EXPERIMENTAL STUDY OF MICROWAVE-INDUCED THERMOACOUSTIC IMAGING

by

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B.S., University of Colorado Denver, 2011

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirements for the degree of
Master of Science
Electrical Engineering
2016
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April 29, 2016
ABSTRACT

Microwave-Induced Thermoacoustic Imaging (TAI) is a noninvasive hybrid modality which improves contrast by using thermoelastic wave generation induced by microwave absorption. Ultrasonography is widely used in medical practice as a low-cost alternative and supplement to magnetic resonance imaging (MRI). Although ultrasonography has relatively high image resolution (depending on the ultrasonic wavelength at diagnostic frequencies), it suffers from low image contrast of soft tissues. In this work samples are irradiated with sub-microsecond electromagnetic pulses inducing acoustic waves in the sample that are then detected with an unfocused transducer. The advantage of this hybrid modality is the ability to take advantage of the microwave absorption coefficients which provide high contrast in tissue samples. This in combination with the superior spatial resolution of ultrasound waves is important to providing a low-cost alternative to MRI and early breast cancer detection methods. This work describes the implementation of a thermoacoustic experiment using a 5 kW peak power microwave source.

The form and content of this abstract are approved. I recommend its publication.

Approved: Mark Golkowski
DEDICATION

I dedicate this thesis to my family and to my son Jose.
ACKNOWLEDGMENT

This work would have not been possible without support from the following senior design and Undergraduate Research Opportunity Program (UROP) team members Linh Vu, Sultan Allabbas, and Abdulkarim Alhassoun. In addition to the senior design team this project could have not been completed without the support and guidance of my advisors Dr. Mark Golkowski and Dr. Yiming Deng. For simulation work and experimental assistance I am indebted to Xiaoye Chen and Mohand Alzuhiri. For design guidance and fabrication of the experimental setup I thank the Calibration Lab staff which include Tom Thuis, Jaq Corless, Randy Ray, Deven Eldridge, Eric Losty, Khyrsten Tatum and Rich Wojcik. The project received support and funding from CU Denver Faculty Development Grants and the donation of a high power microwave source form Super Pulse in addition to UROP funding.
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1. Introduction

Most imaging technologies, whether used for bio-medical applications or non-destructive evaluations, use only one source of energy to send and receive signals that are then processed for image reconstruction. For example, ultrasound imaging involves radiated pulses of acoustic waves and reception of the echoes or reflections of the acoustic waves. This method provides high resolution results in real time but is limited by the contrast for materials with similar acoustic properties. Another example is microwave imaging, currently an area of ongoing research for early breast cancer detection. Microwave imaging usually operates in the hundreds of megahertz to low gigahertz frequencies and as a result suffers from the poor resolution due to the long (several cm) wavelengths at these frequencies. To overcome the limitations of each of these individual methods so called hybrid imaging can be employed. By combining different imaging modalities it is possible to exploit the strengths of each individual imaging modality while avoiding its respective weakness. An example of hybrid imaging is photo-acoustic imaging. By using a short high powered laser pulse it is possible to generate acoustic waves that are detectable by ultrasound transducers to produce an image \[5\]. While photo-acoustics has been studied in the past thermoacoustic imaging has received less attention. Unlike photo-acoustic imaging which used electromagnetic radiation in the optical band thermoacoustic imaging uses electromagnetic radiation in the microwave band, the low gigahertz range. We next describe each of the components in more detail.

1.1 Ultrasound Imaging

Ultrasound imaging is a fast and cost effective imaging technique widely used in medical applications. This imaging modality is based on the fact that different materials will have different acoustic reflection coefficients. Phased arrays of transducers allow for the forming of a narrow beam. Transducers are used for transmitting and receiving pulses of acoustic waves. The received waves are then processed and recon
structured into an image. Ultrasound Imaging offers sub-millimeter resolution since it operates in the high megahertz (typically from 1 to 5 MHz) but suffers from poor contrast from materials having very similar acoustic properties as is common for many types of soft tissue (fat, muscle, etc.). However, ultrasound imaging provides results in real time, uses non-ionizing radiation and is relatively inexpensive.

1.2 Microwave Imaging

Microwave imaging is a fast, non-ionizing high contrast imaging technique. Here microwaves usually in the high megahertz to low gigahertz range are used to characterize and image samples. With different materials absorbing and diffracting differently it is possible to observe how the microwaves scatter to determine the makeup of a sample. This method has received much attention in the area of early breast cancer detection due to its ability to provide high contrast images with non-ionizing radiation. Unlike acoustic waves, microwaves experience significantly different prop-
agation properties in soft tissues and these differences are the basis of the improved contrast. However, the shortcoming of microwave imaging is that at these frequencies the multi-centimeter wavelength results in poor spatial resolution.

1.3 Hybrid Imaging

Hybrid Imaging is the combining of two or more imaging techniques. The goal of combining modalities is to exploit the strengths of each one while minimizing the weaknesses. An example of such a technique that we have already mentioned is photo-acoustic imaging. Here a short powerful laser pulse is used to create thermal expansion. This then generates pressure waves that can be detected by transducers.

