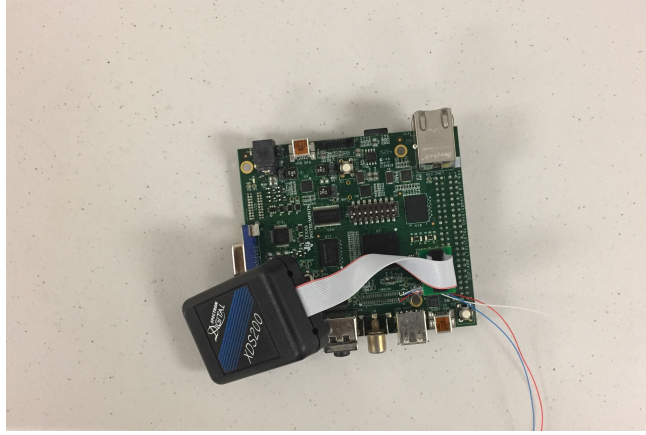


Figure 8.1: TI OMAP-L138 Development Kit(LCDK) with XDS200 JTAG

The TI Code Composer Studio IDE was used for developing programs for the C6748 DSP and then debugged using the XDS200 JTAG probe. The TI Real Time Operating System(RTOS) provided software libraries for selecting the timing parameters for ADC and DAC chips in sampling and generating signals. The test for generating signals with the C6748 processor was done with using the TI TLC5615 DAC chip, and the test for sampling signals was done with the TI TLC4541 DAC chip.

8.1 Test for Signal Generation

Signal generation using the C6748 processor was done by using the SPI protocol to communicate with the TI TLC5615 DAC chip. The TI TLC5615 is a 10-bit voltage output DAC with a buffered high input reference input, and has a settling time of $12.5 \mu s$ [13]. It uses a single 5 V supply, utilizes a 3 wire serial interface for communication, and has an output range of 0-5 V.

The OMAP-L138 Development board was used to provide the power supply and the reference voltage input to the DAC chip, and connections were made between the 3 wire serial interface terminals of the chip and that of the board. The C program to

produce a 1 kHz sine wave sampled at 50 kS/s is shown in Appendix A. The program starts by generating the 10 bit binary values for a single period of the sine wave. The SPI peripheral of the C6748 processor is then enabled and the timing parameters for sampling are set in the RTOS SDK. The bits are then transmitted using the 3 wire SPI connection from the board to the DAC chip and the output signal is shown on an oscilloscope. Figure 8.2 shows the output signal from the oscilloscope. The concepts in creating a 40 kHz wave will be similar but will require a higher resolution DAC chip with a much higher sampling rate capability.

