Underwater Communication via Compact Mechanical Sound Generation

by

Wyatt Ubellacker

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Abstract

Effective communication with underwater remotely operated vehicles (UROV) can be difficult to accomplish. In water, simple radio communication is quickly dissipated at higher frequencies and lower frequencies require a large antenna, which may not be practical in all applications. Light can also be used to communicate with the vehicles, but requires line of sight between the source and detector. Sound can also be used as a communication method, and has many advantages. It can propagate long distances underwater and does not require line of sight to work effectively. However, generating sound electronically underwater requires a large power speaker to produce tones loud enough to travel far distances. Generating sound mechanically can take advantage of physical resonance and produce high intensity tones in a compact device with a relatively low power input. This can allow for a compact, high intensity method to communicate with remotely operated underwater vehicles.

Thesis Supervisor: H. Harry Asada
Title: Ford Professor of Mechanical Engineering

Acknowledgments

I would like to thank Professor Asada for allowing me to participate in the UROP program in his lab for this past year and work on highly maneuverable underwater robotics. From that, he has allowed me to continue and explore a main problem in underwater robotics, communication.

I would also like to thank my direct supervisor, Ani Mazumdar. Over the last year, I have learned a great deal from him, not only from a mechanical engineering and robotics perspective, but also advice on what classes would be most useful for furthering my education and career. As we moved forward with underwater robot project, I learned many simple tricks to solve problems quickly and efficiently. Beyond this, he gave me the freedom to explore what interested me within the project. This independence led me to gain experience in discovering problems, and then working to find elegant solutions to these problems. I feel that this is an extremely valuable tool, and I thank Ani for giving me the opportunity and guidance to develop that skill. Aaron Fittery has also been important to the robotics project and helped to create an enjoyable team atmosphere.

Finally, I would like to thank my parents, family, and friends who have always supported me in all of my endeavors, and giving me the mentality that anything is possible if I put my mind to it. Without their encouragement and confidence in me I would never have been able to achieve the successes I have had in life.

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Chapter 1

Introduction

1.1 Remotely Operated Underwater Vehicles

Remotely operated underwater vehicles are used in a wide variety of applications, from ocean floor mapping to ship hull inspection. These vehicles help take data or perform functions in places that would be impractical, dangerous, or impossible for humans to access and operate. Some of these tasks can be completed by robots operating autonomously, which can collect data and then analyze it itself, or store it to be analyzed by humans later. However, in many applications it is advantageous to have a human operator to control the vehicle– using it as an extension for human observation and anaylsis.

There are many methods capable of controlling these ROUVs. Many times, a wire tether to the vehicle can be used for communication, transmitting information via direct wire contact. This can give very reliable data transfer and fast speeds. However, the distance the vehicle can travel is limited by the length of the tether, and in some cases physical constraints make a tether impractical or impossible. If the vehicle needs to go in tight spaces or around corners, such as in a piping system, or if it needs to avoid contact and damage to the structure, a tether becomes an impossibility. In order to communicate with vehicles subject to this constraint, a variety of wireless methods can be used. First, radio waves can propagate through water to some degree at lower frequencies[1]. This gives a data rate that scales with the frequency, and results in a tradeoff between range and speed. Finding a workable solution often requires a high power transmitter and a large antenna on both the base station and the vehicle, something that may be difficult to achieve if given size constraints. Light can also be used to communicate, but requires line of sight with the device[2]. This cannot be used in all cases as many application have obstructions that occlude vision of the vehicle.

Lastly, sound can be used to send data to the vehicle. Sound travels well underwater and can propagate far distances without dissipating[3]. It is not constrained by line of sight, and a sound generator and detector can be constructed in a compact device. This compact device can generate sound by either electronic (via an underwater speaker) or mechanical means (via collision or sudden release of energy from a physical device). Mechanical generation offers some unique advantages over electronically generated sound in this case, as will be explained later. Though the data speed may not be able to stream a live video feed, it can achieve baud rates high enough to control motion of the vehicle or transmit some data from a sensor. This thesis will explore the use of sound, specifically mechanically driven sound, as a method to communicate with and control small underwater vehicles.