1.4 Thermoacoustic Imaging

Thermoacoustic Imaging (TAI) leverages the high contrast capabilities of microwave imaging and the high resolution of the ultrasound imaging. By combining these two imaging modalities it is possible to exploit the strength of each modality in a single hybrid modality. This technique relies on sub-microsecond pulses of high power microwaves. These short, high power microwave pulses cause the target to very quickly heat up and then cool down. This quick heating and cooling causes the target
Figure 1.3: Diagram of how a photoacoustic imaging system works.\cite{3}

to expand and contract. It is the expanding and contracting of the target that generates the acoustic waves. The frequency of the ultrasound waves created is directly proportional to the inverse of the pulse width of the microwaves. Depending on how much microwave energy is absorbed into the target (and different parts of the target may absorb different amounts of microwave energy) will determine the amplitude of the acoustic wave. TAI can easily be applied to medical applications such as early breast cancer detection or tumor detection but also to Non-Destructive Evaluation (NDE) for cement structures to image defects or for locating metal objects inside the structure. A coupling medium is critical for the acoustic waves to get from the target to the ultrasound transducer. A block diagram of a TAI experimental setup can be seen in Figure \ref{fig:TAIsetup}.

1.5 Past Work on Thermoacoustic Imaging

One of the first publications showing significant imaging capability using the TAI technique was the work by Kruger in 1999\cite{9}. A kidney was successfully imaged in this work. However, the Kruger study used a 25 kW power microwave source and has not been replicated in any subsequent work. Another publication showing the effects of the contrast with different dielectric mediums was done by Xu in 2005\cite{8}.
A thin wire was embedded into a tissue sample. The study was successful in creating an image which showed the location of the thin wire within the sample by using a 20 kW microwave power source. Finally, a paper presented by Mashal in 2009 uses microbubbles to determine the effect of microbubbles on the contrast for TAI. This paper does not report 2D data (or images of the samples) but does show 1D data of the amplitude of the acoustic waves generated based on the concentration of microbubbles in the solution, in this work a 30 kW microwave power source was used.

1.6 Thesis Scope

The primary focus of this thesis is the construction of a novel experimental setup and the subsequent test results. The theory of TAI is discussed in Chapter 2. Chapter 3 describes the hardware setup and design of the experiment. Chapter 4 presents the data from the experimental tests and finally Chapter 5 is the conclusion and summary.
2. Theory

In the TAI hybrid imaging technique high power pulsed microwaves are used as the generating source. The generated signals are acoustic signals that are received and interrogated for imaging. Since microwaves absorption depends on several factors (such as conductivity and relative permeability) different strength acoustic signals are generated based on the thermal expansion and contraction properties of various targets. With acoustic waves being the received signal, a higher resolution (based on the diffraction limit) is possible that what traditional microwave imaging can provide. The diffraction limit of traditional microwave imaging (2.45 GHz assumed) is 6.11 cm verses the diffraction limit of ultrasound (2 MHz assumed) which is 0.5 mm.

2.1 Electromagnetic Waves

This experiment uses an electromagnetic (EM) frequency of 2.4 GHz. Figure 2.1 shows how the EM spectrum is divided. The 2.4 GHz frequency is chosen for several reasons. First it allows the EM waves to have greater penetration into the target to allow for deeper imaging of targets. Second, the 2.4 GHz is in the ISM (Industrial, Scientific and Medical) band. This band is unlicensed and can be freely used as long as the power radiated into the environment does not exceed 30 dBm (or 1 W). Third, technology for 2.4 GHz is mature, readily available, and inexpensive.

![Electromagnetic Spectrum](image)

Figure 2.1: Electromagnetic Spectrum
All EM waves and their interactions in free space or in a dielectric medium are governed by Maxwell’s equations

\[
\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} - \vec{M} \quad \text{Faraday’s Law} \tag{2.1}
\]

\[
\frac{\partial \vec{D}}{\partial t} = \nabla \times \vec{H} - \vec{J} \quad \text{Ampere’s Law} \tag{2.2}
\]

\[
\nabla \cdot \vec{D} = \rho \quad \text{Gauss’s Law for Electric Fields} \tag{2.3}
\]

\[
\nabla \cdot \vec{B} = \rho^* \quad \text{Gauss’s Law for Magnetic Fields} \tag{2.4}
\]

with definitions

\[
\nabla \cdot \vec{J} = -\frac{\partial}{\partial t} \rho \quad \text{Continuity Equation for Electric Fields} \tag{2.5}
\]

\[
\nabla \cdot \vec{M} = -\frac{\partial}{\partial t} \rho^* \quad \text{Continuity Equation for Magnetic Fields} \tag{2.6}
\]

where

- \( \vec{B} \): Magnetic flux density \((WB/m^2)\)
- \( \vec{D} \): Electric flux density \((C/m^2)\)
- \( \vec{E} \): Electric field intensity \((V/m)\)
- \( \vec{H} \): Magnetic field intensity \((A/m)\)
- \( \vec{J} \): Electric current density \((A/m^2)\)
- \( \vec{M} \): Magnetic current density \((V/m^2)\)
- \( \rho \): Electric charge density \((C/m^3)\)
- \( \rho^* \): Magnetic charge density \((Wb/m^3)\)
In a lossy medium defined by conductivity $\sigma$ and relative index of refraction $\epsilon_r$, the attenuation rate and propagation number can be calculated as follows:

$$\alpha = \frac{\omega \sqrt{\mu_0 \epsilon_r \epsilon_0}}{\sqrt{2}} \left[ 1 + \left( \frac{\sigma}{\omega \epsilon_r \epsilon_0} \right)^2 - 1 \right]^\frac{1}{2}$$

(2.7)

$$\beta = \frac{\omega \sqrt{\mu_0 \epsilon_r \epsilon_0}}{\sqrt{2}} \left[ 1 + \left( \frac{\sigma}{\omega \epsilon_r \epsilon_0} \right)^2 + 1 \right]^\frac{1}{2}$$

(2.8)

where

$\alpha$: Attenuation constant

$\beta$: Phase constant

$\omega$: Angular frequency

$\epsilon_r$: Relative permittivity

$\epsilon_r$: Permittivity of free space

$\sigma$: Conductivity

Snells law shows the relationship between the angles of incidence and refraction for a wave traveling from one medium to another for electromagnetic and acoustic waves. Equation 2.9 shows Snell’s law and Figure 2.2 shows the geometric context.

