Contents

Abbreviations

Notation	Description
CT	Computed Tomography
DC	Direct Current
LOW-RES	Low Resolution
MRI	Magnetic Resonance Imaging
US	Ultrasound

Glossary

Notation	Description
adiabatic	Any process that happens without heat gain or loss is considered adiabatic
Doppler effect	A change in frequency of a wave in relation to an observer who is moving relative to the wave source

Reading comprehension

This section of the report will explain to the reader how to reference this document and explain the fundamental structure of the project as well as the report. Throughout the report, the reader will be assumed to be knowledgeable of basic circuit analysis and familiar with standard abbreviations typically used in electrical engineering. If not, readers can refer to the denotation section at the beginning of the report. It is assumed that the reader has a basic knowledge on the science of electrical engineering, physics, and circuit analysis.

Please refer to Acronyms, Glossary, and Nomenclature pages for explanations to terms found within the report.

Furthermore, as a notation convention, large-signal DC quantities are denoted by uppercase letters with uppercase subscripts. Small-signal quantities are denoted using lowercase letters with lowercase subscripts. Quantities composed of both large-signal and small-signal elements are denoted using lowercase letters and uppercase subscripts.

Sources

Calculus expressions present in the report will typically have a reference explaining their origin. All references are prominently displayed with square brackets and a number, directing to the appendix in the last section of the report.

Chapters

The report is divided into five chapters, where the first part is an introduction to the project. The second chapter will focus on explaining the theory of the topic of the project. The third chapter focuses on the synthesis of a system for experimental testing. The fourth chapter explains the production of the hardware. The fifth chapter will explain the testing methodology performed on the hardware. Finally, additional documentation of testing, code, circuit diagrams, and of laboratory setups can be found in the appendix.

1 Introduction

The progress of diagnostic imaging has advanced significantly during the 20th century. As the cost of high speed computational systems has grown increasingly accessible, so has the use of of medical imaging become prominent. Potentially millions of people have been spared painful exploratory surgery through noninvasive diagnostic imaging. And thus, lives can be saved by early diagnosis and intervention through medical imaging. Advancement in scientific visualization have in turn generated more complex datasets of increased size and quality. Four major technologies used are ultrasound, X-ray, Computed Tomography (CT), and Magnetic Resonance Imaging (MRI). Each of the technologies have distinct advantages and disadvantages in biomedical imaging, thus each are still relevant for modern medicine. Table 1.2 contains a comparison and summary of the various fundamental diagnostic imaging modalities.

Modality	**Ultrasound**	**X-ray**	**CT**	**MRI**
Topic	Longitudinal, shear, mechanical properties	Mean X-ray tissue absorbtion	Local tissue X-ray absorbtion	Biochemistry (*T1* and *T2*)
Access	Small windows adequate	2 sides needed	Circumferential around body	Circumferential around body
Spatial resolution	Frequency and axially dependent, $0.2\,\mathrm{mm}$ to $3\,\mathrm{mm}$	$\sim 1\,\mathrm{mm}$	$\sim 1\,\mathrm{mm}$	$\sim 1\,\mathrm{mm}$
Penetration	Frequency dependent, $3\,\mathrm{cm}$ to $25\,\mathrm{cm}$	Excellent	Excellent	Excellent
Safety	Excellent for $>$ 50 years	Ionizing radiation	Ionizing radiation	Very good
Speed	Real-time	Minutes	20 minutes	Typical: 45 minutes, fastest: Real-time (LOW-RES)
Cost	$	$	$$	$$$
Portability	Excellent	Good	Poor	Poor
Volume coverage	Real-time 3D volumes, improving	2D	Large 3D volume	Large 3D volume
Contrast	Increasing (shear)	Limited	Limited	Slightly flexible
Intervention	Real-time 3D increasing	No, fluoroscopy limited	No	Yes, limited
Functional	Functional ultrasound	No	No	fMRI

Table 1.2: Comparison of Imaging Modalities [7]