1.2 Previous Work

There is current development of an multi degree of freedom, highly maneuvrable underwater robot for the inspection of nuclear rectors[4][5]. Currently this robot is controlled using a 400 MHz wireless serial link. Though this is capable of communicating with the robot to some depth, the radio waves are quickly dissipated in the water. Some research has been done into alternative communication methods. One method used frequency shift keying of light to communicate with the robot[2]. However, this requires line of sight to work properly. A more complete method of communication with the robot is needed.

There are current acoustic modems on the market that offer high speed and long range communication. These devices are large and consume more power than desired for the small inspection robot. A more compact and efficient device is needed than the ones currently on the market.

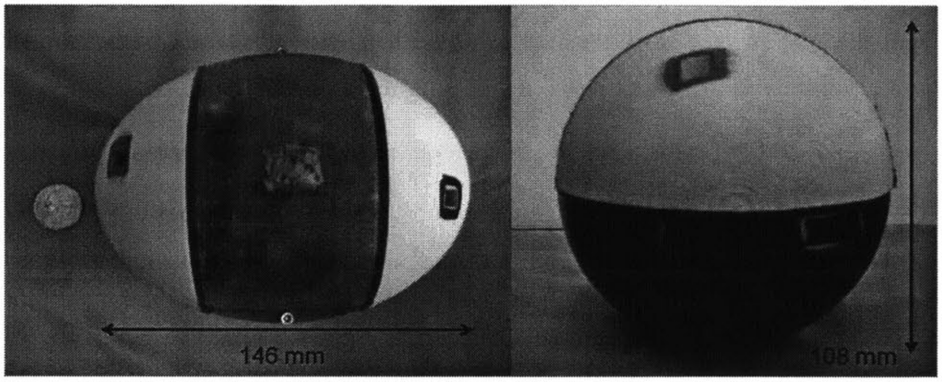


Figure 1-1: Photograph of the small, highly maneuverable robot[5]

1.3 Motivation

As time goes on, robotics is finding more and more places in science, research, and our everyday lives. It is especially prevalent in data collection in inhumane environments, such as space, volcanoes, or underwater. However, in most cases, robots are not intelligent enough know what specific pieces of a feature to focus on and must be operated autonomously.

Underwater robotics is of particular interest due water's prevalence in our everyday lives. Water is all around us and we take advantage of its unique properties for transportation, cooling, and in many other ways. We have built and are still building many devices that work in water and with water, devices that need monitoring and inspection to ensure proper and safe operation. Underwater robotics fills this niche, and humans can use these robots to collect data on ships, bridge supports, and piping systems among many other applications[6].

Communication with these robots is critical, and there are many different options, as mentioned earlier. Each option has its pros and cons, and no one method is the most practical in all situations. It is important to find solutions that suit the problem, and in the case of a large piped system, such as a nuclear power plant cooling pool, a small untethered robot may be ideal [4]. Matching a communication system with these types of vehicles is important to developing an elegant solution to a problem.

1.4 Outline of Paper

This thesis starts by answering the question of why sound can be an effective method for underwater communication. Next, it analyzes the methods that can be used to produce sound underwater, from electrically driven sound generation to mechanically driven sound generation. The advantages of mechanical sound generation are outlined and devices for creating sound mechanically are explored in detail. The physical cause of sound production from different sources and in different mediums is modelled. Next, protocols to use this sound generation to transfer data are outlined and explained in depth. The experimental results of sound propagation form a mechanical source are researched in air and water. The performance of the communication schemes in terms of data throughput, range, and robustness are then presented and analyzed. The paper will conclude with the anticipation of future work and other possible applications for this type of device.

Chapter 2

Sound Generation and Propagation

2.1 Sound Generation

At its core, sound generation comes from a release of energy into a medium. This energy can come from a wide variety of sources, from the sudden release of energy from a snapping twig, to the vibration of vocal cords, to electronically generated sound from a speaker. All sound sources work by converting energy into vibration of a physical object at a frequency or set of frequencies. This vibration is then transferred and propagated through a medium in a signal that is perceived as sound.

