Acoustic Vector Intensity Measurements in a Confined Underwater Environment

Gabriel H. Fronk

A senior thesis submitted to the faculty of

Brigham Young University

In partial fulfillment of the requirements for the degree of

Bachelor of Science

Tracianne B. Neilsen, Advisor

Department of Physics and Astronomy

Brigham Young University

April 2021

ABSTRACT

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Humans can tell direction of sound sources by comparing the pressure signal received at each ear. Similarly, in an underwater environment two hydrophones can be used to determine directionality of sound. Acoustic vector intensity, the metric used to determine directionality and sound level of sources, varies depending on assumptions made about the free-field propagation of sound and reflections present in the environment. An environment in which sound propagates freely without reflections is said to be anechoic. To ensure correct interpretation of intensity measurements made in our water tank, we first characterized the reflections in the tank. With this knowledge, we have made the first acoustic intensity estimates using this two-microphone approach, or pressure gradient method, to determine directionality and sound intensity in our lab's water tank. These results will provide a good foundation for future intensity measurements done in our lab.

Keywords: Acoustic vector intensity; Pressure gradient; Underwater acoustics

Acknowledgments

I would like to acknowledge the BYU College of Physical & Mathematical Sciences for allotting me research funds to participate in research for three and half years of my college career, which paved the way for this thesis. I also want to acknowledge the Office of Naval Research for awarding the BYU Underwater Acoustics Lab the Defense University Research Instrumentation Program N00014-18-S-F007 Grant 12671398. The funds from this grant allowed for the purchasing of the many vital instruments used to conduct the research of this thesis. Thank you to Dr. Tracianne B. Neilsen, my advisor, who guided and taught me with patience and kindness through much of my undergraduate career and through my senior research project. In addition, thank you to Cameron Vongsawad, a master's student, and the undergraduate students of the BYU Underwater Acoustics Lab that helped conduct the experiments of this thesis. Finally, thank you to friends and family that supported me through my academic journey thus far, most especially my lovely wife, Rachel.

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1 Introduction

1.1 Motivation

Most work in acoustics relies on measuring pressure as the major metric of experimentation. This approach makes sense since microphones, the archetypal measuring tool for acoustics, is a pressure-based device. However, pressure measurements only give acoustical information at a specific point in space. For many questions related to acoustics, how acoustic energy interacts with its environment as it propagates is of more importance. In order to get this broader knowledge of the environment, acoustic intensity can be used.

Acoustic intensity is the amount of power from sound waves per unit area; it is a vector quantity with the vector pointing perpendicular to the unit area, usually in the direction of propagation of sound. Because it is a vector quantity, acoustic intensity has many applications in acoustics-related work beyond the capabilities of pressure measurements alone. For example, using only a pressure measurement, it would be impossible to tell where a sound is coming from;

the measurement would only tell how loud the sound is but not the direction of travel. On the other hand, vector intensity measurements can be used to determine the position of sound sources. Additionally, intensity measurements can also be used to describe how an environment affects propagation of sound. An open environment would allow sound from a source to propagate outward freely with no interruption (a free-field) compared to a very confined environment with many obstructions which would cause sound to bounce off many surfaces in many directions (a diffuse field). The acoustic intensity of the former situation would reflect the simple propagation of a sound wave, whereas the latter diffuse field would describe sound waves coming from seemingly many directions.

Acoustic intensity is derived from sound pressure and particle motion. As the acoustic wave propagates through a medium, the individual particles oscillate back and forth to pass the energy onward as the wave progresses. The direction of the passed energy from oscillating particles provides the direction of the acoustic vector intensity. This particle motion, which is vital to determining acoustic intensity, is useful in many research areas such as developing models of acoustic properties of seafloor sediments, improving source localization methods, and fish biology. Since the auditory sense of fish is based on particle motion, intensity measurements are of interest to understanding how fish interact with their environment. This thesis will explore how acoustic vector intensity can be used for many kinds of underwater acoustics work at Brigham Young University.

1.1.1 Fish Biology

One application of interest to BYU's underwater acoustic group is the use of acoustic intensity measurements in fish behavioral studies. The auditory organs of most fish are particle velocity sensors rather than sound pressure sensors.[1] While most vertebrates have ears that sense pressure waves, the fish hearing organ actually relies on masses known as otoliths to detect particle velocity. Figure 2 of Ref. 1 shows the fish inner ear with three white otolith masses surrounded by fluid that have similar density and acoustic impedance as the rest of the body of the fish and ocean water. The otoliths are oriented in each of the three spatial orthogonal axes so that motion in any direction is accurately sensed. Because the surrounding fluid has the same acoustic impedance as the ocean, the fluid moves exactly with any motion of the water surrounding the fish. The fluid pushes on the otoliths which then activates signals corresponding to its motion in hair cells near the otolith that go the nervous system.

The mechanics of otoliths in a fish inner ear is similar to that of a typical accelerometer. Accelerometers typically consist of a mass (m) supported by a spring (k) as seen in Fig. 1.1. This model relates to the mass of the otoliths and the spring-like motion of the fluid. As the mass moves, one can measure its acceleration and thus deduce velocity. Chapter 2 describes how particle velocity determines intensity.

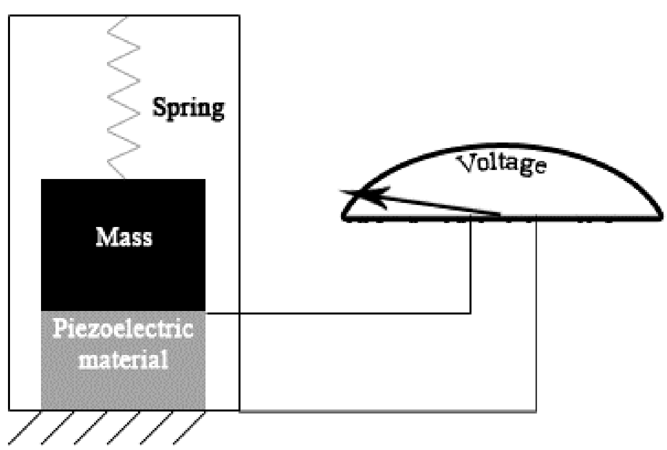


Figure 1.1 Schematic of an accelerometer. Credit: https://en.wikipedia.org/wiki/File:PiezoAccelTheory.gif

