# M.ENG PROJECT: TOADFISH BEHAVIORAL ROBOT FOR FISH AGGRESSION STUDY

**A Design Project Report**

**Presented to the School of Electrical and Computer Engineering of Cornell University**

**in Partial Fulfillment of the Requirements for the Degree of**

**Master of Engineering, Electrical and Computer Engineering**


**Submitted by**

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Cornell University

# Abstract

**Master of Engineering Program**
**School of Electrical and Computer Engineering**
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**Project Title: Toadfish Behavioral Robot for Fish Aggression Study**

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**Abstract:**

This project intends to aid Professor Andrew H. Bass and his team from the department of Neurobiology and Behavior to study the behavior of the toadfish. Why study the toadfish? Toadfishes are simple vertebrates that can communicate with each other acoustically. By creating a robot fish that can successfully re-produce the toadfish's communication, the team can study how other toadfish respond to these "sound" in a controlled environment.

Therefore, the toadfish project aims to build a robot that essentially mimics toadfish communication. One distinguishing feature about the male toadfish is that they make different types of sound to communicate. The toadfish makes loud growling or grunting sounds to fend off other male toadfish near their nesting site and also sings nest hums to attract female toadfishes. These sounds are generally in the frequency range of 100 ~ 200Hz with a sound intensity level of 110dB re 1uPA 15cm away from source. In order to mimic the toadfish, the robot has to re-produce these sound underwater while meeting the frequency and sound intensity levels. Different types of speakers/transducers will be tested to generate sound underwater in addition to meeting the sound requirements. The speaker will be encased in a 3D printed toadfish model underwater and peripheral circuitry to drive the transducer will be designed and built outside of the robot. As there are many constraints on speaker size, frequency range, and sound intensity, different types of speakers were tested for performance.

# Executive Summary

The goal of this project is to build a robot toadfish that will help Professor Andrew H. Bass and his team from the department of Neurobiology and Behavior study toadfish behavior. The robot will have to be able to mimic toadfish communication so that the team can see how other toadfishes react to the sound. Typical toadfish sounds are within frequency range of 100Hz to 200Hz with a sound intensity level of 110dB re 1uPA 15cm away from source. This is a very low frequency sound with a high volume considering the small toadfish size, which is typically around 8 inches in length.

One of the key components in making the toadfish robot is creating the audio system that meets all the requirements. The speaker must be small so that it can be placed inside a robot toadfish, water-proof so it can generate sound underwater, and be able to generate low frequency sound with large intensity. Finding a suitable speaker was the first step in this project.

Two different types of speakers were tested for performance. The electrodynamic speaker N50 from PUI Audio and the piezoelectric speaker SX53 from Sensortech. Although the SX53 was more ideal for underwater sound generation, the N50 speaker was tested first as it was easier to acquire. Two different circuit were designed for each of the speakers as they had different electrical specifications. Each of the speakers were then tested in air, playing .wav files of regular sine waves of different frequencies (100Hz, 150Hz, 200Hz, 500Hz), and sound recordings of actual toadfishes provided by Professor Bass. Output waveforms were checked with an oscilloscope to see if any distortions or sound clipping existed. Unfortunately, there were no calibrated hydrophones to accurately measure the sound intensity levels underwater. Therefore, a sound meter app was used to obtain dB in air and simple conversion equation that converts dB in air to dB in water was used to get a rough estimate of sound intensity level underwater. Direct underwater sound level measurements were also made with the sound meter app but these measurements will not be very accurate as these apps are not designed for underwater sound measurements.

From test results, the SX53 piezoelectric speaker performed better in underwater sound generation. Even though the N50 speaker had better sound intensity levels in air, it suffered huge dB loss in water due to its material composition. The SX53 produced sound intensity levels close to 110dB at 200Hz. However, the speaker could not be tested with real toadfish because Professor Bass' lab did not have toadfishes at the time. However, it would be worthwhile to test the speakers with toadfishes to see if they react to it.