Since medical imaging has been reportedly performed over 5 billion times as of 2004 [3], and later numbers from 2011 show a general doubling, and particularly a ten-fold increase

in ultrasound examinations between year 2000 and 2011 [7]. Recent data reveals that this trend of doubling has continued through the years 2010 to 2020 [11], and reveals that even though patient processes were disrupted during the global SARS-CoV-2 pandemic, the number of medical imaging examinations per 1000 patients, still increased. The reasons for this, and particularly why ultrasound has been notably increased in use, can be attributed to its high, but inconsistent, resolution, cost effectiveness, portability, and real-time interventional imaging. The downside of ultrasound is its limited penetration and restrictions for use in certain body parts. When just comparing soft-tissue examinations, which ultrasound is limited to, both CT and MRI can image the entire body with consistent resolution and contrast, but are more expensive and has poor portability due to immense size of its hardware.

The cardiovascular system, which transports oxygen and nutrients to tissue, produces a complex flow pattern that cause velocity fluctuations. Several cardiovascular diseases are also known to cause abnormal blood flow. As mentioned earlier, ultrasound is a powerful tool for conducting non-invasive imaging of the cardiovascular system [4], [6], and has no adverse risk to patients. Determining Power Spectral Density (PSD) of a received signal is a common way to estimate blood velocity. A processed image of the PSD over time is commonly known as a sonogram, where changes in blood velocity over time can be seen.

1.1 Project scope

The aim of this project is to study the application of ultrasound in the context of blood flow measurements. Various scientific articles have been studied to gain knowledge of prior research [1], [2], [5], [8]–[10]. The desire is to build upon the vast knowledge already gathered by prominent researchers in the field of ultrasound systems for blood velocity estimation. Finally, using the knowledge gained, to design and implement a device capable of performing these measurements using a novel approach.

1.1.1 Learning objectives

See below for an outline of the project activities

Project specification
Learn a class-D amplifier topology, calculate component values
Understand and design a self-oscillating modulator amplifier
Investigate and test open loop output filter
Investigate and test closed loop output filter
Investigate output filter parasitic elements affects control loop
Make quantifiable performance measurements on system
Write a technical report documenting the project work

Table 1.3: Project specification table

2 Theory

2.1 Acoustical properties of ultrasound

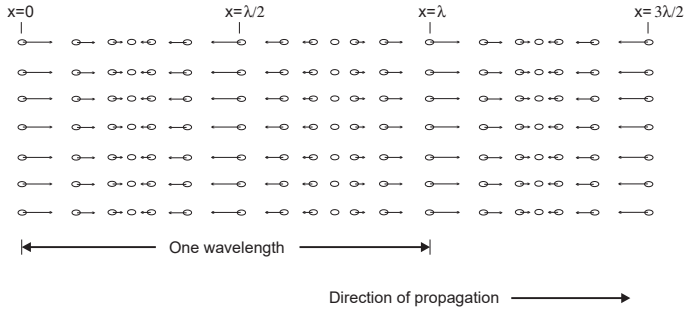

Figure 2.1: Particle displacement for a propagating ultrasound wave [6]

Ultrasound is a technology that transmit sound wave with frequencies above the audible range (20 to $20\,000\,\mathrm{Hz}$) to mechanically vibrate matter. The particles in the medium would be at rest and distributed uniformly before any disturbance. The wave propagates as a disturbance and the particles oscillate around their mean position due to the presence of the ultrasonic wave. Typically the US frequency band used in clinical settings are from 2 to $12\,\mathrm{MHz}$. Figure 2.1 visualizes the propagation of a plane wave in matter. The oscillation occurs parallel to the wave's direction, making it longitudinal, and the disturbance will propagate with the variable c, which is determined by the medium and is given by eq. (2.1).

$$c = \sqrt{\frac{1}{\rho_0 \kappa_S}} \tag{2.1}$$

Where ρ_0 is the mean density ($\mathrm{kg\,m^{-3}}$) and κ_S is the adiabatic compressibility ($\mathrm{m^2\,N^{-1}}$). Since in the majority of cases, the propagation of ultrasound is linear, it is assumed in this work.