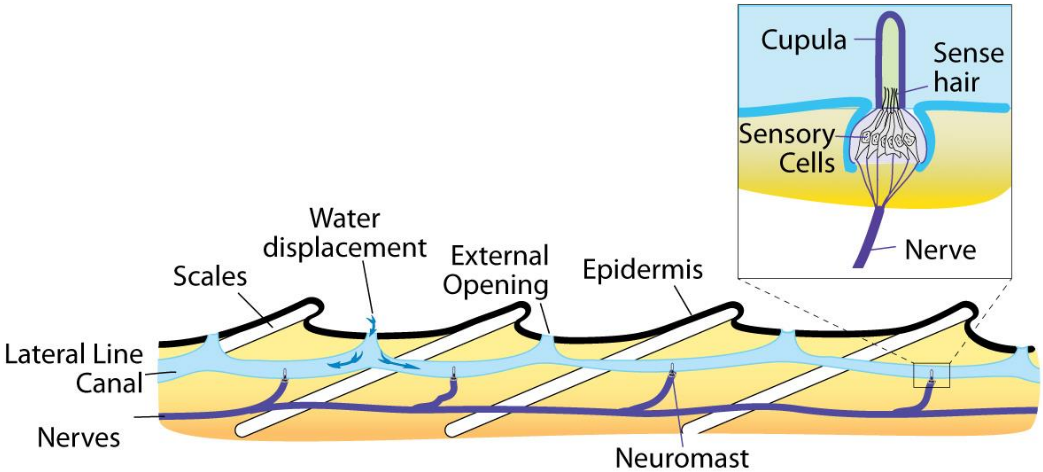


Figure 1.2 Diagram of the lateral line system with zoomed-in image of sensory hair in the lateral line. Credit: https://commons.wikimedia.org/wiki/File:LateralLine_Organ.jpg

Along with the inner ear, fish have a second sensory system for detecting acoustic waves in water known as the lateral line. The lateral line, illustrated Fig. 1.2, consists of a series of hair cells on the surface of the fish body as well as in small canals along the side of the fish. The lateral line uses particle motion in water to detect nearby fish and objects. Use of the lateral line relates to schooling behaviors of fish as well as mating patterns and predator detection.[2] Using particle motion, the lateral line may allow fish to interact with others even in murky waters that limit visibility. Our lab hopes to understand better how the lateral line detects particle motion. With this information we can better understand the biological and acoustical reasons behind several fish behaviors.

1.1.2 Localization of Underwater Sound Sources

A major motivation behind the majority of underwater acoustics research is the application of SONAR to determine the location of sound sources in the ocean. An acoustic vector sensor (AVS) is a device made up of a hydrophone and multiple particle motion sensors that is used for such applications. Acoustic vector intensity offers many advantages over pressure-only methods of localizing sound sources. These advantages include better spatial resolution and overcoming spatial aliasing in signals.[3]

1.1.3 Acoustic Characterization of Seafloor Environments

Similarly, intensity measurements have been shown to be useful in inferring geoacoustic properties of seafloor sediments. In 2017, Dahl and Dall'Osto used an AVS called IVAR (intensity vector autonomous recorder) to study sound propagation in the New England mud patch.[4] These kinds of intensity measurements give new insights into developing models of sound propagation and attenuation in seafloor sediments, allowing researchers to understand better how sound interacts with the seafloor.

1.2 BYU Underwater Acoustics Lab

To contribute to these and other research topics relating to underwater acoustics, the Underwater Acoustics Lab at BYU was established, beginning in 2019. This lab was designed for small-scale ocean modeling experiments, utilizing the ability to scale wavelengths to match the environment (i.e. a 100 Hz sound traveling 150 m corresponds to a 100 kHz traveling 15 cm). With the use of proper transducers, we can also perform intensity measurements for any type of water environment including fish aquariums. Several considerations need to be addressed before reliable estimates of intensity can be found in a tank environment.

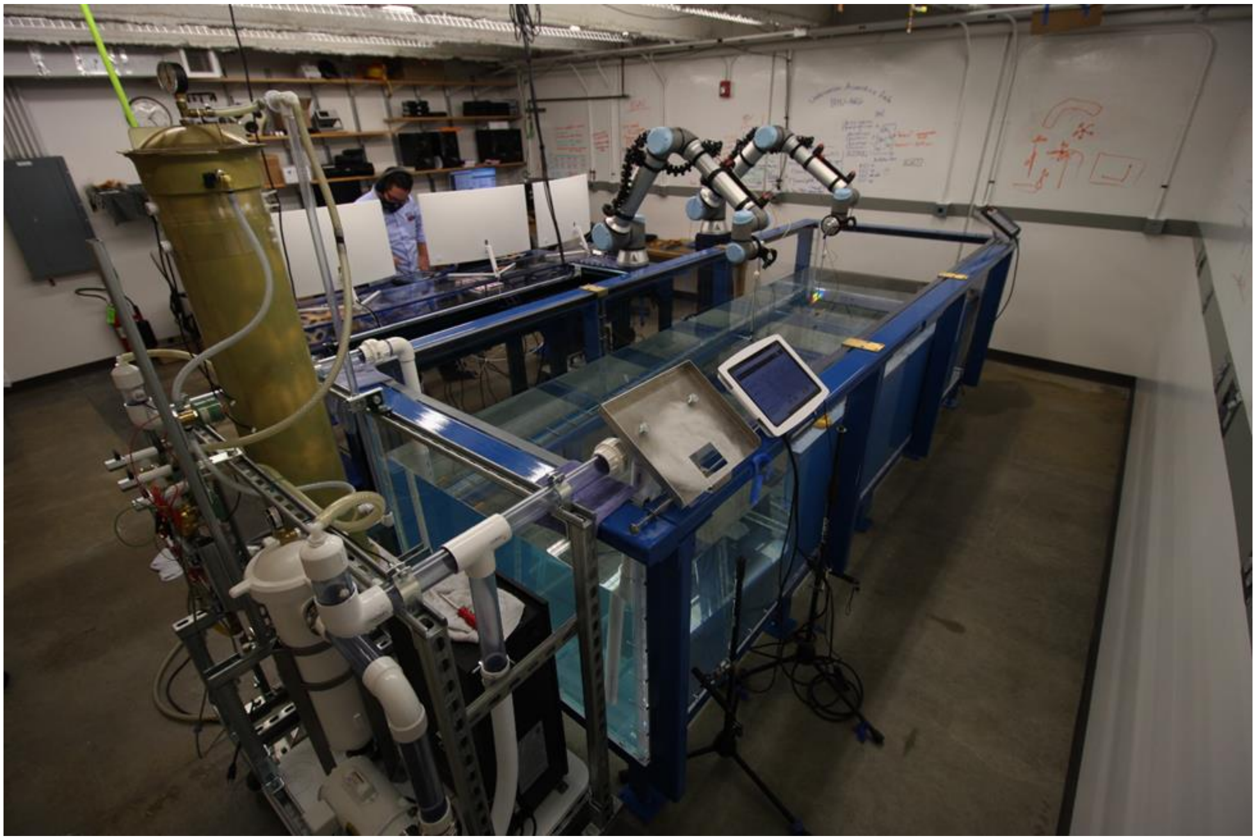


Figure 1.3 Acrylic tank with filtration system in the Underwater Acoustics Lab at BYU

These considerations pertain to understanding how well a water tank can act as a scale-model of the ocean. One limitation of a tank in modeling the ocean is the presence of walls around the perimeter of the tank. These walls can introduce reverberation to the water as sound bounces off the walls. Understanding the reverberation at different positions in the tank is critical to accurately interrupting intensity measurements made. Reverberance in lab tanks has caused issues for other acoustic experimentalists and remedying this has proven equally difficult.[1] Anechoic panels, which are designed to absorb sound, can be used to mitigate these echoes. The efficiency of these panels is addressed in Ch. 3.