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# 1. Introduction

Accurately reproducing the toadfish's sound underwater to study the response of other toadfish is an important goal of the project. Therefore, selecting suitable speakers for underwater sound generation was the first task of the project. Two speakers were selected for testing, mostly based on the frequency range it can produce and their general sound intensity level. Based on these requirements, the N50 electrodynamic speaker from PUI Audio and the SX53 piezoelectric speaker from Sensortech were selected. However, there was no information about sound generation underwater for the N50 speaker as it was designed for use in air. Although the SX53 was designed for use underwater, there was no information on its frequency response around 100Hz to 200Hz. After selecting the speakers, different circuits to drive each of the speakers were designed. The circuits were tested if they produced clean output and the speakers were tested if they produced large enough sound.

# 2. Speakers

Speaker selection was a critical part of this project to meet the specifications of the toadfish sound. The most important factors for consideration were size, ability to generate low frequency sound waves, and sound intensity level. The speaker will have to be small enough to actually fit in a real sized toadfish robot and generate sound that other toadfishes can hear and react to. Taking these factors in consideration, two different types of speakers selected to be tested for performance - the electrodynamic speaker (N50 from PUI Audio), and the piezoelectric speaker (SX53 from Sensortech).

Fig 1. N50 speaker from PUI Audio[10]

Fig 2. SX53 from Sensortech

# 3. Electrodynamic vs. Piezo Speakers

Electrodynamic and piezo speakers have different characteristics. Electrodynamic speakers are generally intended for use in air. They operate when an alternating current audio signal is applied to its terminals. The alternating current causes the inductive coil within the speaker to move back and forth, which then causes the diaphragm of the speaker to move and produce sound waves. Electrodynamic speakers are widely used because they generally have better frequency response over a wider range of frequencies to play music. However, compared to piezoelectric speakers, they are bigger and thicker, especially for low frequency sound generation. In addition, depending on the material of the diaphragm, their sound generation level underwater greatly reduces due to the higher density of water. Electrically, they are inductive loads with coils that move with alternating current flowing through.

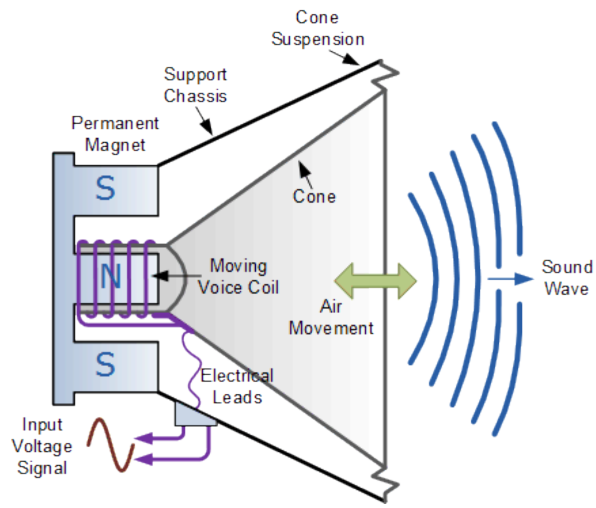


Fig 3. Electrodynamic speaker operation

Piezoelectric speakers operate when electric fields are applied to its terminals. When exposed to electric fields, piezoelectric material on the front face of the speaker expands and shrinks while the base material stays the same. Therefore, electric field applied to the piezoelectric speaker will cause it to move and generate sound. Piezoelectric speakers can be made much smaller compared to electrodynamic speakers but they generally have worse frequency response and are generally used to generate sound at fixed frequency. Therefore, piezo speakers are used to produce large sound in a specific frequency range. Another disadvantage of piezoelectric speakers is that they require higher voltage range for operation. However, an important characteristic about piezo speaker is that they are more robust in generating sound in different medium. Most piezo speakers are made with crystals, which is a relatively hard material. These materials are much more efficient in generating waves in different medium. Below is an image that shows piezoelectric speaker operation and a table that outlines important characteristics of each type of speaker.

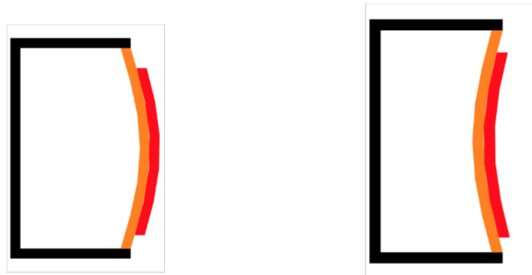

Fig 4. Piezoelectric material movement when under electric field [9]

| Piezo speaker | Electrodynamic speaker |
|---|---|
| Smaller size factor | Limitation on size for low freq. sound |
| Robust in different environments | Not ideal for underwater use |
| Requires higher voltage/current | Lower voltage/current requirements |
| Worse frequency response | Good frequency response |
| Expensive | Inexpensive |

Table 1. Different characteristics between Piezoelectric and Electrodynamic speakers

## 3.1 N50 Electrodynamic Speaker Testing

The electrodynamic speaker were tested first as they were easier to obtain. The N50 speaker was selected as it had a relatively small form factor (40mm in diameter) and could produce low frequency sound with high sound intensity. The basic specifications are shown below.