$$\frac{\sin(\theta_1)}{c_1} = \frac{\sin(\theta_2)}{c_2}$$

(2.9)

By using Snell’s it is possible to express the amplitudes for the reflected and transmitted waves for the reflection coefficient and the transmission coefficient [6]. For electromagnetic waves, the reflection and transmitted coefficients depend on the po-
The materials used in the construction of the experiment where chosen very carefully to maximize the amount of electromagnetic power that is transferred into the target chamber and to minimize reflections. The acrylic tank and the safflower oil have both been chosen because they both have a relative permittivity that closely matches that of air and should appear transparent to the microwaves at the frequencies of interest. Figure 2.3 shows the $S_{11}$ (or the reflection coefficient; $\Gamma$) of the system with and without a sample.
2.2 Acoustic Waves

Acoustic waves are mechanical pressure waves. Unlike electromagnetic waves which do not require a medium for propagation acoustic waves do require the interaction of molecules in a medium through pressure. The medium can be anything from a gas to a solid. The velocity at which the acoustic waves propagate depends on the particle displacement, particle velocity, pressure and temperature. Acoustic waves are all governed by the acoustic wave equation

\[
\left( \frac{1}{c_0^2} \frac{\partial^2}{\partial t^2} - \nabla^2 \right) p_a = 0 \quad (2.11)
\]

where

- \( p_a \): Acoustic pressure
- \( c_0 \): Speed of sound

Acoustic waves can be classified into the following categories shown in Figure 2.4. The range of interest for this experiment is from 1 to 5 MHz. This would falls in between sonochemistry and the diagnostic ultrasound range.
Like with all waves, acoustic waves will reflect or refract. The amount the wave reflects depends on the characteristic acoustic impedance. This characteristic impedance is related to the pressure and particle velocity of the wave\[4\]. The greater the difference between the characteristic impedance of the mediums the larger the reflection will be and subsequently the smaller the transmission will be: $T = 1 - \Gamma$.

The refraction of the acoustic wave is based on Snell’s law \[7\] which is shown in Equation \(2.9\). Similarly to EM waves these equations apply at the boundaries of the medium, any place that the characteristic impedance is changing.

The high resolution of ultrasound imaging comes from the short wavelength of the acoustic waves. This diffraction limit is equal to half of the wavelength. The wavelength of the ultrasound can be calculated by using Equation \(2.12\)

$$\lambda = \frac{c}{f}$$  \hspace{1cm} (2.12)

where

$\lambda$: Wavelength

c: Speed of sound in the medium

$f$: Frequency

This then gives a diffraction limit of 0.5 mm with a 2 MHz ultrasound signal assumed.
2.3 Theory Behind Thermoacoustic Imaging

TAI is based on the interaction of microwaves and acoustic waves in the target medium. Microwaves deposit energy into the target in the form of heat. The deposited heat leads to thermal expansion and generation of acoustic waves. The incident microwave pulse width is inversely proportional to the acoustic frequency that is generated during microwave absorption. For example, a 1 µs pulse will generate a 1 MHz acoustic wave. Targets that have distinct permittivity and electrical conductivity (such as tumors) will generate significantly different TAI signals based on the microwave absorption which was shown in Equation 2.7 which is used to calculate the skin depth $\delta = 1/\alpha$. By using a radiation frequency of 2.45 GHz it is possible to achieve deeper penetration into the sample. Since the acoustic waves or ultrasound signals are the received signals and have a lower velocity compared to that of electromagnetic waves giving a much shorter wavelength this allows for greater resolution. This short wavelength is the limiting factor of what can be imaged and is the primary advantage of using this hybrid imaging technique.

2.3.1 The Thermal Elastic Equation

The driving equation for TAI is shown in Equation 2.13

$$\nabla p(r,t) - \frac{\partial^2}{\partial t^2} p(r,t) = -\beta_c \rho \frac{\partial^2}{\partial t^2} T(r,t)$$  \hspace{1cm} (2.13)

$$\Delta T = \frac{SAR \times \tau}{C_p}$$  \hspace{1cm} (2.14)

$$SAR = \frac{\sigma |E|^2}{2\rho}$$  \hspace{1cm} (2.15)

where

$p$: Acoustic pressure at location $r$ and time $t$

c: Speed of sound in medium
\[ \beta: \text{Volume expansion coefficient} \]

\[ \rho: \text{Mass density} \]

\[ T: \text{Temperature rise of the sample from microwave absorption} \]

\[ \tau: \text{Microwave pulse length} \]

\[ SAR: \text{Specific absorption rate} \]

\[ C_p: \text{Specific heat} \]

\[ \sigma: \text{Effective electrical conductivity} \]

Starting with Equation 2.15 it is seen that the higher the conductivity of the sample the more microwave absorption will occur. This microwave absorption will then directly cause an increase in the temperature (Equation 2.14) of the sample under test. The faster the microwave energy is deposited into the sample the sharper the temperature gradient will be when it heats and cools. This change in temperature \((\Delta T)\) is then related to the change in pressure. It is important to note that while a high value of \(\sigma\) results in large absorption, it can also lead to reflection from the target surface, preventing EM energy from entering the target. Practically there is an optimum value of \(\sigma\) for a given permittivity of a target. If a large amount of microwave energy is deposited onto the sample with a sub-microsecond pulse this will cause the sample to expand and contract due to the change in temperature is directly proportional to the change of pressure in the sample. It is this expanding and contracting on a sub-microsecond time scale that generates acoustic waves in the diagnostic region of the acoustic wave spectrum. This then indicates that the faster the microwave energy is deposited the higher the acoustic waves will be. For example, a 1 \(\mu s\) pulse will generate an acoustic wave of \(\approx 1\) MHz.