2.2 Sound Propagation

Sound energy travels through a medium by direct contact between the molecules of the medium. The sound source interacts physically with these molecules, creating a pressure waves that travel through the medium and is interpreted as sound [paper on sound propagation]. These pressure waves propagate in all directions from the source, spreading out as distance from the source increases. The sound obeys the inverse square power law (2.1) and the energy density decreases with the square of the distance from the source.

This is the inverse square power law. P is the power at the source, r is the distance from the source, and I is the intensity at that distance [3].

$$I = \frac{P}{4\pi r^2} \tag{2.1}$$

In addition to this, the energy transition between molecules is not perfect, and some losses occur at the interface. The amount of energy lost depends on both the medium the sound is travelling through and the frequency of the sound. Lower frequencies tend to have fewer intra-molecular losses and can propagate farther than higher frequencies without dissipating [paper on sound frequency dissipation]. Additionally, the intra-molecular losses using water as a medium are comparatively low, allowing sound to travel far distances without dissipating [3].

2.3 Controlled Sound Generation

We can take advantage of the properties of sound in water, and generate waveforms that can be used to send data wirelessly. To do this we first realize that there is more than one method to generate sound. This section will focus on electronically generated frequencies using a standard underwater speaker, and mechanical sound generation by the vibration of a resonator in response to an impulse hit.

2.3.1 Electronically Driven Generation

An ubiquitous example of electronically driven sound generation is the speaker. This device use an electromagnet, know as a voice coil, to control the frequency of the sound generated. The voice coil receives a frequency signal from a signal generator in the form of a varying voltage. This voltage draws current through the voice coil and creates a magnetic force. The force acts to push a diaphragm in and out. This transfers the energy to the medium at the frequency of the signal by driving the diaphragm against the medium, creating a tone.

The pitch and frequency of the tone is entirely dictated by the signal given to the voice coil. As such, the speaker can produce a wide variety of frequencies, and the diaphragm is designed to have subdued resonance and a flat frequency response to maintain fidelity across the frequency spectrum.

The power requirements for the speaker are determined by the voltage applied to the voice coil and the current drawn by the impedance of the coil. This is voltage drop and current supply are given by the signal power source to the speaker, and are is not affected by outside forces. It is important to note that the voice coil must be able to respond on the level of the frequency command, and must constantly be using energy to drive this frequency.

Voltage, $V_L(t)$, is given by the signal source, and current, $i_L(t)$, will be drawn according to the inductance of the voice coil, L:

$$V_L(t) = L\frac{di_L(t)}{dt}$$

Integrating, it is shown that:

$$\begin{aligned}\int V_L(t) &= L\int di_L \\ &= L * i\end{aligned}$$

Thus

$$\begin{aligned}P &= i_L(t)V_L(t) \\ &= \frac{V_L(t) * \int V_L(t)}{L}\end{aligned} \tag{2.2}$$

Thus power, P, through the speaker depends only on the applied voltage of the signal and the inductance of the voice coil.

The speaker system can be modelled as a direct force-added mass system. Physically, we assume the mass of the diaphragm has negligible inertial effects, and the spring constant is negligible due to the flat response nature of the diaphragm. Due to the geometry of the speaker, drag on the diaphragm is a negligible dissipation mode.

$$m_{added}\ddot{x} = F(t) \tag{2.3}$$

Where m_{added} is the added mass of the system, and F(t) is the applied force generated by the voltage across the voice coil. It is found that the system frequency matches the input, and all energy is immediately dissipated to the medium, characteristic of an ideal speaker.

For the case of underwater operation, it is important to understand the effects of the medium on the operation of the speaker. The added mass is equal to the volume of medium displaced by the diaphragm. For a uniformly displaced circular diaphragm [7]:

$$\begin{aligned} m_{added} &= \alpha\rho_{added}V \\ &= \alpha\rho_{added}\pi r^2 l \end{aligned} \tag{2.4}$$

Where l is the characteristic length approximately equal to the maximum displacement of the voice coil and $\alpha \approx 0.7$. Thus the general case gives:

$$\alpha\rho_{added}\pi r^2 l\ddot{x} = F(t) \tag{2.5}$$

The added mass's density, ρ_{added} only this affects the displacement of the response. Since momentum is conserved, taking a control volume around the system will show that power dissipated to the medium is not dependent on m_{added} and only dependent on the input, given in (2.2).