The acoustic pressure of the harmonic plane wave is expressed by eq. (2.2)

$$p(t,z) = p_0 e^{j(\omega t - kz)} \tag{2.2}$$

And propagates along the z-axis. ω is the angular frequency, k is the wave number and is expressed by $k = \omega/c = 2\pi/\lambda$, and $_0$ is the acoustic pressure amplitude. A spherical wave is expressed by eq. (2.3)

$$p(t,r) = p_0 e^{j(\omega t - kr)} \tag{2.3}$$

Where r is radial distance, and is defined in a polar coordinate system. For each time instance, the acoustic pressure $p(t,r)$ is constant over a fixed radial position. In this scenario, the pressure amplitude is given by $p_0(r) = k_p/r$, where k_p is a constant since the energy of the outgoing wave must be constant. Particle speed u is dependent on the pressure caused by a wave expressed by eq. (2.4)

$$u = \frac{p}{Z} \tag{2.4}$$

Where Z is the characteristic acoustic impedance, defined as the ratio of acoustic pressure to particle speed at a given position in the medium and is expressed by eq. (2.5).

$$Z = \rho_0 c \tag{2.5}$$

Characteristic acoustic impedance Z is one of the most significant variables in the characterization of propagating plane waves. Reference values for density, speed of sound, and characteristic acoustic impedance can be seen in table 2.2.

Medium	**Density** $\mathrm{kg/m^3}$	**Speed of sound** $\mathrm{m/s}$	**Characteristic acoustic impedance** $\mathrm{kg/(m^2\,s)}$
Air	1.2	333	0.4×10^3
Blood	1.06×10^3	1566	1.66×10^6
Bone	1.38–1.81×10^3	2070–5350	3.75–7.38×10^6
Brain	1.03×10^3	1505–1612	1.55–1.66×10^6
Fat	0.92×10^3	1446	1.33×10^6
Kidney	1.04×10^3	1567	1.62×10^6
Lung	0.4×10^3	650	0.26×10^6
Liver	1.06×10^3	1566	1.66×10^6
Muscle	1.07×10^3	1542–1626	1.65–1.74×10^6
Spleen	1.06×10^3	1566	1.66×10^6
Distilled water	1×10^3	1480	1.48×10^6

Table 2.2: Approximate density, sound speed, and acoustic impedance of human tissue types [6]

In the following sections, various acoustic wave phenomena will be briefly described.

2.1.1 Scattering

A wave propagating across a medium continues in the same direction until it encounters a new medium. When this occurs, a portion of the wave is transmitted into the new medium, with a change in direction. Because the scattered wave is the result of several contributors, it is necessary to define it statistically. The amplitude distribution is Gaussian [6] and can thus be fully described by its mean and variance. The mean value is zero because the dispersed signal is caused by variances of the acoustic characteristics in tissue.

The correlation between multiple data is what allows ultrasound to determine blood velocities. Because minor movements have a significant correlation, it is feasible to discover alterations in location by comparing sequential measurements of moving structure, such as blood cells. In medical ultrasound, just one transducer is utilised for transmitting and receiving, and only the backscattered signal is analysed.

The power of scattered signal is defined by the scattering cross-section, which in small cases mean a uniform intensity I_i, and is expressed by eq. (2.6).

$$P_s = I_i \sigma_{sc} \tag{2.6}$$

Where σ_{sc} is the scattering cross-section.