\[
 f_{\text{acoustic}} \simeq \frac{1}{\text{PulseWidth}} \tag{2.16}
\]

This inverse relationship, shown in Equation 2.16, between the microwave pulse and the acoustic frequency is used to determine the appropriate center frequency for the
ultrasound transducer.
3. Experimental Setup

The experimental setup has gone through several iterations and consists of the following components:

- Acrylic Tank
- Safflower Oil
- Microwave Shielding
- High Power Pulsed Microwave Source Epsco PG5KB
- Olympus Ultrasound Transducer v306
- Olympus Pulse/Receiver 5800
- R&S RTO 1014
- Open Ended Waveguide WR340
- 2D Scanner

3.1 Tank Design

3.1.1 Commercially Available Tank

The tank that holds the oil and the targets under test is constructed out of acrylic also referred to as Plexiglas. Acrylic was chosen because it is readily available and more importantly due to its electrical properties in the microwave band. Acrylic appears mostly transparent to microwave frequencies around 2.4 GHz with $\epsilon_r \approx 3$ thereby minimizing reflections and absorption of the microwave energy. For this reason it has also been used by other researchers in TAI experiments [1]. However, it is difficult to find tanks under 15 gallons made out of acrylic. The first tank that was used to run experiments was a commercially available 15 gallon tank. The tank fit the targets well but required a large amount of oil to fully submerge targets based upon the
size of the waveguide and/or antenna that was being used. Another issue was that the transducer needed to be perfectly normal to the target and this proved difficult since the experiment was designed to suspend targets in the path of the microwaves with little flexibility in orientation. The commercial tank brought challenges to proper alignment between the target and the transducer. This misalignment between the target and the transducer always had to be adjusted so that the transducer was able to detect the maximum amount of signal that was generated by the target. Additionally, to shielding such a large volume proved to be difficult since the target always had to be suspended in the oil.

3.1.2 Custom Designed Tank

To overcome the obstacles associated with the commercially available tank and to ensure repeatable experiments, a custom designed tank was built. The new tank is roughly 3.4 gallons measuring 10” × 10” × 10” with about 3/8” thick acrylic walls. This tank was not designed to hold a target vertical but rather to have the target lay horizontally, at the bottom. This made it possible to have microwaves radiate from
the bottom of the tank and not the side which was the case with the commercially available tank. By doing this we are able to eliminate the need for holding the target and can take advantage of gravity to help orient the transducer normal to the sample under test. It is critical to have the acoustic sensor orthogonal to the sample to ensure that the maximum amount of signal is coupled to the transducer. As shown Figure 3.2 the new tank design used laser cut acrylic sheets that went together like puzzle pieces. This increased the amount of surface area of where the tank would be glued together, increasing the strength of the tank ensures that it will be able to hold the needed amount of liquid. Once all of the acrylic pieces had been cut they were then glued together with a acrylic cement glue. With the construction of the tank complete it was then necessary to test the tank to verify that it can hold liquid without any leaks. This step did require some re-gluing of the joints on the tank but was ultimately successful. This design had the advantage of using less oil to run experiments lowering the cost compared to the commercial tank.

Figure 3.2: Custom Designed Acrylic Tank

3.2 Safflower Oil

For the best results possible a contact transducer would be needed to avoid attenuation/reflections with the signal propagating across different mediums. While this
is good from a theoretical standpoint, it doesn’t lend itself very easily to practical implementation when testing a diverse set of targets. Also, a contact transducer will provide a different set of challenges such as dealing with interference from radiation coupling. With this in mind an alternative is to use a submersible transducer for acquiring the acoustic signals. This provides minimal performance degradation due to attenuation and reflection. While any liquid medium should work for acoustic coupling, the medium’s electromagnetic properties have to be matched to the microwaves to minimize reflection and absorption. For example, water while a cost effective medium, has absorption characteristics that are unsuitable to efficient microwave propagation. We would essentially be heating up the water and not creating the required temperature gradient in the target needed for thermoelastic expansion. We needed a liquid that would appear as transparent as possible to the microwaves in terms of its index of refraction. This leaves only a few options, most of which are oil based. We opted to go with safflower oil since it is a close match to that of the acrylic and will minimize reflections. Another reason is that it has been used in other published works[1].

3.3 Shielding

Since the hybrid imaging system uses high power pulsed microwaves to generate sharp temperature gradients for thermoelastic expansion, shielding becomes a concern. The experiment uses a 5 kW peak power supply at 2.45 GHz. This can cause interference with WIFI signals, Bluetooth signals and other infrastructure that is operating in the 2.4 GHz ISM band. Not only is it interference between radiated signals, the high power microwaves also couple into the transducer adding noise to the signal that is difficult to remove in post processing. If not properly shielded the high power microwaves can cause damage to the equipment around the experiment, this includes the ultrasound pulser/receiver, computer and even cell phones. To minimize leakage into the environment, steps were taken to absorb and isolate microwave power. The
first attempt was to use aluminum foil and wrap it around the 15 gallon tank. This worked but only to a point. Lacking sophisticated measurement equipment it was not possible to measure the amount of isolation that the aluminum foil provided but microwave safety sensors where used to measure what the FDA’s maximum allowed leakage from a commercially available microwave oven, which is 5 mW/cm$^2$. These sensors (one with an analog readout and one with a digital readout) where used to quantify if the leakage was within acceptable limits. We quickly found that the leakage greatly exceeded the allowable limits. This led to the use of microwave absorbent foam that was placed around the tank as well as construction of a rigid aluminum casing that went around the microwave absorbent foam and the 15 gallon acrylic tank. The casing is made out of 0.125” thick aluminum plates that have been welded together, this design provided rigid shielding with less holes and gaps then what the foil was able to provide. The microwave leakage was once more tested and was found to be within acceptable limits. However, it was observed that the Wi-Fi inside the lab would no longer function while the microwaves were being pulsed, indicating that there was still a non-negligible amount of RF leakage. Since this shielding proved to be the most effective at keeping interference to a minimum the same shielding techniques where used on the second revision of the setup. For the second revision shielding the acrylic tank was surrounded by microwave absorbent foam which was then encased with 0.125” thick aluminum plates. The top of the tank does not have the microwave absorbent foam but does have an aluminum sheet covering the top. This is the greatest cause of reflections in the setup. The 2D scanner and the ultrasound transducer are all enclosed within the shielding. This design has proven to no longer interfere with signals in the ISM band.