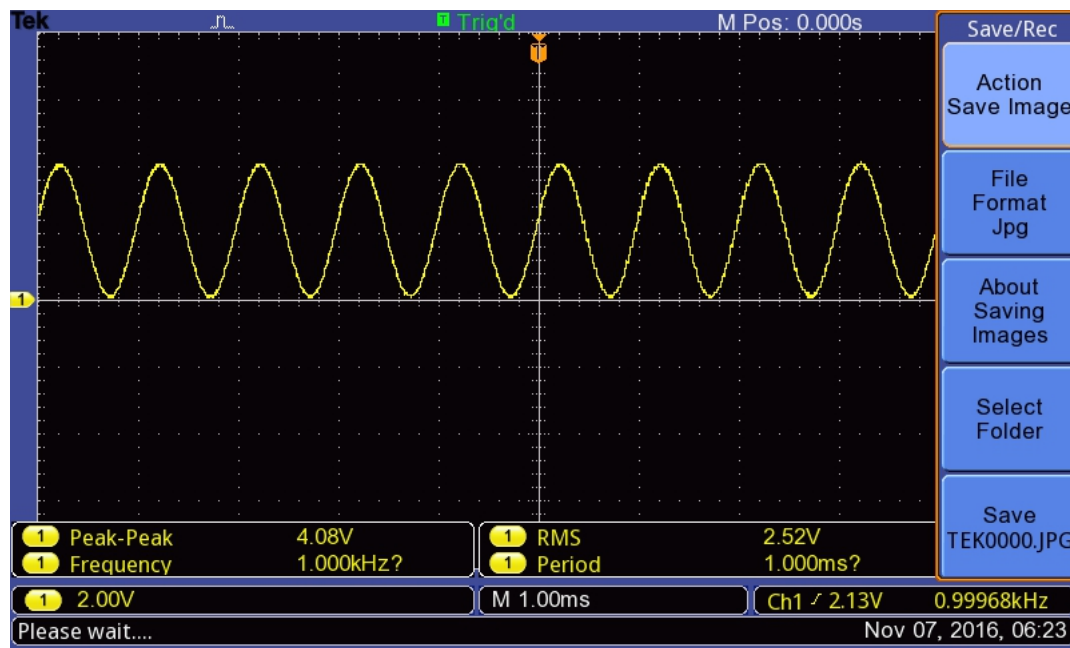


Figure 8.2: 1 kHz sine wave generated from TI C6748 and TLC5616 DAC

8.2 Test for Sampling signals

The TI TLC4541 ADC chip was used to test for the sampling of signal by interfacing it with the C6748 DSP on the TI OMAP-L138 Development Kit(LCDK). The TI TLC4541 is a low power 16 bit ADC with a sampling rate of up for 200 kS/s. It has an SPI/DSP serial interfaces with a serial clock speed of up to 15 MHz, and an optimized DSP interface [14]. The chip requires an input supply voltage and reference

input voltage of 5 V, and uses an in-built oscillator as the conversion clock with a $2.94 \mu\text{s}$ conversion time.

The 5 V supply on the OMAP-L138 board was used to provide the 5 V supply and input reference voltage to the ADC chip. The 4-wire Serial Peripheral Interface pins for the processor and the ADC chip were connected to each other using jumping wires. A 1 kHz sine wave generated using a function generator was sampled at 100 kS/s and the 16-bit numeric data was saved and collected from the chip memory. The C program for sampling the data is available in Appendix B. The program starts by enabling and initializing the SPI peripheral registers for communication with the chip. The TI RTOS Timer is used to set the timing periods for a 100 kS/s rate, which triggers the conversion process of a sample of data. The samples of data are saved in an 16-bit array and the data was then collected from chip memory through the TI Code Composer IDE Debug window. The plot of 1000 samples of the data collected is shown in figure 8.3. The same principle of operation will be used in sampling of signals from the transducer.

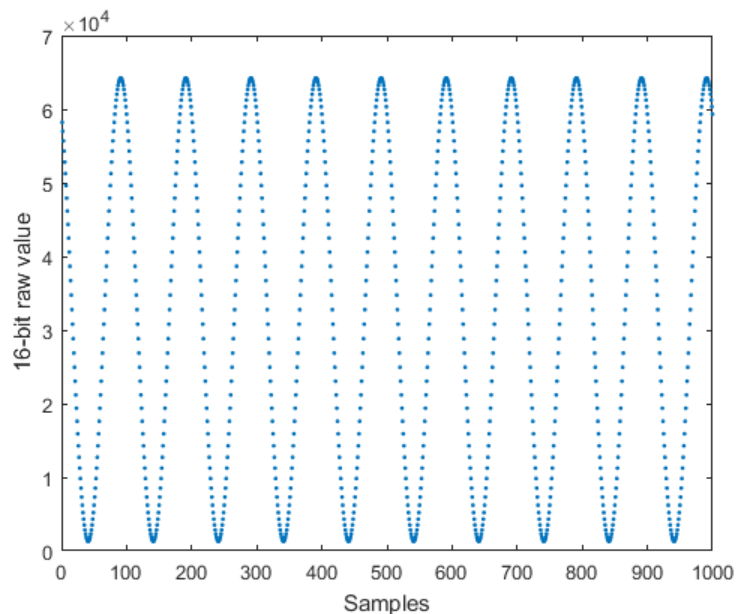


Figure 8.3: 1000 samples of 1 kHz sine wave sampled with TL4541 ADC

9. Conclusion and Future Work

The work shows the use of an Ultrasonic Doppler Sonar sensor system to analyze the Doppler signature of a human walk from which gait parameters can be extracted. The principles of the UDS were examined, and studied and a validation of the system was done by comparing it to results of a pulse-Doppler system using radars. The UDS sensor system can be used in monitoring the walks of people over time and using the gait features extracted for Fall Risk Assessment.

A portable sensor system that can automate data collection was also developed to ease the collection of data in a house without the need of a person to control the data acquisition process. The different Doppler features of a human walk were investigated and the effects they had on the gait parameters needed for analyzing human gait. The Doppler signature of the leg motion, which was the main focus of the walk signature could still be distinguished in the Doppler signature captured from the walk. The design of a low cost data acquisition system, with the use of custom ADC and DAC chips was tested with the use of C6748 DSP's to sample a test signal and also to generate a sinusoidal signal needed for the UDS sensor system.