2.1.2 Attenuation

2.1.3 Transducer

A layperson knows transducers as speakers and microphones in the context of PA systems. In the case of medical ultrasound it is the device that generates the acoustic pressure field, which is emitted into tissue. The transducer has a piezoelectric crystal inside the housing. When excited, this crystal emits ultrasound waves toward flowing blood. The red blood cells will

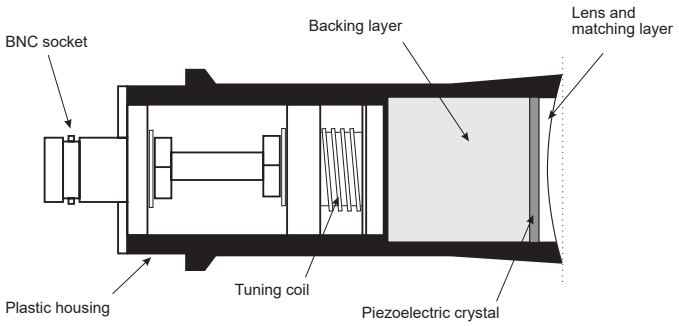

Figure 2.2: Single element ultrasound transducer construction [6]

reflect a fraction of the emitted waves. These reflected waves are of a different frequency than the transmitted wave. If the red blod cells are moving away from the transducer, the frequency will be lower. If the red blod cells are moving towards the transducer, the frequency will be higher. This is caused by the Doppler effect. The reflected ultrasonic waves return to the crystal and are converted back into electrical signals. The single element transducer shown in fig. 2.2 has a minimal imaging window and has to be mechanically manipulated to get a wide window, which is unfeasible for responsive high-frequency imaging. Thus, usually an array transducer is used. Various ultrasound transducer types exist with different strengths and weaknesses, shown in fig. 2.3.

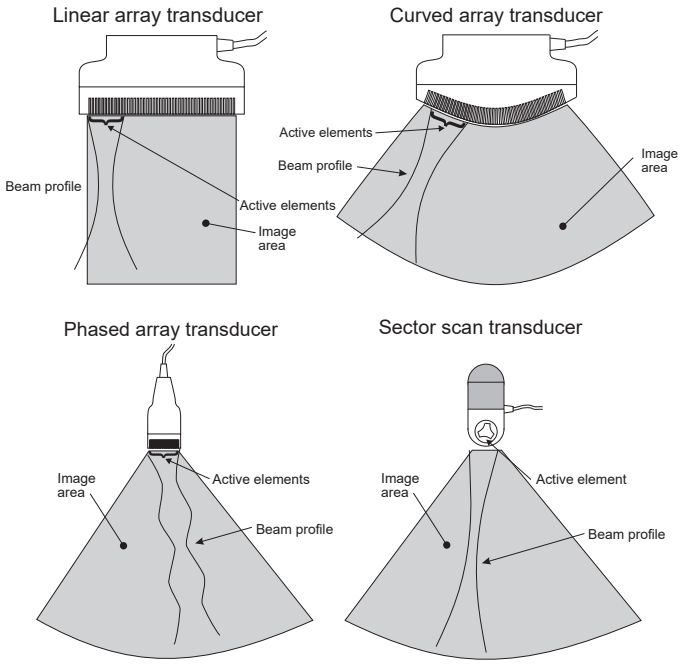

Figure 2.3: Single element ultrasound transducer construction [6]

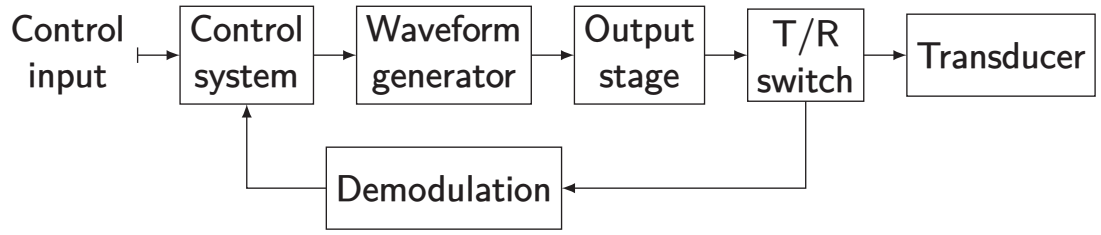

Figure 2.4: Simple overview of the system

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