3.4 Microwave Power Supply

TAI requires a fast temperature change for acoustic signals to be generated. It is this quick thermal expansion and contraction that will create the acoustic wave.
The amplitude of the acoustic wave is determined by how much energy is absorbed into the material. The more energy that is absorbed the larger the acoustic wave amplitude. The experiment was conducted with two different power supplies. The first one is a 2 kW peak power supply that uses a magnetron, therefore fixing its frequency at 2.45 GHz. The power supply also has an adjustable repetition rate and the minimum pulse width is 1 $\mu$s which should generate an ultrasound signal around 1 MHz.

![Image](image.png)

Figure 3.3: Power supplies used for experimental testing.

The second power supply that was used is a 5 kW peak power supply, Epsco PG5KB. This power supply has an adjustable frequency output from 2.4 to 4.45 GHz, an adjustable repetition rate and a minimum pulse length of 0.3 $\mu$s. By having a shorter pulse length we are able to deposit the microwave energy into the sample in a shorter amount of time. This then provides a higher frequency acoustic wave to be generated. Also when testing and measuring the power supply it is found that by shortening the pulse to less than 0.3 $\mu$s this also decreases the peak power as detected by a crystal detector and observed on an oscilloscope. This decrease in power could be a limitation of the crystal detector. The detector may not be fast enough to capture
Figure 3.4: Typical pulse width used for running experiments from the Epsico 5kW power supply.

the full amplitude of the pulse. Alternatively, if the power supply can not supply a pulse that fast and if the pulse is degraded less microwave energy will be transmitted.

3.5 Acoustic Measurements

To generate and receive acoustic signals an Opcard (which is a PCIe integrated ultrasound card for the computer) and/or an Olympus P/R 5800 (standalone acoustic amplifier with filtering) were used. The goal of this pulse-echo mode operation was to validate the predicted time for TAI signals. After that data was collected the pulser/receiver was changed to receive mode to record the thermoacoustic signal. This is discussed later on in Section 3.5.4.

3.5.1 Opcard

After using the Opcard for all of the experiments before the major system redesign the Opcard was damaged due to a short on the FPGA that made the card non-functional. Before this happened the noise floor of the Opcard was measured and found to be high and it is believed that this is the cause of not being able to detect a TAI signal despite the large amount of averaging that was done. Although the averaging did help to lower the noise of the system overall, it was only able to resolve periodic system noise from the computer or from the card itself. The source of the noise was never determined.
3.5.2 Olympus P/R 5800

The Olympus P/R 5800 provides filtering and amplification for the acoustic signals that have been detected by the transducer. This conditions the signal to to be digitized by using a high speed digital oscilloscope (R&S RTO 1014) to save the data for post processing. The Olympus P/R 5800 allows for selection for the gain and for the pole settings for the high pass and low pass filters. At this point it had already been determined that the experiment would benefit from the use of an acoustic amplifier. This amplifier was custom designed to fit this particular application and it was also cheaper to manufacture and build than it was to order a ready product from a vendor. The amplifier is detailed in Section 3.6.

3.5.3 Ultrasound Transducers

For this experimental study two different types of transducers where used. The first one is a submersible(immersion) transducer which must be placed in a liquid medium. This is the transducer type that a bulk of the experimental tests where
done with. The liquid provides the coupling that is needed from the sample to the piezoelectric elements inside the transducer. The transducer is a videoscan series with an nominal element size of 13 mm and a center frequency of 2.25 MHz. We also have another submersible transducer with identical specifications with the exception of the center frequency. The second submersible transducer has a center frequency of 1 MHz. This transducer was mainly used in the validation of the experimental measurement process. However, there is no reason that this sensor could not be used to acquire TAI data. The second one is a contact transducer. The contact transducer does require a coupling medium to work properly. Typically this medium is a gel that provides the coupling between the sample and the piezoelectric elements with in the transducer. This sensor has a center frequency of 1 MHz.

3.5.4 Acoustic Measurement Validation

To eliminate any possibility that the system was acquiring data incorrectly, it was necessary to validate the measurement technique by using acoustic measurements of known values. This measurement was conducted in the first version of the experimental setup so it includes reflections from shielding elements that were not included in the second iteration of the setup. A schmatic is shown in the appendix. Both
the 1 MHz and the 2.25 MHz submersible transducers where used in the validation measurements. The two sensors where placed at the same distance above the bottom of the tank, they had to be vertically aligned. To ensure that the maximum amount of the signal is coupled into the receiving transducer the sensors also had to be horizontally aligned. Two identical pulser/receivers (P/R) where used, one in pulse/echo mode (Tx mode) and the other in receiving mode (Rx mode) only. The expected outcome for this test would be that the simulated target transducer would send out a signal in p/e mode while the receiving transducer would just record signals. The time difference would be calculated to prove that using p/e mode before running a thermoacoustic test was a valid way to estimate the location (in time) of the thermoacoustic signal generated by the target.
3.6 Noise Issues and Solutions

This section discusses the signal to noise (SNR) issues that have been encountered and the solutions that were implemented to overcome them. Since the experiment has gone through two iterations over which the recording of the analog output from the P/R has changed, some of the issues are no longer valid but are still discussed for completeness.