**Specifications**

| Parameters | Values | Units |
|---|---|---|
| Rated Input Power | 5 | Watts |
| Max Input Power | 6 | Watts |
| Impedance | 4 ± 15% | Ohms |
| Sensitivity (SPL @ 1W/50cm) (800, 1000, 1200, and 1500 Hz) | 84 ± 3 | dBA |
| Distortion (Max @ 1W, 1 kHz) | <5% | |
| Resonant Frequency | 150 ± 20% | Hz |
| Frequency Range | 100 ~ 20,000 | Hz |
| Housing Material | ABS | |
| Magnet Material | NdFeB | |
| Weight | 21.5 | Grams |

Table 2. Electrical specifications of N50 speaker

However, as these speakers are generally intended to be used in air, there was no information about how these speakers would perform underwater. Therefore, testing the speakers underwater was crucial. A circuit was designed as below to drive the speakers.

The LM386 op-amp from Texas Instruments was used to amplify the input audio signal. Audio files containing recordings of toadfish sound provided by Prof. Bass was played on the computer. The computer provided the input signal to the circuit board through the 3.5mm audio jack. The LM386 amplified the input signal with a gain value of 0 to 200 depending on the resistance from the 10KOhm potentiometer. A 12V supply voltage was used to generate maximum power.

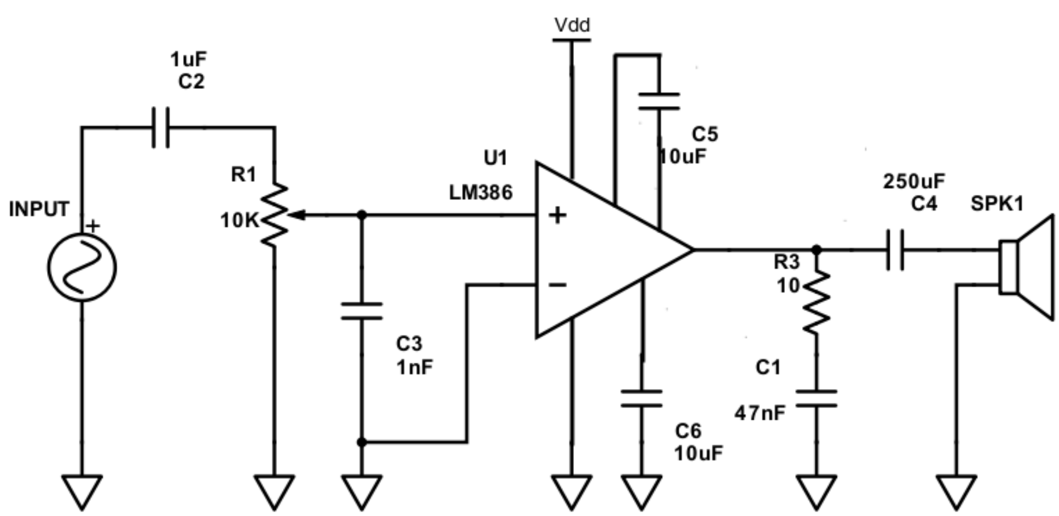


Figure 5. Circuit designed for N50 speaker

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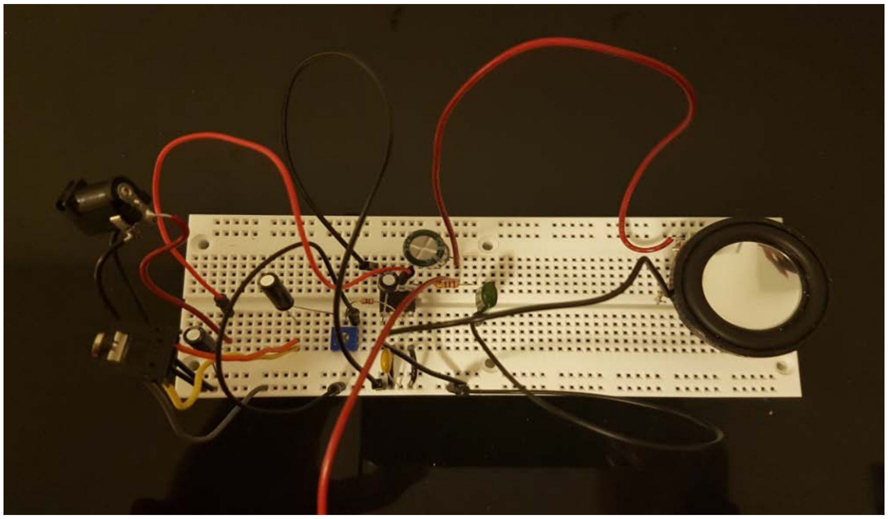

Figure 6. Circuit board with N50 speaker on breadboard

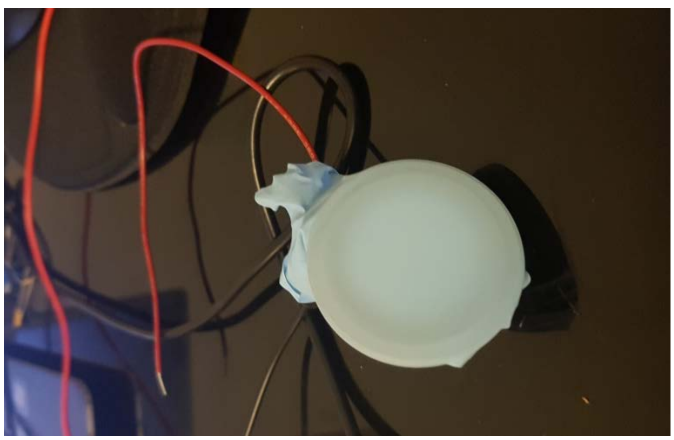

Figure 7. N50 speaker wrapped for underwater testing

## 3.2 SX53 Piezoelectric Speaker Testing

The piezoelectric speaker (SX53) was then tested for performance. The speaker was selected again because it had small size (2 inches in diameter), and could generate sound frequency as low as 100Hz. Below is the general specifications of the speaker.

| Parameters | Values |
|---|---|
| Resonance Frequency | 750Hz |
| Beam Angle Radial 3DB AT FR | Omnidirectional @ 750Hz |
| Depth Rating | 2 meters |
| Transmit Voltage Response | 110 dB re 1uPa/V @ 1meter |
| Usable Frequency Range | 100Hz - 5KHz |
| Rated Power to Duty Cycle | 0.5 Wrms |
| Operating Range | +/- 15V |