Intensity measurements done for application to fish biology are done at low frequencies. At these frequencies (below roughly 5000 Hz), the dimensions of the tank impact sound propagation. Because the dimensions of the tank are on the same scale of a wavelength at lower frequencies, far-field assumptions are not valid. These assumptions include viewing the propagating sound as a ray and assuming steadily decaying energy as the sound wave moves away from the source. At frequencies below 5000 Hz, it becomes difficult to position receivers in the tank far enough away from sources to find freely propagating waves and the decay of sound waves that accompanies the assumption of free-field spreading. As a result of these considerations, we must view these measurements as being in the near-field. The consequences of this are detailed in Ch. 3.

Another result of the close quarters of the tank is the existence of modal resonances. In this low frequency regime, standing waves are set up and frequency-dependent resonances are excited based on the location of the source. Models describing how these modes affect sound propagation have been researched extensively.[5] One such model which has been used extensively by our research group was created by Westwood *et. al.*[6] and is called ORCA. ORCA is a normal mode model for wave propagation in a cylindrical waveguide, which has two assumptions: 1) axial symmetry and 2) range-independent stratification of the ocean, meaning that the ocean environment does not change as distance increases from the source. This model is designed explicitly for real-world ocean tests and determines the vertical modes of sound propagation between the water surface and into the seafloor sediment and the spreading and attenuation of the sound waves.

1.3 Previous Acoustic Vector Intensity Research

1.3.1 Tools for Determining Acoustic Vector Intensity

As mentioned above, fish are able to detect particle motion through mechanics similar to that of an accelerometer. Accelerometers provide a large bandwidth of frequencies over which to measure particle motion. One would think, then, that using an accelerometer or other motion-based sensor such as a seismic geophone would be the best method of determining particle motion in a lab setting. However, the bulk of these devices as well as buoyancy and other complications of using them in underwater environment usually prevents them from being used in lab work. Additionally, in a lab where calibration and environmental noise can be carefully monitored, deriving particle motion from pressure measurements through the pressure gradient method is a useful approach.[7] Because of these and other considerations, pressure gradient methods (described in Section 2.2) are used to calculate sound intensity for the purposes of this thesis.

1.3.2 Acoustic Vector Intensity Research at BYU

At BYU, research into intensity measurements in the air has led to the creation of another method of estimating acoustic vector intensity.[89] The phase and amplitude gradient estimator method (PAGE) utilizes the magnitude and phase of a complex pressure signal in the frequency spectrum. This approach varies from the traditional pressure gradient method which separates and uses the real and imaginary portions of a complex pressure signal. The PAGE method has the advantage of overcoming aliasing restrictions of a spatial Nyquist frequency. However, the PAGE method does have limitations when the signal is dominated by mode resonances as in the water tank at low frequencies as discussed in Section 1.2. The PAGE method is not discussed further in this thesis but should be studied more in future underwater applications.

1.4 Overview

This thesis details preliminary efforts to ensure valid acoustic vector intensity measurements for various underwater applications. Chapter 2 deals with the methods used to collect data on intensity measurements. The mathematical formulation of how acoustic vector intensity is derived from pressure measurements taken by hydrophones is laid out; an explanation of the experimental use of lab hardware is then given. Chapter 3 describes the results of testing anechoic panels and provides initial intensity estimations. Finally, conclusions and discussion on future work are given.

2 Methods

Many theoretical and experimental considerations were necessary before acoustic intensity measurements could be performed. First, a mathematical derivation is presented to explain how acoustic intensity is estimated from hydrophone measurements made in the lab. Then, the set-up and tools used in the measurements are explained.

2.1 Theory

Sound intensity is determined from two basic attributes of acoustic waves, pressure and particle velocity. Pressure, $p(t)$, is a scalar and particle velocity, $\boldsymbol{u}(t)$, is a vector quantity as denoted by the bold print; therefore, sound intensity is a vector quantity from the following relationship:

$$\boldsymbol{I} = \frac{1}{t}\int p(t)\boldsymbol{u}(t)dt. \tag{1}$$

The acoustic pressure of a signal can be easily recorded by any microphone, hydrophone, or other pressure-based transducer. Because the particle velocity is a vector quantity, it cannot be simply measured by a pressure transducer. Instead, the particle velocity is determined using an estimate of the pressure gradient from two measurements in what is referred to as the p-p method.

2.1.1 Pressure Gradient Method (p-p Method)

The p-p method relies on how Euler's equation relates acoustic pressure and particle velocity. Assuming particle velocity to have time-harmonicity with frequency ω and defining the ambient medium density as ρ_0, particle velocity can be directly related to the pressure gradient in a complex relationship as follows:[10]

$$\rho_0 \frac{\partial \boldsymbol{u}}{\partial t} = -\boldsymbol{\nabla} p, \tag{2}$$

$$\boldsymbol{u} = \frac{j}{\rho_0 \omega} \boldsymbol{\nabla} p. \tag{3}$$

In the frequency domain, the complex intensity can be rewritten as

$$\boldsymbol{I}_c = \frac{1}{2} p \boldsymbol{u}^*, \tag{4}$$

with * indicating complex conjugate. The factor of $\frac{1}{2}$ arises from the time averaging of the peak amplitudes. This complex intensity can then be separated into real and imaginary parts to obtain the active and reactive intensities respectively. Active intensity can be thought of as describing how much net transport of sound energy leaves some sample volume; reactive intensity describes local oscillation or 'sloshing' of sound energy in some volume of space.[10] One characteristic of intensity measurements in free-field propagation is that the reactive intensity approaches zero, since no obstructions reflect sound in the directions other than the directions of propagation. In a diffuse field with modal behavior, the reactive intensity dominates the active intensity.

To calculate the complex, frequency-dependent intensity, the pressure received by two hydrophones can be used; the pressure of each hydrophone is described by amplitude P and phase ϕ:

$$p_1 = P_1 e^{j\phi_1}, \tag{5}$$

$$p_2 = P_2 e^{j\phi_2}. \tag{6}$$

In practice, two pressure measurements only give one component of the three-dimensional vector of acoustic intensity – along the direction of the line connecting the two pressure transducers. The pressure used in the complex intensity formulation comes from averaging the absolute values of the pressures obtained from each hydrophone to obtain the pressure at a point exactly between the hydrophones:

$$p = \frac{p_2 - p_1}{2}. \tag{7}$$

Using Eq. 3, the particle velocity at this middle point is found. The pressure gradient is approximated by the difference of the two pressures divided by the distance d between them.[10] Again, this two-pressure approximation only gives one dimension of the particle velocity, in this case the y-dimension:

$$u_y = \frac{j}{\rho_0 \omega}\left(\frac{p_2 - p_1}{d}\right). \tag{8}$$

Successful localization of sources will depend on the ability to determine the location of sources in three dimensions. However, this research only addresses one-dimensional vector intensity as a proof-of-concept.