3.6.1 Low Noise Amplifier Design

Since this experiment is exploring the lower bounds of how much microwave energy is needed to generate a TAI signal, the generated signals are expected to be close to the noise floor of the system. The first thing that was needed is a measurement of the noise floor on the instruments that are being used to acquire the TAI signals. By doing this we can then design a low noise amplifier to bring the signal out of the noise before it is digitized and further processed. The design requirements were determined as follows: 50 Ω output impedance to minimize reflections on the coaxial cable, an amplification bandwidth of 1 to 5 MHz minimum (this covers the range of the bandwidth on the transducers available to us), 1 nV/√Hz to stay below the noise of the acquisition system. The low noise amplifier (LNA) had to use a bipolar design since the TAI signal was centered around zero going both positive and negative. This LNA was realized with a three stage gain amplifier. The first stage is the noise critical stage since it will separate the signal from the noise. This stage has to have the lowest noise input noise while provide significant amount of gain. The second stage provides the most gain, this is done so that less averaging could be performed and faster data collection could be achieved. The third stage is an output buffer stage to provide the needed current to drive the TAI signal to the P/R. The schematic of the proposed amplifier is shown in Figure [A.1] This schematic shows all three gain
Figure 3.9: Pre-Amp simulation results from MultiSim

stages as well as the passive filtering. Before the LNA was built it was necessary to simulate the design to ensure proper performance. The simulations used Multisim from National Instruments (NI). This software package provides models from all the major IC vendors. The simulation is where the gain was optimized and AC coupling issues were sorted out. Using the actual parts files supplied by the manufacture in the simulation improved accuracy. As seen from Figure 3.9 the simulation bandwidth is achieved. With the simulation verifying the design the amplifier was manufactured. While opamps are readily available and inexpensive, each gain stage does provide a certain amount of voltage offset and input bias current that if not taken into account will have a significant effect on the performance of the LNA. To compensate for the voltage offset introduced by each opamp stage, it is necessary to AC couple each of the opamp stages together. This forces the offset to be centered on 0 V. The drawback to AC coupling each stage is that the input bias current needed by each opamp must then be considered. For example, opamps with higher output current capabilities were chosen or alternatively JFET input opamps were chosen for their low
input bias currents. To measure the bandwidth of the amplifier a calibrated vector network analyzer (VNA) was used. Figure 3.10 shows that the LNA provides the needed bandwidth for the TAI signal. Next, the noise floor of the LNA was measured using a spectrum analyzer (SA) and found to be $0.9 \text{nV}/\sqrt{\text{Hz}}$. With the bandwidth and the noise floor requirement achieved, the next step was to test it in the system. The same setup that verified the data acquisition was used to test the LNA. This is because signals of known amplitude that are easily controlled are needed to properly test the LNA. Figure 3.12 shows the acoustic test data with and without the LNA. This test setup was an exact copy of the setup show in Figure 3.8. The test was then repeated in the new setup shown in 3.11 just for verification purposes.

### 3.7 Microwave Coupling

With the first power supply that was used, it was found that the microwaves that were being generated by the magnetron were coupling into the transducer. For the safety of the transducer and for the fidelity of the measurement several different methods where tested to eliminate the coupling.
Figure 3.11: Setup for acoustic preamp testing.

Figure 3.12: Pre-Amp acoustic test to verify the amplifiers response and ability to properly amplify acoustic signals
3.7.1 Transducer Shielding

The first attempt to shield out the microwaves from the transducer was based on simple Faraday cage. The idea here is that if the microwave energy could not reach the sensor then it can’t be coupled into the signal. The first Faraday cage that was tested was a copper pipe that fit snugly over the sensor. This was difficult because the sensor had to be electrically isolated from the copper pipe. To allow the acoustic waves to pass, a metal strainer that is commonly found on drains and faucets was used. The issue with this approach is that it was very difficult to get the copper pipe and the sensor properly aligned (pointing normal) to the target and therefor the design was changed. The second design that was tested included making the Faraday cage much larger. A larger cage made it easier to design an apparatus that could hold the sensor normal to the wall of the tank. This approach was initially thought to be successful. For this Faraday cage design a galvanized steel mesh with a spacing of 0.25 inches was used to allow the acoustic signals to pass through. Since this wire mesh was much further away from the transducer it is clearly identifiable when using pulse/echo mode, this would have also effected the acoustic signals generated by the target. However, after building several different Faraday cages it was found that this method also had flaws. The energy from the microwaves was still getting into the signal. The next attempt was to shield the actual coaxial cable with a steel mesh that was grounded, this didn’t have any effect on the microwave interference.

3.7.2 Time Domain Subtraction

Since the microwave coupling could not be removed by using a Faraday cage, we then tried to subtract the microwave pulse out of the target data. This was done by turning on the microwaves without a target in the tank and recording the signal. Next a target was placed inside the tank and the experiment was run. Once the data was collected the data without a target was subtracted from the data with the target. By doing this the hope is that the pulse from the microwaves would be completely
or mostly removed. However, when the data was subtracted the pulse still remained. Unfortunately, the pulse from the microwaves was not consistent enough for time domain subtraction to be effective.