Table 3. Basic specifications of SX53 speaker

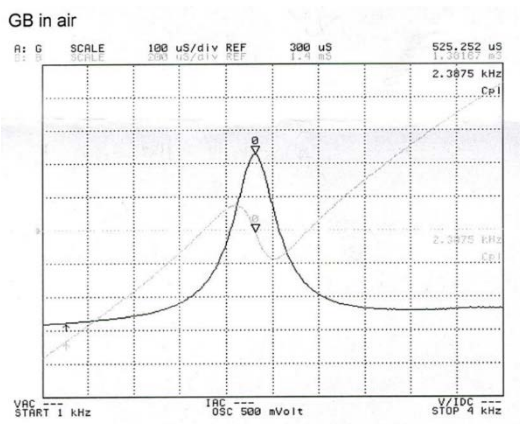


Fig 8. Gain vs. Frequency in air

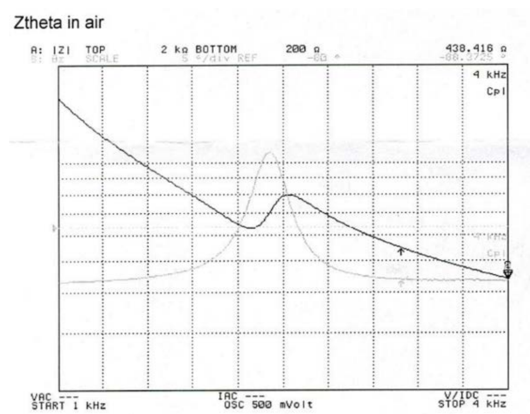


Fig 9. Impedance vs. Frequency in air

A different design was used as the piezoelectric speaker required higher voltage to produce maximum sound intensity level. From the frequency vs. gain graph, it can be seen that the response at lower frequency is worse. Therefore, maximum electric field must be applied to the speakers to generate sufficient sound intensity. Class B amplifier design with some modifications was used to drive the piezoelectric speaker and a different op-amp (LF411 by Texas Instruments) was used because the LM386 only operated up to 12V. The first stage amplifier on the left was used to create a voltage gain of 20 by using two feedback resistors. The second stage amplifier was used with as a power follower (unity gain) to reduce cross-over distortion by having a feedback loop from the output of the two transistors. The amplifier was also used to drive the two transistors (2N3903, 2N3906 by On Semiconductors) before driving the speaker to supply more power. The amplifiers were connected to a +/- 15V supply to generate maximum output voltage.

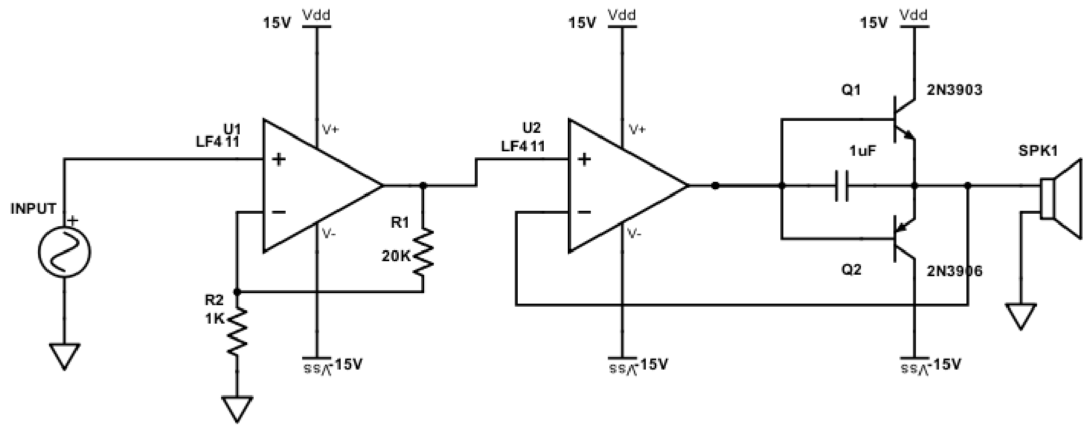


Fig 10. Circuit designed for SX53 speaker

The class B amplifier is a widely used design to drive speakers. It contains an amplifier that drives two transistors (1 NPN, 1PNP) that will help drive the speaker with more power. The amplifier works by having one transistor provide power to the speaker during one half of the waveform cycle and the other transistor provide power for the remaining waveform cycle. However, this type of amplifier design generally suffers from cross-over distortion when the amplifier output is between -0.7V and 0.7V. In this case, neither of the transistors are fully turned on to drive the speaker.

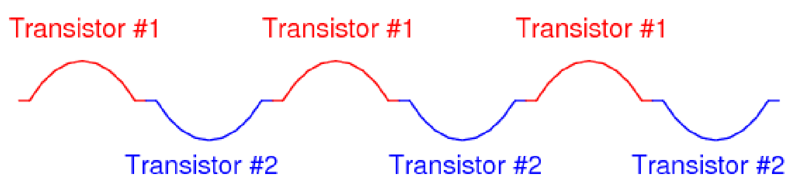


Fig 11. Crossover distortion in Class B amplifier [2]

Although the cross-over distortion was already reduced by the first stage of amplifier as it amplifies the input signal with a large gain, distortion was further reduced by the second stage amplifier by having a feedback look to the input of the speakers. In addition, by placing a 1uF additional capacitor between the output of the 2nd stage amplifier and the input of the speaker, distortion was further reduced. The final circuit was soldered on a perf board as shown below in Figure 12.