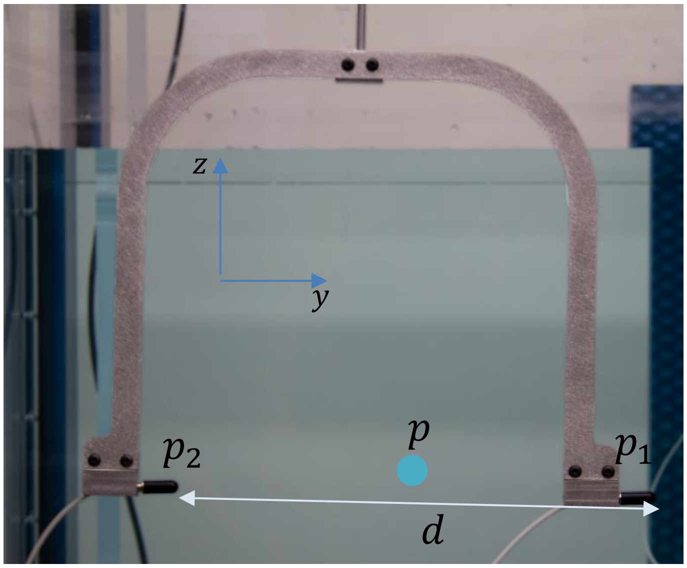


Figure 2.1 Y-mount, a two-receiver probe, illustrating physical interpretations of above formulas.

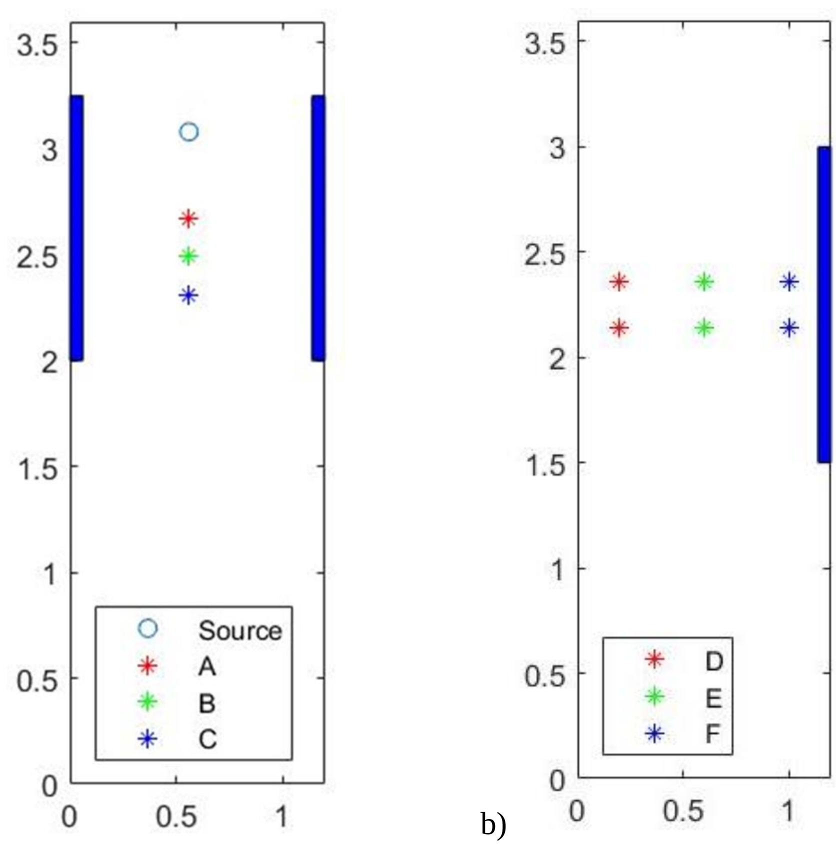
Using this p-p method of calculating sound intensity has two important limitations. At low frequencies, the physical distance between transducers can become very small relative to the wavelength. This relatively small distance causes the phase mismatch between transducers to become significant compared to the phase difference between the pressure signals received. At high frequencies, the wavelength becomes so small that it becomes difficult to place the two transducers closer than half a wavelength, which corresponds to the spatial Nyquist frequency. Thus, the spacing between transducers determines the bandwidth over which the p-p method yields good estimates of the vector intensity.

2.2 Experimental Set-up

The experiments occurred in the acrylic tank in the underwater acoustics lab. The transducers used in these experiments were phase-matched Bruel & Kjaer 8103 hydrophones. To avoid the spacing resolution problems mentioned in section 2.1, the two receivers were positioned carefully. The intended bandwidth of the experiment, 60-3000 Hz, corresponds to wavelengths of 25 to 0.5 m. The hydrophones were positioned a distance $d = 0.34$ m apart using the Y-mount shown in Fig. 2.1, relative to the frequency bandwidth, corresponding to a phase range of 4.3 to 216 degrees at the low and high ends of the frequency band. This phase mismatch lower bound is higher than the phase mismatch of the phase-matched hydrophones. The upper frequency bound is slightly higher than the spatial Nyquist frequency for the Y-mount.

To help reduce reflections off the tank walls, Aptile SF5048 Anechoic panels from Precision Acoustics were placed in the tank for some measurements. Because these panels were rated for ultrasonic bandwidths, it was uncertain how well they would attenuate sound for the frequencies of these measurements. An environment that is anechoic has little acoustic energy bouncing off of surfaces in the form of echoes. A more anechoic environment means lower reflections and less reverberation; sound propagates out from the source and not from other directions. The anechoic nature of an environment affects intensity measurements because intensity is a vector quantity. For example, if a receiver were positioned towards a source with a wall directly behind it, the receiver would detect an acoustic signal from the source as well as sound reflected from the rear wall going the opposite direction. The resulting constructive or destructive interference could change the received pressure. In order to understand the anechoic nature of the tank, we tested the efficacy of these panels over the 60-3000 Hz band before performing intensity measurements.

To perform this anechoic testing, we positioned a source-receiver pair on the Y-mount 24 cm (now oriented towards one another rather than facing the same direction) apart from each other and moved the pair across the tank as shown in Fig. 2.2(b). Figure 2.2 shows a bird's eye view of the lab tank with positions of hydrophones denoted by the colored stars and anechoic panels represented by the blue rectangles. This set-up allowed us to see differences between reflections off the acrylic walls versus the anechoic panels.



a) b)

Figure 2.2 Schematics of the 1.2 x 3.6 m acrylic tank showing the set-up of (a) the preliminary intensity measurements and (b) the anechoic panel testing. The blue rectangles designate positions of the anechoic paneling.