$$\begin{aligned} F(t) &= m_{added}\ddot{x} \\ &= \alpha\rho_{added}\pi r^2 l \end{aligned} \tag{2.6}$$

2.3.2 Mechanically Driven Generation

To generate sound mechanically, energy is transferred to nearly any mechanical system. When the system encounters an energy input, it responds by the interactions between its apparent spring constant k, mass of the system, and damping due to internal or external friction. In the real world these systems have many modes of vibration, which are frequencies than can be sustained within the system. All other frequencies experience destructive interference and are quickly dissipated. If the system is vibrating in a medium, the medium acts as a damping agent, removing energy from the system. This energy is removed in tune with the vibration of the system and creates waves of pressure in the medium at the same frequency. The simplest system that exhibits this behaviour is a mass-spring-dashpot system.

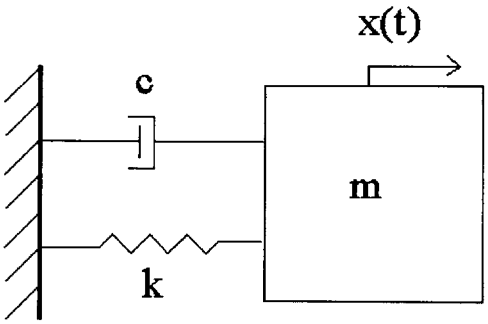


Figure 2-1: Mass-spring-dashpot model. This gives rise to one mode of vibration in response to an impulse and is a good approximation for a pure resonator, such as a tuning fork.

This can be modelled by the differential equation:

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{2.7}$$

Due to the geometry of the device, drag is a major mode of dissipation. Here the damping is taken to be caused solely by the friction against the medium in which it the system exists. There also is a contribution to the mass of the system by the added mass of the medium.

$$m = m_{added} + m_{vibrating}$$

In this case, the geometry of the mass is assumed to be cubic, and the added mass becomes [7]:

$$m_{added} = \alpha\rho_{added}s^3$$

Where $\alpha \approx 0.7$ and s is the side length of the cube.

c is dependent on the friction applied to the system– the drag on the mass. The drag is dependent on the shape of the moving mass and the density of the medium.

$$c = \frac{C_d A \rho_{added}\dot{x}}{2} \tag{2.8}$$

Where C_d and A are dependent on the geometry of the mass.

If the system is hit with an impulse, the system responds by vibrating at its one mode of vibration, and produces a tone at the same frequency. Plugging in expressions for the variables from (2.1):

$$(\alpha\rho_{added}s^3 + m_{vibrating})\ddot{x} + \frac{C_d A \rho_{added}}{2}\dot{x}^2 + kx = \delta(t) \tag{2.9}$$

Though this is a second order non-linear differential equation, the response of the system decays on the order of $e^{c\sqrt{\frac{k}{m}}t}$. Thus, as the density of the medium increases, the system decays and dissipates its energy to the medium faster.

Taking a control mass around the system, and using conservation of energy it is found that all inputted energy is transferred to the medium. The duration and intensity of this transfer is dictated by (2.9) it is found that the power level of this phenomena is dependent on the medium in which it takes place. We can take advantage of this in an underwater system. From (2.9) it is found that water is a very good dissipative agent. This means the energy we input to the mechanical sound system will be dissipated as a short, powerful impulse of sound. The higher impulse will travel farther and a signal can be received at a greater distance.

On the energy input side, by using a resonator, the driving solenoid only needs to respond on the order of the duration of the signal, not on the order of the frequency. Thus, a small solenoid can be used to store energy in the form of a spring or momentum for the next impulse while the resonator is still ringing, increasing the energy released during the impulse. This allows the device be driven by a smaller, lower power actuator, but still retain a high power, though intermittent, output.

2.3.3 Comparison of Generation Types

Given comparably sized devices and equivalently powered solenoids/voice coils between the speaker and the mechanical devices, there a a few differences between the two methods of generating sound. Overall, the speaker is able to produce a wide variety of frequencies and maintains a nearly constant power output profile. The mechanical device uses a solenoid comparable to the voice coil to build up energy and then release it all at once, creating a power profile with high-power spikes followed by regions of no output. This is especially pronounced in water due to the nature of medium-dependent dissipation. Though the total energy over time is the same, the mechanical device trades constant output for intermittent high power output. Essentially, this is a trade off between speed and distance as the high power increases the range and the intermittency decreases the speed. However, this tradeoff of data rate for distance is optimal for the use case of this device.