Future work to do is to complete the design of the custom made data acquisition system using ADC and DAC chips with high enough sample rates to satisfy the UDS sensor requirements for generating a 40 kHz signal and sampling the reflected signals at 100 kS/s. The chips would then be fabricated on a Printed Circuit together with the amplifier circuit and the processor to be used. The use of a battery to power the system and development of a wireless system to send the data to a central server will be necessary for using it at homes. The new system would be cheaper in cost and

much smaller and shows promise in being a cost effective way of monitoring the gait of humans. Image processing techniques to extract the leg velocities and other gait features from the spectrogram plots will be necessary to monitor the gait features of subject with time.

10. Appendix

10.1 Appendix A

This is the code used for generating signal using the DAC chip.

```
/*
 * ===== main.c =====
 */
#include <xdc/std.h>
#include <xdc/runtime/System.h>
#include <ti/sysbios/BIOS.h>
#include <ti/sysbios/knl/Task.h>
#include <xdc/cfg/global.h>
#include <xdc/runtime/Timestamp.h>

#include <stdio.h>
#include <c6x.h>
#include <math.h>
#include <ti/csl/soc_C6748.h>
#include <ti/csl/cslr_spi.h>
#include <ti/csl/cslr_syscfg0_C6748.h>

#define PERIOD 50
#define PI 3.14159265358979323846
```

```

    Uint16 data[PERIOD];
    Uint16 buffer[PERIOD];

    void init_data(void);
    void init_SPI(void);
    void spi_pinmux_enable(void);
    void transmit_bits(void);

    CSL_SpiRegsOvly spi1_regs = (CSL_SpiRegsOvly)CSL_SPI_1_REGS;
    CSL_SyscfgRegsOvly syscfg0 = (CSL_SyscfgRegsOvly)CSL_SYSCFG_0_REGS;

    void main(void){
        init_data();
        init_SPI();
        BIOS_start();
    }

    void init_data(void){
        double sin_data[PERIOD];
        Uint8 index=0;
        double vref_x2 = 4.0;
        for (index=0; index<100 ; index++){
            sin_data[index] = 2 + 1.9*sin(2*PI*index/PERIOD);
        }
        for (index=0; index < 100 ; index++){
            data[index] = ((Uint16)(sin_data[index] * 1024 / vref_x2)) << 2 ;
        }
    }

```

```

void transmit_bits(void){
static Uint16 index = 0;

/*transmit the bits boom*/

CSL_FINS(spi1_regs->SPIDAT1, SPI_SPIDAT1_TXDATA, data[index]);

while (!CSL_FEXT(spi1_regs->SPIFLG, SPI_SPIFLG_TXINTFLG));

buffer[index] = 0x0000FFFF & spi1_regs->SPIBUF;
index++;

if (index >= PERIOD){
index=0;
}

}

void init_SPI(void){
spi_pinmux_enable();

/*Initialization of a 4 Pin SPI Master Mode according to 30.2.19 Tech Ref*/
CSL_FINST(spi1_regs->SPIGCR0, SPI_SPIGCR0_RESET, IN_RESET);

CSL_FINST(spi1_regs->SPIGCR0, SPI_SPIGCR0_RESET, OUT_OF_RESET);

CSL_FINST(spi1_regs->SPIGCR1, SPI_SPIGCR1_ENABLE, DISABLE);
CSL_FINST(spi1_regs->SPIGCR1, SPI_SPIGCR1_LOOPBACK, DISABLE);

```



```

CSL_FINST(spi1_regs->SPIGCR1, SPI_SPIGCR1_CLKMOD, INTERNAL);
CSL_FINST(spi1_regs->SPIGCR1, SPI_SPIGCR1_MASTER, MASTER);

CSL_FINST(spi1_regs->SPIPC0, SPI_SPIPC0_SOMIFUN, SPI);
CSL_FINST(spi1_regs->SPIPC0, SPI_SPIPC0_SIMOFUN, SPI);
CSL_FINST(spi1_regs->SPIPC0, SPI_SPIPC0_CLKFUN, SPI);
CSL_FINST(spi1_regs->SPIPC0, SPI_SPIPC0_ENAFUN, GPIO);
CSL_FINST(spi1_regs->SPIPC0, SPI_SPIPC0_SCSOFUN0, SPI);

CSL_FINST(spi1_regs->SPIPC1, SPI_SPIPC1_SOMIDIR, INPUT);
CSL_FINST(spi1_regs->SPIPC1, SPI_SPIPC1_SIMODIR, OUTPUT);
CSL_FINST(spi1_regs->SPIPC1, SPI_SPIPC1_CLKDIR, OUTPUT);
CSL_FINST(spi1_regs->SPIPC1, SPI_SPIPC1_SCSODIRO, OUTPUT);

CSL_FINST(spi1_regs->SPIDAT1, SPI_SPIDAT1_DFSEL, FORMAT1);
CSL_FINS(spi1_regs->SPIDAT1, SPI_SPIDAT1_CSNR, 0);
spi1_regs->SPIDEF = 0x000000FF;

CSL_FINS(spi1_regs->SPIFMT[1], SPI_SPIFMT_PRESCALE, 14u);
CSL_FINS(spi1_regs->SPIFMT[1], SPI_SPIFMT_CHARLEN, 16u);
CSL_FINST(spi1_regs->SPIFMT[1], SPI_SPIFMT_SHIFTDIR, MSB);
CSL_FINST(spi1_regs->SPIFMT[1], SPI_SPIFMT_PHASE, NO_DELAY);
CSL_FINST(spi1_regs->SPIFMT[1], SPI_SPIFMT_POLARITY, LOW );

CSL_FINS(spi1_regs->SPIDELAY, SPI_SPIDELAY_C2TDELAY, 1);
CSL_FINS(spi1_regs->SPIDELAY, SPI_SPIDELAY_T2CDELAY, 1);

//CSL_FINST(spi0_regs->SPIGCR1, SPI_SPIGCR1_LOOPBACK, ENABLE);