### 3.7.3 Filtering

With the Faraday cage and time domain subtraction proving not to be viable options, post processing the data with filters was tried. This was to mostly filter out any noise or frequencies that where not anticipated. The filtering worked to smooth out the noise but had little to no effect on the microwave pulse that is being coupled into the sensor.

### 3.8 Antenna System Matching Measurements

To measure the impedance match to the system from the waveguide a network analyzer was used to measure the $S_{11}$ from the waveguide. Figure 3.13 shows the results of the measurement. Two different measurements were conducted. The first one was without a tissue sample in the tank, the second was with a typical tissue sample in the tank. Without the sample in the tank the $S_{11}$ goes as low as about -13 dB but with the sample in the tank the $S_{11}$ increases so that the lowest is at about -7 dB.

### 3.9 2D Scanner

To move the sensor within the custom designed tank in the second revision of the experiment, a custom designed and fabricated 2D scanner was built and integrated with the setup.

#### 3.9.1 2D Scanner Design

This scanner moves in the $x$ and $y$–axis. The movement is achieved with stepper motors. A custom designed circuit board, schematic shown in the appendix, was made to control the stepper motors. The main idea behind the circuit board is that it would receive commands from a computer and then translate those commands to
the stepper motor IC. This makes the 2D scanner a versatile tool and lends itself to being controlled quickly and easily using Python or MATLAB. The board registers as a virtual com port which simplifies design and computer interfacing. One full revolution of the stepper motor is equivalent to 1 mm in distance. A single step of the stepper motor is equivalent to 7.5 degrees and with the stepper IC quarter and sixteenth size steps which will provide sub-millimeter resolution for the sensor placement. Edge detection switches are placed around the sensor to ensure that it will stay within the boundaries of the acrylic tank. Figure 3.14 shows the whole design and modeling for the scanner. The model was created to machine the needed parts for the scanner. Also custom C code was written for the micro-controller.

3.9.2 2D Scanner Fabrication

The scanner was built using as many off-the-shelf components as possible. However, due to its unique design requirements many parts still had to be custom built. The main frame, slide rails and rail mounts were purchased. The motor mounts, platforms and sensor mounts were custom made. The sensor is held inside an acrylic tube to cause as little interference with the microwaves as possible. The custom made parts are all machine milled out of aluminum.
3.9.3 2D Scanner Testing

The scanner is able to move with an accuracy of 1 mm or less depending on the step size chosen for the experiment. The smaller the step size the greater the error in the positioning the sensor back to the starting location. The design goal of the scanner was to have accuracy to be less than a cm and with fine tuning sub-millimeter accuracy could be achieved.
4. Experimental Results

All TAI experiments herein were preceded by a pulse/echo mode data collection used to estimate the expected arrival time for the TAI signal. This procedure allowed for narrowing the time span to be sampled and analyzed for TAI signals. The pulser/receiver is subsequently changed to receive only mode and the power supply high voltage is enabled and increased to the desired power level. For all reported experimental test runs the length of the power supply pulse and the power of the pulsed microwaves is fixed and not changed. In the case where 1D data is reported an arbitrary location close to the center of the target is chosen and remained fixed at that location for the duration of the experiment. In the case where a line scan (or 2D data) is acquired the transducer was moved from edge to edge of the open ended waveguide. The transducer was positioned to be in the center of the target. The following summarizes the experiment conditions:

- Microwave Peak power: 4.5 kW
- Microwave Pulse Width: 0.5 µs
- Transducer $f_c=2.25$ MHz
- Olympus P/R 5800 Gain 60 dB
- Olympus P/R 5800 LPF: 3 MHz
- Olympus P/R 5800 HPF: 300 KHz
- 45 equally spaced points for the line scan
- Number of Averages: 1024
4.1 Preliminary Data Results

The first successful TAI signal that was taken is shown in Figure 4.1. The top plot is the pulse/echo mode signals from the target. The signal takes $40\mu s$ to make the round trip to the target at back to the transducer again. We are then able to estimate that if the target was to generate its own acoustic signal that it would take $20\mu s$ to reach the transducer. When the Olympus pulser/receiver is externally triggered in receive mode, it outputs a pulse to indicate the $t = 0$ reference for the subsequent signal reception. Unfortunately, it was found that due to the large size of the reference pulse, the recovery time of the receiver is on the order of $25\mu s$. During the recovery time, the signal is offset from the zero value and any observations made during this time are subject to corruption. One solution is to record this without the microwaves on when there is no TAI signal and to use this as a calibration curve for future single processing based on subtraction. Once this calibration curve is recorded the microwaves are turned on and the TAI signal is recorded as seen in the second plot. The calibration curve in red and the TAI signal in blue. By subtracting the calibration curve from the TAI signal it is much easier to see the acoustic signals generated by the microwave pulses this is shown in the last plot of Figure 4.1. The first signal that is detected occurs at $20\mu s$, this is from the tissue sample that was placed inside the tank. The signals that occur at $32\mu s$ are believed to come from the tank itself since this signal lines up very well with what is shown in the pulse/echo mode data.

4.2 Verification of TAI Data

With signals successfully being generated, the next step was to verify that the signals were TAI signals and not noise. To do this two different samples with two different thicknesses where used. The time of arrival should be different for the two targets of different thickness. The results from this test are shown in Figure 4.2. The top plot is the pulse/echo mode data. This clearly shows that the two targets have a
different thickness. Sample 1 is shown to have a pulse/echo mode arrival time of 50µs and sample 2 has an arrival time of 44µs. This means that the TAI signal should be seen at about 25.38µs and 21.96µs respectively. The bottom plot shows the TAI signals generated by the two different targets and that that time of arrival is where the signals were expected. By measuring the sample thickness before the test and calculating that difference between the two samples to be 0.6 cm we are able to do a calculation to measure the sample thickness.

\[ V_{oil}(t_{Sample1} - t_{Sample2}) = D \]  \hspace{1cm} (4.1)

where

- \( V_{oil} \) is the velocity of sound in Safflower Oil
- \( t_{Sample1} \) is the arrival time for Sample1
- \( t_{Sample2} \) is the arrival time for Sample2
- D is the calculated difference in thickness between the two samples
In this case $V_{oil} \approx 2000\,m/s$ by substituting in the values we find that the calculated thickness is 0.684 cm.