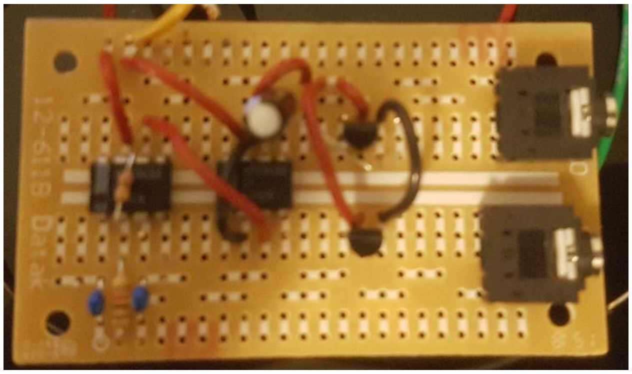

Fig 12. Circuit for SX53 soldered on perf board

# 4. Results

The output waveforms from the amplifier was checked with an oscilloscope for any distortion. Clean sound needed to be outputted so that the toadfish sounds can be accurately reproduced. Regular sine waveforms of different frequency and the toadfish recordings from Prof. Bass were tested. As shown below from the oscilloscope images, the circuit successfully amplified the input signal up to +/-15V without distortion.

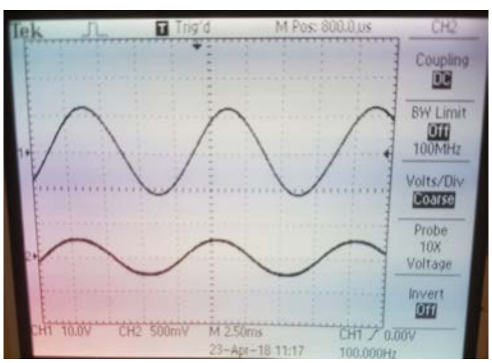


Fig 13. Input and output sine wave (100Hz)

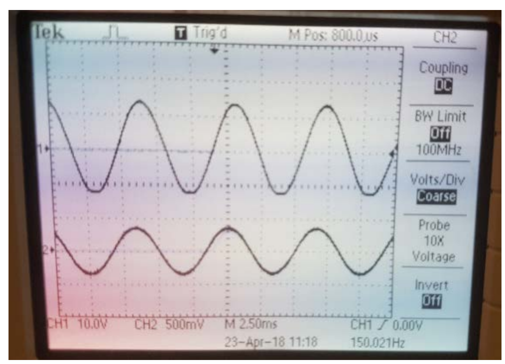


Fig 14. Input and output sine wave (150Hz)

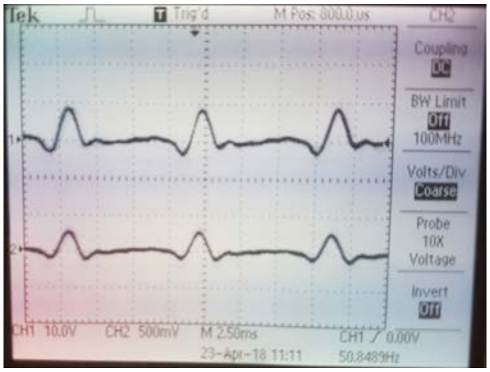


Fig 15. Grunt input and output waveform

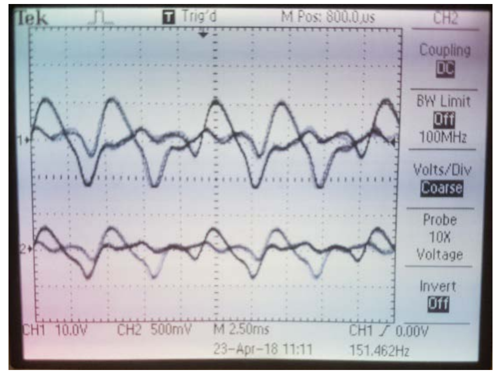


Fig 16. Nest hum input and output waveform

Sound level measurements were made for each design. The mobile phone application "Sound Meter" was used to make sound measurements 15cm away from the speaker in air. Then the sound measurements in air was converted to sound levels in water using the simple conversion equations below.

$$dB = 20\log(p_{air}/p_{water}) = 26dB$$

$$10\log(3600) = 36\ dB$$

Fig 17. Simple conversion equation accounting for pressure, acoustic impedance difference of air and water [5]

The first equation accounts for the difference in pressure for air and water. The sound pressure level in air is referenced to 20uPa, while sound pressure level in water is referenced to 1uPa. Using the first equation, this gives a 26dB difference for pressure comparison. The second equation accounts for the acoustic impedance difference between air and water. This is a measure of how the pressure in the medium rises when a given intensity is applied. The acoustic impedance of water is 1,540,000 Pa/m$^2$ while acoustic impedance of air is around 430 Pa Pa/m$^2$. This gives an additional 36dB difference from acoustic impedance. These equations together gives a rough conversion factor of 62dB for sound intensity levels in air and water. Therefore, a sound intensity of 50dB in air will result in 112dB in water.