```

```

CSL_FINST(spi1_regs->SPIGCR1, SPI_SPIGCR1_ENABLE, ENABLE);

}

void spi_pinmux_enable(void){
/*Give CPU Priviledged Mode of Operation*/
syscfg0->KICK0R = 0x83E70B13;
syscfg0->KICK1R = 0x95A4F1E0;

/*Enable PINMUX for SPI Functional Pins*/
CSL_FINST(syscfg0->PINMUX5, SYSCFG_PINMUX5_PINMUX5_23_20, SPI1_SIM00);
CSL_FINST(syscfg0->PINMUX5, SYSCFG_PINMUX5_PINMUX5_19_16, SPI1_SOMIO);
CSL_FINST(syscfg0->PINMUX5, SYSCFG_PINMUX5_PINMUX5_11_8, SPI1_CLK);
CSL_FINST(syscfg0->PINMUX5, SYSCFG_PINMUX5_PINMUX5_7_4, NSPI1_SCS0);

}

```

10.2 Appendix B

This is the code used for sampling signals using the ADC chip.

```

/*
 * ===== main.c =====
 */
#include <xdc/std.h>
#include <xdc/runtime/System.h>
#include <ti/sysbios/BIOS.h>
#include <ti/sysbios/knl/Task.h>
#include <xdc/cfg/global.h>
#include <xdc/runtime/Timestamp.h>

```

```

#include <stdio.h>

#include <c6x.h>

#include <math.h>

#include <ti/csl/soc_C6748.h>

#include <ti/csl/cslr_spi.h>

#include <ti/csl/cslr_syscfg0_C6748.h>


#define SAMPLE_SIZE 1000

#define PI 3.14159265358979323846


void init_SPI(void);

void spi_pinmux_enable(void);

void init_ADC(void);

void get_bits(void);


Uint16 buffer[SAMPLE_SIZE];

Uint16 result;


CSL_SpiRegsOvly spi1_regs = (CSL_SpiRegsOvly)CSL_SPI_1_REGS;

CSL_SyscfgRegsOvly syscfg0 = (CSL_SyscfgRegsOvly)CSL_SYSCFG_0_REGS;


void main(void){

    init_SPI();

    init_ADC();

    BIOS_start();

}

```

```

void get_bits(void){

static Uint16 index = 0;

/*get the bits boom*/

CSL_FINS(spi1_regs->SPIDAT1, SPI_SPIDAT1_TXDATA, 0xABCD);

while (!CSL_FEXT(spi1_regs->SPIFLG, SPI_SPIFLG_TXINTFLG));

buffer[index] = 0x0000FFFF & spi1_regs->SPIBUF;
result = buffer[index];
index++;

if (index >= SAMPLE_SIZE){
index=0;
}

}

void init_SPI(void){
spi_pinmux_enable();

/*Initialization of a 4 Pin SPI Master Mode according to 30.2.19 Tech Ref*/
CSL_FINST(spi1_regs->SPIGCRO, SPI_SPIGCRO_RESET, IN_RESET);

CSL_FINST(spi1_regs->SPIGCRO, SPI_SPIGCRO_RESET, OUT_OF_RESET);