The next test that was done to verify the data was to implant a material with significantly different conductivity than that of the surrounding tissue sample. A metal wire was chosen to be inserted into the tissue sample. Two different scans where done first without the wire and then with the wire. We expect there to be a significant difference in the TAI signal with the wire vs without the wire. The reason for the change is because the metal wire will not absorb the microwave energy and lead to generation of a smaller acoustic signal. The data from this experiment can be seen in Figure 4.3. The top plot is the pulse/echo data. This plot clearly shows the difference between with and without the wire. The acoustic reflection from the tissue sample surface is at $20\,\mu s$ and the wire is clearly seen about $9\,\mu s$ after the tissue sample surface ($29\,\mu s$). We then expect the TAI signal to be seen at $10\,\mu s$. The bottom plot shows the TAI results from the experiment. The red trace is the sample only (no wire) and the blue is with the wire. There is a clear difference between the two
Figure 4.3: Contrast Test With and Without Wire In Sample

4.3 Thermocoustic Line Scan Data

Figure 4.4 shows a line scan with a wire embedded into the sample. In the line scan the wire can be clearly seen in pulse/echo mode. The line scan was done with 45 discrete steps equal distance apart. At the end of the line scan the transducer was positioned back to its original location. Once the microwaves where turned on the TAI scan was started with same parameters and settings as the pulse/echo mode line scan. In the pulse/echo mode scan the surface is seen first followed by the acoustic reflections from the wire. With the microwaves turned on and since the wire has a very high conductivity, it will not absorb any of the microwave radiation. This will cause a dark spot directly behind the metal wire. This dark spot can be seen in the TAI line scan. Also it is interesting to point out that the curve or shape of the surface of the sample in the pulse/echo mode scan is highly correlated to what is shown as the surface of the TAI scan.
The next test that we ran was the one to verify the highly conductive materials will not produce a strong TAI signal. To do this a tissue sample was soaked in saltwater so that the conductivity of the meat would go up without significantly affecting its acoustic properties. This highly conducted tissue sample was then embedded into another tissue sample that has similar conductivity as the previous TAI experimental runs. Figure 4.5 shows the results of the experimental run. The pulse/echo mode data from the scan is highly irregular and difficult to identify an outline of any sample. However, the TAI line scan clearly shows that the outline of the regular tissue sample and then where the high conductivity sample is there is very weak to no TAI signals being generated. This indicates that TAI is an effective method of improving contrast in soft tissue detection which shows little contrast for a purely acoustic technique. Early breast cancer detection is an example application where soft tissue contrast is important.

A main drawback to using lower power pulsed microwaves is that the generated acoustic signals are very close to the noise floor of the system. To overcome this and provide stronger signals the pre-amplifier described in Section 3.6.1 was tested to determine its effectiveness. Figure 4.6 shows the experimental setup and the data.
Figure 4.5: Line scan showing pulse/echo mode and TAI mode line scans with similar tissue samples with different conductivity with and without the preamp. For this experiment test a tissue sample was placed into the tank. A line scan was performed over the sample. The data that was acquired without using the preamp, shown in Figure 4.6b. The boundary of the sample can be seen but it is close to the noise that is also detected. The next scan made use of the preamp in Figure 4.6c. Here, the boundary of the sample is clearly defined and separated from the noise of the system. However, it was discovered that the preamp does need to be shielded from outside interference. There is EMI from the power supply that the preamp is coupling in and amplifying. This noise is most likely due to the triggering of the power supply and poor quality coaxial cables that were used since the noise source is only at the being of the data acquisition and not throughout. With a proper case for the preamp this interfering noise will be kept to a minimum.
Figure 4.6: Plot a compares the line data with and without a preamp. Plot b shows a line scan of the target with no additional amplification. Plot c shows a repeated line scan over the same section with the addition of the preamp.
5. Conclusion

This thesis describes an experimental setup and design for TAI and investigates the opportunities and challenges of this hybrid imaging modality. TAI show much promise as a good alternative to both microwave imaging and ultrasound imaging for early breast cancer detection, tumor detection/localization, as well as NDE for cement structures. Since this imaging modality uses microwaves which is a non-ionizing radiation it has no harmful long term side effects. The concern would be with microwave power that is used. Since TAI uses pulsed microwave power with a very low duty cycle the makes the average microwave power very low. Like with ultrasound imaging by implementing a phased array of transducers it would be possible to generate results in real time so eliminating the need for a patient to remain still for long periods of time.

The details of the design have been presented along with current issues and the issues that have been successfully advised. The microwave peak power of 5 kW used in this work is significantly lower than in previous works [1] [8] [9] and holds promise for applying this technology to the medical field. While this system works well it can still be improved. Future work would include modifying the setup to do tomography scans by having the transducer rotate around the target. Implementation of a ultrasound phased array to acquire real time results, along with suspending the target off the bottom of the tank. Finally, test targets such as concrete with and without defects as well as composite materials should be used to validate the use of TAI on those materials.
REFERENCES


APPENDIX A. Schematics

Figure A.1: Pre-Amp Schematic
Figure A.2: Stepper Controller schematic Page 1
Figure A.3: Stepper Controller schematic Page 2