For our preliminary intensity measurements, one hydrophone was set in a fixed position to act as the source. Two other hydrophones, the receivers, were positioned in the tank using the Y-mount attached to a Universal Robotics UR10e robotic arm, which allowed for precise movement of the receivers across the tank. Figure 2.2(a) illustrates this set-up with the stars indicating the center positions of the two-receiver probe.

In order to produce the pressure signal studied in the tank, we implemented a measurement chain of several amplifiers and signal converters. The signal used in the experiments was created using an in-house LabView-based software called Easy Spectrum Acoustics Underwater (ESAU). A TEGAM power amplifier 7200 passed the signal from the Spectrum M2p.xxxx-x4 DAQ to the source hydrophone. The receiver hydrophones were connected to a NEXUS conditioning amplifier 7209, which then sent the signal back to the DAQ to be recorded by the ESAU software. The NEXUS amplifier was matched in pressure sensitivity to each individual piezoelectric transducer and amplified the signal by 10 mV/Pa.

3 Results and Conclusions

With the tools and set-ups discussed in Chapter 2, I performed tests to understand the reverberant nature of the tank and anechoic paneling and conducted the initial acoustic intensity measurements. The anechoic testing provided insights into the propagation of sound in the water tank, as is shown in Section 3.1. Section 3.2 discusses the results from the preliminary acoustic vector intensity measurements. General conclusions and suggestions for future work are then given.

3.1 Anechoic Panel Test

The intensity measurements performed in the tank will be greatly affected by reverberations in the tank; because of this, understanding how the tank's reverberation is vital to being confident in future intensity measurements. After placing the receiver and source 24 cm apart from each other and moving the pair across the width of the tank, we were able to determine the anechoic nature of the tank walls for this low frequency bandwidth.

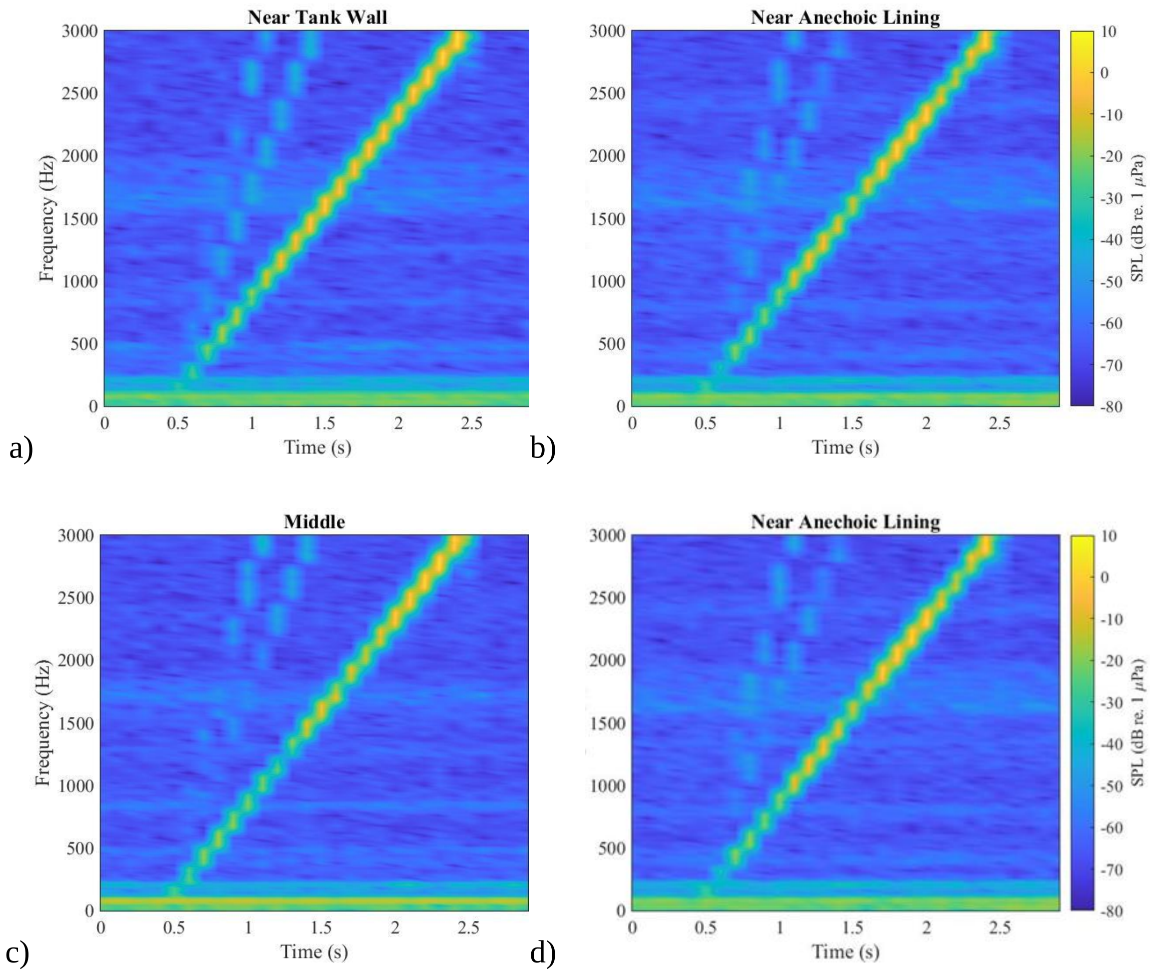


Figure 3.1 Spectrograms of the received sound pressure level when the source-receiver pair were (a) 20 cm from tank wall, position D in Fig. 2.2(b); (b) 20 cm from anechoic lining, Fig. 2.2(b) position F; and (c) in the middle of tank, Fig. 2.2(b) position E. For convenience part (d) is a repeat of part (b).

To evaluate the anechoic nature of the tank, I compared the reverberation from reflections off surfaces near the source and receiver depending on different positions in the tank. Figure 3.1 shows the sound pressure levels (SPL) in decibels (referenced to 1 μPa) recorded from a linear chirp (50-3000 Hz) at various positions in the tank, with the brighter colors denoting more acoustic energy at that time and in that frequency bin. The values of SPL may not be correctly calibrated to the transducers' sensitivities, which have a sensitivity of -210.9 dB/μPa at 4 kHz, the lowest bound of the sensitivity chart. Low ambient noise is seen throughout the measurements. The faint lines with a steeper slope than the main signal correspond to the harmonics of the frequencies measured.