Sound measurements underwater was also tested with the same mobile app. Although the application is not designed for underwater measurements, it was used mainly for comparing sound intensities between the two speakers. The measurement result for each speaker is shown below.

| Sound file | dB in air | dB using conversion equation | dB measurement underwater |
|---|---|---|---|
| Sine wave (100Hz) | 36dB | 98dB | 89dB |
| Sine wave (150Hz) | 39dB | 102dB | 96dB |
| Sine wave (200Hz) | 46dB | 108dB | 103dB |
| Sine wave (500Hz) | 51dB | 113dB | 110dB |
| Toadfish Nest-hum | 41dB | 103dB | 100dB |
| Toadfish Grunt | 51dB | 113dB | 101dB |
| Toadfish Growl | 40dB | 102dB | 98dB |

Table 4. Sound intensity levels of SX53

| Sound file | dB in air | dB using conversion equation | dB measurement underwater |
|---|---|---|---|
| Sine wave (100Hz) | 42dB | 104dB | 82dB |
| Sine wave (150Hz) | 49dB | 111dB | 86dB |
| Sine wave (200Hz) | 61dB | 123dB | 91dB |
| Sine wave (500Hz) | 69dB | 131dB | 96dB |

Table 5. Sound intensity level of N50

As expected, the N50 performed better in generating larger sound in air but once it was placed underwater, it suffered significant dB loss compared to the SX53. The coil in the N50 was not strong enough to push the soft diaphragm material back and forth underwater, where it experienced much higher resistance. The SX53 performed better underwater and using the dB conversion equation, it generated sound intensity levels close to the requirements. It performed worse at the lower frequencies due to its lower gain characteristics. However, at higher frequency ranges, it produced sufficient sound that would be meaningful to be tested with actual toadfishes. To take note, the dB measurements underwater may not be accurate as these values were measured with applications not intended for underwater use. Real hydrophones with dB measurement capability will be needed to make accurate readings.

# 5. Conclusion

The piezoelectric speaker was better suited for the application as it was designed to be water-proof, and it was generating sound intensity levels close to the requirements. Although the sound levels were insufficient for the lower frequency range near 100Hz, the speaker was able to produce good sound intensity for some of the toadfish recordings such as the grunt sound. Meanwhile, the electrodynamic speakers performed well in air but experienced significant sound intensity drop when placed in water. Since the simple conversion factor used does not take into account of many other factors such as source frequency and wave propagation efficiency, it would be better to take additional sound intensity measurements with hydrophones. Even if the sound intensity levels are slightly lower than expected, testing the speakers with real toadfish would be important as the goal of the project is to study the response of the toadfishes. As long as the toadfishes react to the sound, researchers can study the toadfishes. Unfortunately Prof. Bass didn't have any toadfishes during the year and the speakers couldn't be tested.

# 6. Future Work

To further improve on this project, the speakers should be tested with real toadfishes. Once it is verified that the speakers are generating sufficient sound intensity so that the toadfishes react to it, the speaker can be placed within a toadfish robot. Further work can be done to make the robot resemble more like the toadfish by having moving parts so that it can move underwater. With more resemblance to the toadfish, better response from toadfish can be obtained. To make the robot more interactive, adding a camera to the robot toadfish would enable researchers to record toadfish behavior even better.

# 7. Acknowledgements

I would like to thank Prof. Bruce R. Land, advisor of this project for supporting this design project and helping me acquire the speakers and many other components needed for the project. He also gave numerous guidance for underwater sound generation and tips for designing the circuit to drive the speakers. I would also like to thank Prof. Andrew H. Bass for providing information about toadfish communication and toadfish recordings. Lastly, I would like to thank Mihir Marathe, fellow M.Eng student in helping me out working with piezoelectric speakers.

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