```

```

CSL_FINST(spi1_regs->SPIGCR1, SPI_SPIGCR1_ENABLE, DISABLE);
CSL_FINST(spi1_regs->SPIGCR1, SPI_SPIGCR1_LOOPBACK, DISABLE);
CSL_FINST(spi1_regs->SPIGCR1, SPI_SPIGCR1_CLKMOD, INTERNAL);
CSL_FINST(spi1_regs->SPIGCR1, SPI_SPIGCR1_MASTER, MASTER);

CSL_FINST(spi1_regs->SPIPC0, SPI_SPIPC0_SOMIFUN, SPI);
CSL_FINST(spi1_regs->SPIPC0, SPI_SPIPC0_SIMOFUN, SPI);
CSL_FINST(spi1_regs->SPIPC0, SPI_SPIPC0_CLKFUN, SPI);
CSL_FINST(spi1_regs->SPIPC0, SPI_SPIPC0_ENAFUN, GPIO);
CSL_FINST(spi1_regs->SPIPC0, SPI_SPIPC0_SCSOFUN0, SPI);

    /*
CSL_FINST(spi1_regs->SPIPC1, SPI_SPIPC1_SOMIDIR, INPUT);
CSL_FINST(spi1_regs->SPIPC1, SPI_SPIPC1_SIMODIR, OUTPUT);
CSL_FINST(spi1_regs->SPIPC1, SPI_SPIPC1_CLKDIR, OUTPUT);
CSL_FINST(spi1_regs->SPIPC1, SPI_SPIPC1_SCSODIRO, OUTPUT);

    */
CSL_FINST(spi1_regs->SPIDAT1, SPI_SPIDAT1_DFSEL, FORMAT1);
CSL_FINS(spi1_regs->SPIDAT1, SPI_SPIDAT1_CSNR, 0);
spi1_regs->SPIDEF = 0x000000FF;

CSL_FINS(spi1_regs->SPIFMT[1], SPI_SPIFMT_PRESCALE, 14u);
CSL_FINS(spi1_regs->SPIFMT[1], SPI_SPIFMT_CHARLEN, 16u);
CSL_FINST(spi1_regs->SPIFMT[1], SPI_SPIFMT_SHIFTDIR, MSB);
CSL_FINST(spi1_regs->SPIFMT[1], SPI_SPIFMT_PHASE, NO_DELAY);
CSL_FINST(spi1_regs->SPIFMT[1], SPI_SPIFMT_POLARITY, LOW );

CSL_FINS(spi1_regs->SPIFMT[0], SPI_SPIFMT_PRESCALE, 14u);

```

```

CSL_FINS(spi1_regs->SPIFMT[0], SPI_SPIFMT_CHARLEN, 4u);
CSL_FINST(spi1_regs->SPIFMT[0], SPI_SPIFMT_SHIFTDIR, MSB);
CSL_FINST(spi1_regs->SPIFMT[0], SPI_SPIFMT_PHASE, NO_DELAY);
CSL_FINST(spi1_regs->SPIFMT[0], SPI_SPIFMT_POLARITY, LOW );

CSL_FINS(spi1_regs->SPIDELAY, SPI_SPIDELAY_C2TDELAY, 1u);
CSL_FINS(spi1_regs->SPIDELAY, SPI_SPIDELAY_T2CDELAY, 100u);

//CSL_FINST(spi0_regs->SPIGCR1, SPI_SPIGCR1_LOOPBACK, ENABLE);
CSL_FINST(spi1_regs->SPIGCR1, SPI_SPIGCR1_ENABLE, ENABLE);

}

void spi_pinmux_enable(void){

/*Give CPU Priviledged Mode of Operation*/
syscfg0->KICK0R = 0x83E70B13;
syscfg0->KICK1R = 0x95A4F1E0;

/*Enable PINMUX for SPI Functional Pins*/
CSL_FINST(syscfg0->PINMUX5, SYSCFG_PINMUX5_PINMUX5_23_20, SPI1_SIMO0);
CSL_FINST(syscfg0->PINMUX5, SYSCFG_PINMUX5_PINMUX5_19_16, SPI1_SOMIO);
CSL_FINST(syscfg0->PINMUX5, SYSCFG_PINMUX5_PINMUX5_11_8, SPI1_CLK);
CSL_FINST(syscfg0->PINMUX5, SYSCFG_PINMUX5_PINMUX5_7_4, NSPI1_SCS0);

}

void init_ADC(void){

```

```
CSL_FINST(spi1_regs->SPIDAT1, SPI_SPIDAT1_DFSEL, FORMAT0);
CSL_FINS(spi1_regs->SPIDAT1, SPI_SPIDAT1_TXDATA, 10u);
while (!CSL_FEXT(spi1_regs->SPIFLG, SPI_SPIFLG_TXINTFLG));
CSL_FINST(spi1_regs->SPIDAT1, SPI_SPIDAT1_DFSEL, FORMAT1);
}
```

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