To accentuate the differences between positions I changed the colorbar range of SPL in Fig. 3.1 from -80 to 10 dB to a new range of -20 to 10 dB in Fig. 3.2. The sound pressure level at high frequencies is lower near the anechoic lining compared to the other measurements. This means that the anechoic panels are useful for attenuating higher frequencies, which is

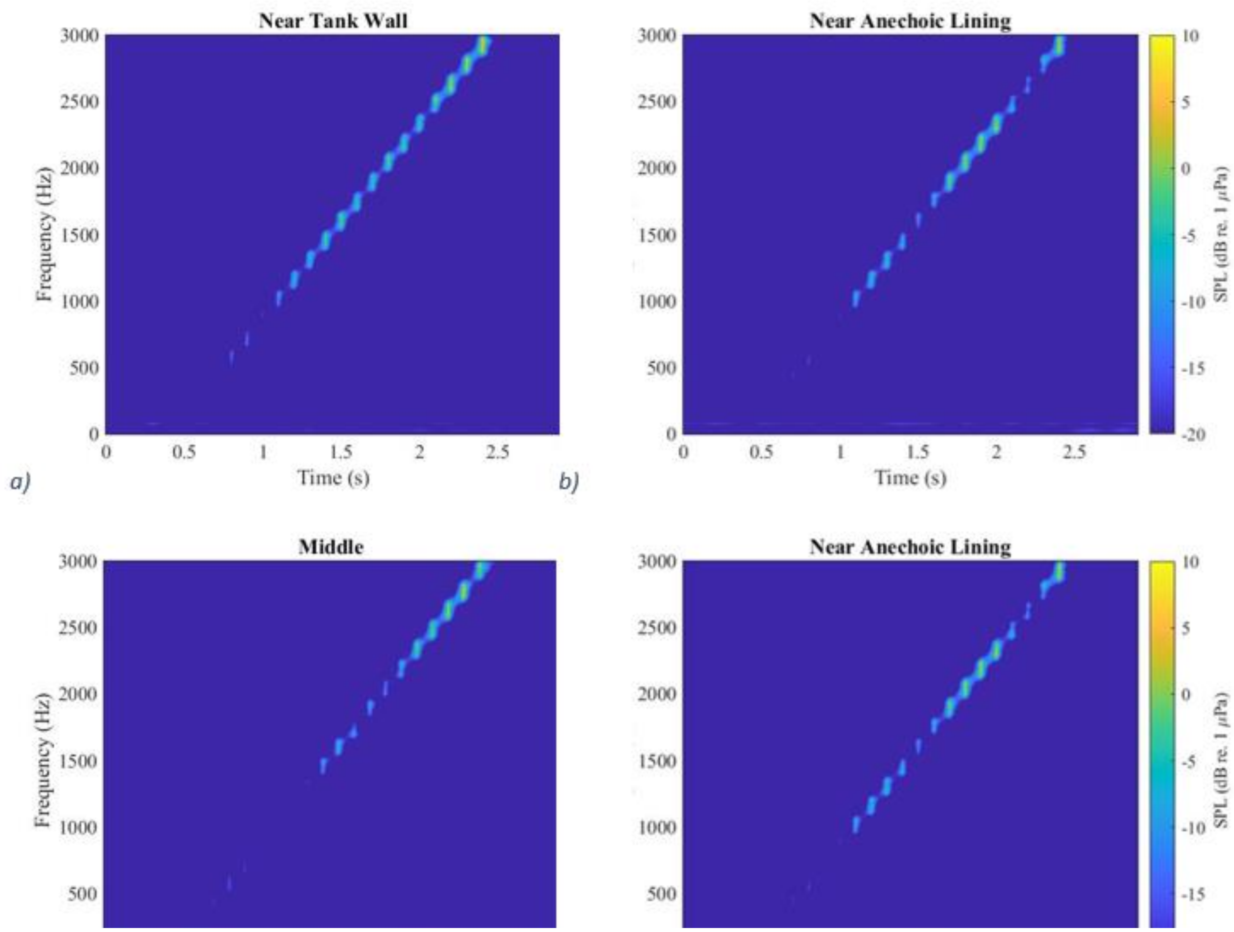


Figure 3.2 Spectrograms, similar to Fig. 3.1, with a narrower scale to emphasize difference between measurements.

encouraging since the panels are designed to attenuate frequencies just slightly higher than this bandwidth. The designed bandwidth of the anechoic panels has a lower bound at 5000 Hz. We also see that the measurement taken in the middle of the tank, away from the side surfaces, has little energy at frequencies below about 1500 Hz. This difference occurs because of two factors. Firstly, the hydrophones used have poor response below this frequency and so are not be able to produce as strong of a signal using these frequencies as higher frequencies. The other relates to the mode shapes of the tank causing destructive interference at the position of the hydrophones. This effect is explained in more depth in the next section.

From the measurements taken, it seems that the acrylic walls will not overtly impede future intensity measurements. Significant time-delayed reflections that would alter the intensity measurements are not present. Since the reflected sound in a diffuse field arrive at the receiver very quickly (within 1 ms) after the direct signal, it is difficult to see these quick reflections in these spectrograms. To see how much acoustic energy is reflected from the environment back to the receiver, the SPL as a function of time is plotted in Fig. 3.3 for two specific frequencies, 1000 and 2000 Hz, over the course of the three second signal. Since the chirp signal is constantly changing frequency, focusing on just one frequency should allow us to see how much the signal lingers. The black lines, corresponding to the recording taken near the tank wall (position D), have higher peaks of the secondary lobes after the main lobe than the dashed red lines from position E. This difference means that more acoustic energy at that frequency arrived at the receiver from the tank wall than from the anechoic lining. The side lobes before the main lobe, before the chirp actually reached the target frequency are results from the harmonics of lower frequencies, as confirmed by the time alignment of the first side lobe from the 2000 Hz plot to the main lobe of the 1000 Hz plot.

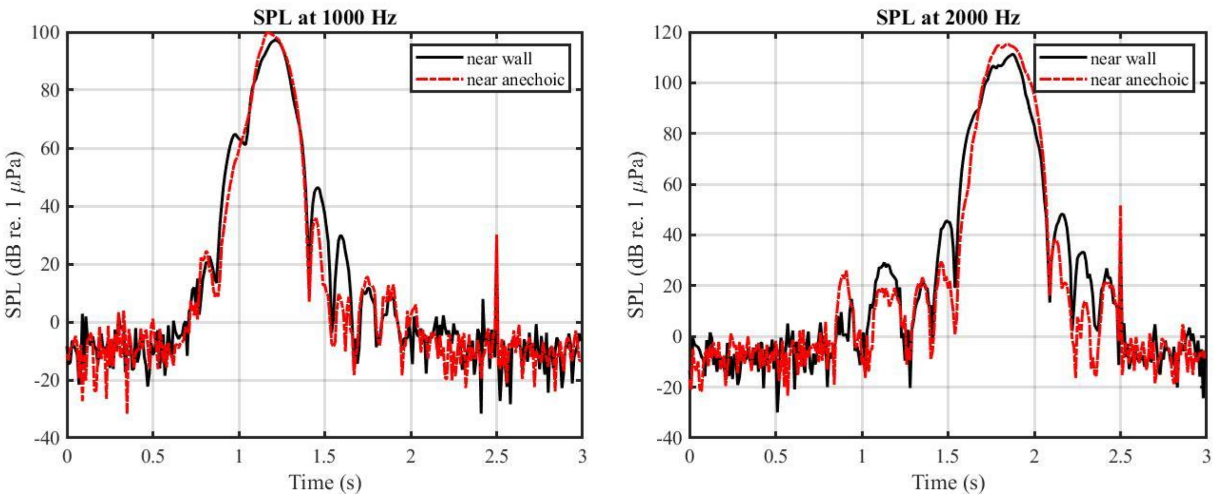


Figure 3.3 SPL of specific frequencies over the three seconds of the measured signal.