2.3.4 Mechanically Driven Generation Devices

There are several ways to construct a device capable of taking advantage of this mechanical phenomena to generate sound. However all of these devices must contain some way of transferring energy quickly to a mechanical resonator and a way to store up energy. All three of the following devices were 3D printed using ABS plastic and use a solenoid as the means to transfer energy. The solenoid is sealed and waterproofed.

Device 1, Fig. 2-2, uses a solenoid to input energy into a suspended aluminium resonator. The signal is sent via a 12v voltage source pulsed at various frequencies and held for a duration of 20 ms per pulse. This allows the solenoid to accelerate the arm, build up kinetic energy, and then hit the resonator with an impulse of force. It is this force that creates the clicking of the resonator. The resonator is suspended somewhat freely, held in place by low force springs. This reduces the natural damping

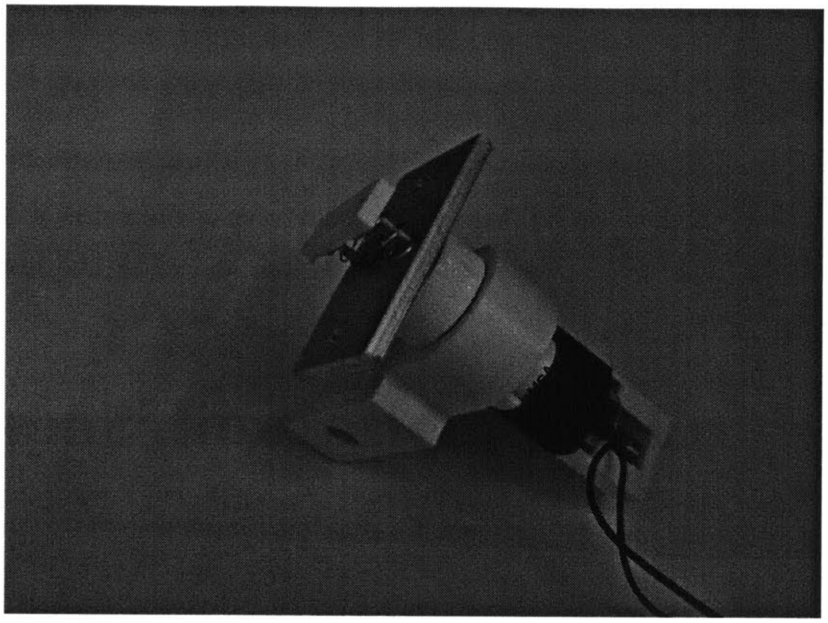


Figure 2-2: Device 1. Notice how the resonator is suspended, giving it minimal damping.

of the device and allows the resonator to ring freely once it is hit. This allows for a maximal amount of energy to be transferred to the medium while still keeping the resonator in position.

Device 2, Fig. 2-3, is similar to Device 1 but the aluminium resonator is cantilevered at one node of vibration. In theory, constraining one node should not add extra damping, but the constraint has some width, and encroaches into the vibrating region a small amount. This tradeoff comes at the advantage of simplicity and robustness, with fewer moving parts, and is an attempt to increase lifespan.

The last device, Fig. 2-4, uses a bistable stainless steel to store energy and then releases it quickly to create a powerful impulse of sound. This devices is capable of generating high intensity sounds by storing up energy in the bistable region. After a certain amount of displacement, the device switches stability modes, realising the stored energy as an intense click. This requires high force to switch the stability and requires a more energy intensive solenoid that the other two devices.