As discussed above, the tank is reverberant for this frequency bandwidth due to the dominance of mode resonances. The Schroder frequency for this tank is about 5000 Hz; frequencies below 5000 Hz will always excite specific modal resonances in the tank that will complicate intensity measurements. If care is taken to perform intensity measurements in the middle of the tank, away from all side surfaces, sound at low frequencies should have fewer reflections.

3.2 Preliminary Intensity Measurements

We made preliminary acoustic vector intensity measurements using the Y-mount shown in Fig. 2.1. The hydrophone measurements were processed using the p-p method to estimate the intensity. Figure 3.4 shows the frequency-dependent active, reactive, and absolute intensity at varying distances from the source to center of the Y-mount. These results come from the measurements taken following the schematics shown in Fig. 2.2(a).

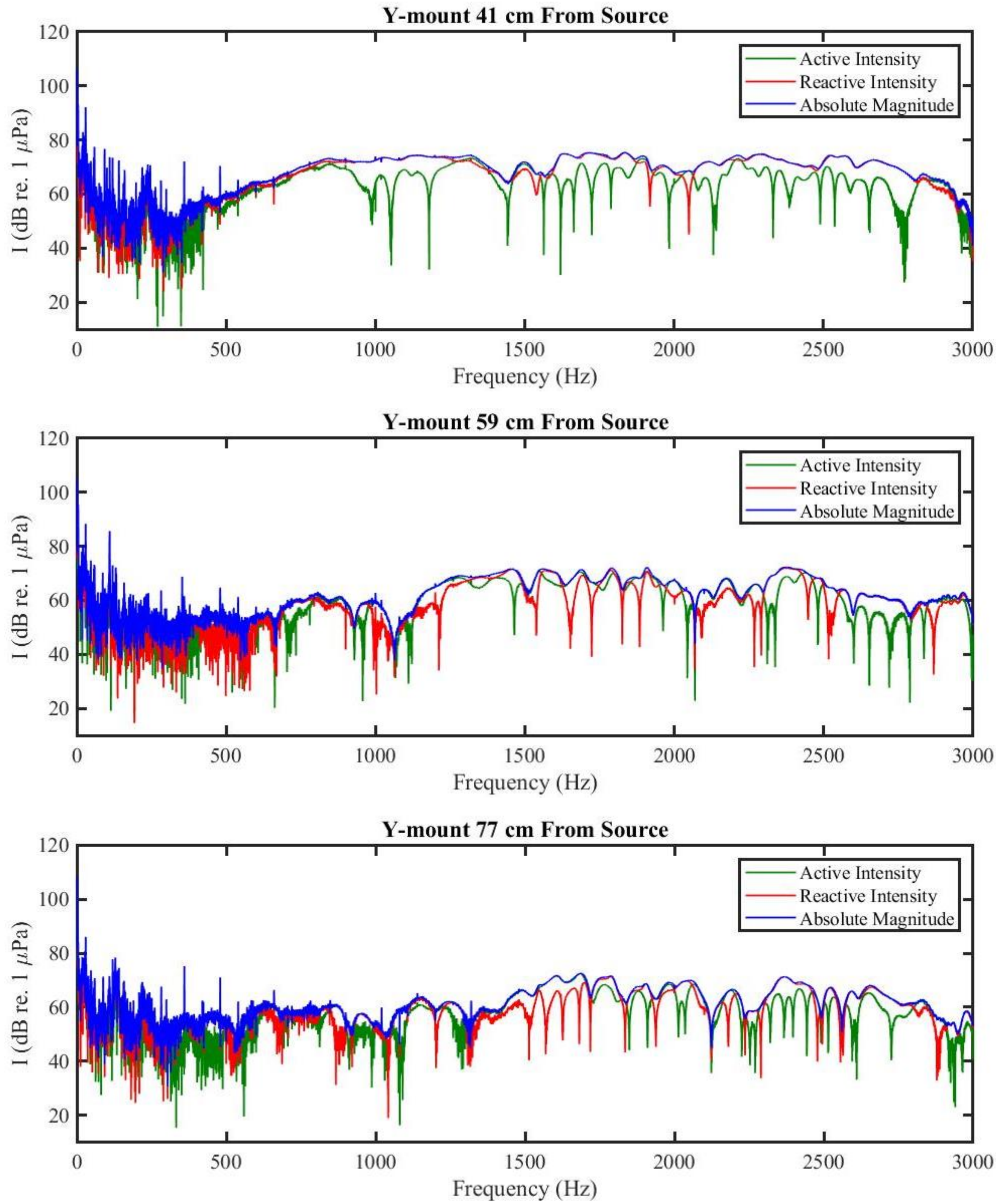


Figure 3.4 Intensity estimates with the p-p method from two receivers on the Y-mount at different distances from source: at positions A, B, and C in Fig. 2.2(a).

The very noisy results at very low frequencies come from the fact that at this very low frequency regime, the wavelengths are very large compared to the size of the tank. Thus, sound at these frequencies essentially act as oscillations in the ambient pressure of the water in the tank. Interestingly, the transition frequency where the intensity becomes more smooth after being so noisy and jagged seems to increase with distance from the source. We are currently unsure what causes this phenomenon. Above this transition frequency, the active and reactive intensities have several sharp dips at different frequencies. Figure 3.5 shows the absolute magnitudes of acoustic intensity at each of the positions in Fig. 2.2(a). Generally, with assumptions of freely propagating waves, we assume that acoustic intensity decays with distance following a 1/r decay. While there is some decrease in level with increasing distance in Fig. 3.5, the levels stay fairly constant as distance to the source increases.

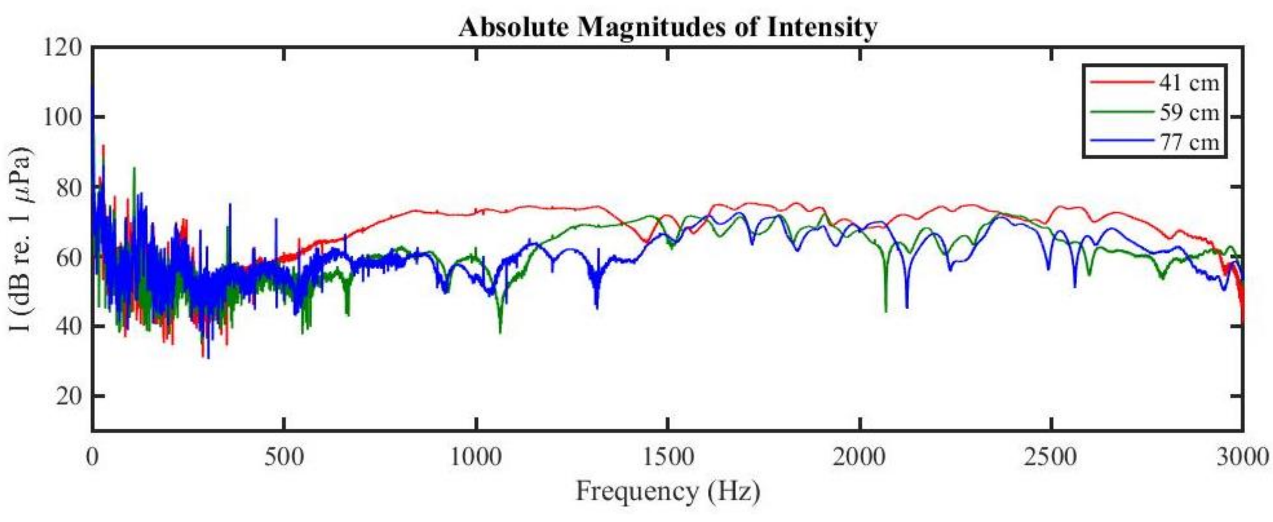


Figure 3.5 Absolute acoustic vector intensity at various distances of receivers. The 41 cm distance line corresponds to position A in Fig. 2.2(a), the 59 cm line to position B, and the 77 cm line to position C.

The explanation for both observations (constant levels and sharp dips of intensity) comes from the fact that the wavelengths of the frequency bandwidth are on the same scale as the tank dimensions. Mode resonances will dominate the response of the receivers. In Fig. 3.5, the dips in intensity at different frequencies do not necessarily decrease as the distance from the source increases. Instead, the dipping intensity levels correspond to frequency modes where the receivers were positioned at a node in the mode shape. Because of these various modes being excited in the tank, standing waves are set up and so the environment becomes more diffuse. This behavior means that acoustic energy is arriving at the receivers from different directions. Sound does not decay with 1/r due to this reverberance of the confining tank.

When the Y-mount sits 41 cm from the source these dips in absolute intensity are much less steep and less frequent compared to the other positions. The lack of similar sharp dips in the reactive intensity at this position as seen in Fig. 3.4 causes this behavior since the absolute intensity is the sum of the real and imaginary parts of the intensity. The reactive intensity lacks these sharp dips since the distance of the Y-mount to the source, 41 cm, is similar to the distance between the receivers in the Y-mount, 34 cm. Since these distances are close to one another, the Y-mount can be thought to be in the 'very near-field' of the sound source and so there is less modal interference in the back-and-forth 'sloshing' of acoustic energy which relates to reactive intensity.

3.3 Conclusions

This research has shown the importance of the assumptions made in acoustic experimentation relating to free-field/diffuse-field and far-field/near-field propagation. The extent to which the diffuse field of the tank affects its reverberation and mode patterns has been investigated. The tank is fairly reverberant with anechoic panels helping to mitigate this effect. At low enough frequencies, below roughly 1500 Hz, the signal attenuates enough to make it hard to detect these frequencies at all. The diffuse field also has affected how we estimate acoustic intensity in the water tank. We found that intensity estimates, at least at the low frequency bandwidth measured, are affected greatly by the modes of the water tank.

The estimation of particle velocity from pressure gradient comes with some uncertainty. Jones *et. al.*[11] concludes that because sound in a small tank cannot be considered a plane wave propagating in a free field, particle velocity is not predictably proportional with acoustic pressure and cannot be derived from it. However, this claim seems to only consider the real component of complex pressure values; the relationship between pressure and particle velocity is complex. While it is true that the real particle velocity associated with active acoustic intensity does not have a linear relationship with acoustic pressure, the pressure gradient does provide information for the imaginary part of the particle velocity function and thus the reactive intensity.[10] Because of this, the intensity estimations obtained represent the complex, reactive sound environment in the tank. We hope to repeat intensity measurements with particle motion sensors, to confirm our estimations.

In the future, better models of acoustic propagation in small water tanks will be used to confirm and improve acoustic intensity estimations. Novak *et. al.*[12] describes a more realistic model of pressure and particle velocity distributions in small water tanks. The model is based on lossy boundary conditions that allow some transfer of acoustic energy through the tank walls, as opposed to rigid boundaries that are typically assumed in mode estimation of tanks. This more realistic model would allow for a more accurate picture of acoustic pressure in the tank, and thus a more accurate estimation of particle velocity.

Because of the results found, we know that resonance frequencies will affect intensity measurements. Depending on the experiment being performed this may not disrupt results. For example, intensity measurements relating to fish behavior may not be affected as this diffuse field can approximate fish habitats such as ocean floors or rivers. Coral and other obstructions will also cause some reverberation which would affect intensity found in real world scenarios.

The knowledge gained from these initial experiments is a first step towards determining the best perform acoustic intensity measurements to better understand fish communication behaviors. Future work will include better characterization of the acrylic tank in order to test models of various seafloor sediments in the tank and improve localization efforts in underwater environments. Overall, the underwater acoustics research group now have the tools to discover much more about underwater acoustics.

Appendix A

Post-Processing and Graph Creation

To create the plots shown in this thesis, the following parameters and functions were used in MATLAB. The data files can be found on the BYU server W:\ drive. It should be noted that the NEXUS preconditioner connected to the receivers had matching sensitivity in pC/Pa to each individual transducer and an amplification of 10 mV/Pa.

A1. Spectrograms:

Path = W:\uw-measurements-tank\2021-02—11\2021-02-11_scan15
Fs = 150 kHz
0% overlap of FFT calculation
Ns = 15000 for spectrograms
Ns = 1500 for frequency-specific SPL line plots
Signal length = 3 s
Reference pressure = 1e-6 Pa

Spectrograms were created in Tank_Spectrograms.m using specgram.m from the byuarg library.

A2. Intensity:

Path = W:\uw-measurements-tank\2021-02-17\2021-02-17_scan8
Fs = 150 kHz
Ns = L*Fs
df = Fs/ns
C = 1478
Rho =1023
Signal length = 3 s
Reference intensity = 6.61e-19

Intensity plots were created in UWIntensityCalc.m using computeBlockFFt.m and

TRAD_func.m from the byuarg library.

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