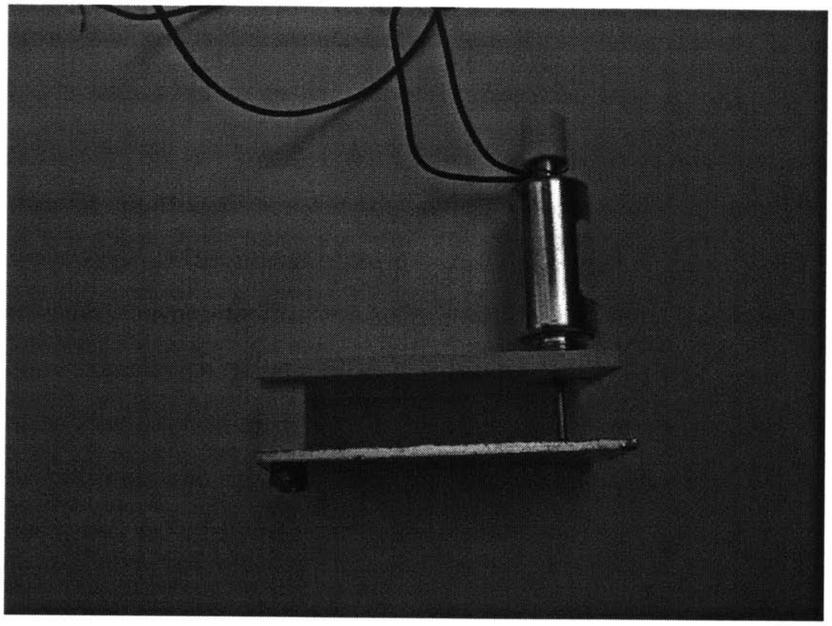


Figure 2-3: Device 2. The resonator is constrained at a node of vibration, and moving part count is reduced.

Figure 2-4: Device 3. The the solenoid is used to store energy in a bistable metal configuration, and then release the energy as an impulse

Chapter 3

Data Transfer using a Mechanically Generated Source

3.1 Introduction

Having a device that generates high intensity click is only the first step in build a acoustic communication system. The second step is developing a way of encoding data into these impulses of sound. An ideal method is would be resistant to noise, robust over long distances, and would allow for fast data rates. In this specific case, the noise resistance and capability to send data long distance are the most considered features, since controls of a vehicle can be supported with a relatively low data rate.

3.1.1 Signal Generating Electronics using Arduino

To generate and interpret the signal in the mechanical devices, an Arduino microcontroller is used. This microcontroller can be programmed in a modified version of C and can be controlled directly from a computer via a USB to FTDI serial communication, or it can operate stand alone off a 5 volt battery source. To drive the solenoid used to actuate the clicking, a digital output from the Arduino microcontroller is used to switch a power MOSFET set to drain on a 12 Volt power source. This same battery is sent through a 5 volt power regulator to provide 5 volts to the Arduino microcontroller. The reception circuitry is also powered from the 5 volt power regulator, and is used to drive to op amp amplifiers in series, see Fig. 3-1. The amplifier receives the signal via an underwater microphone and amplifies it to the saturation point of the op amp. This takes the regular sinusoidal signal from the sound being used to communicate and converts it to and easy to use digital signal, see Fig. 3-2.

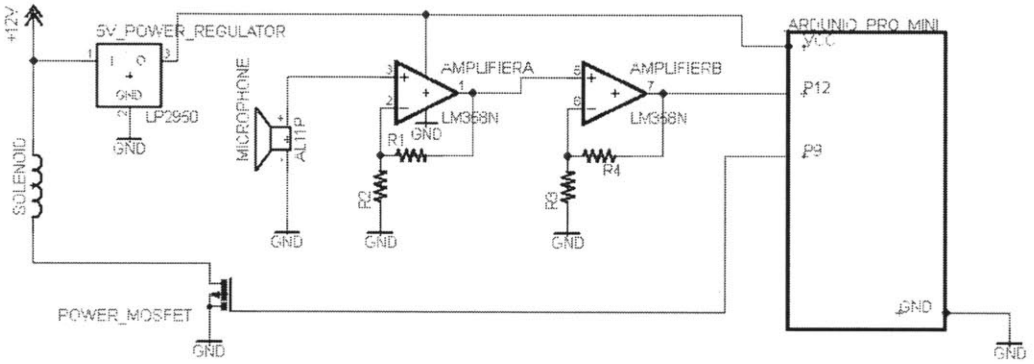


Figure 3-1: Transceiver circuit for data communication. Data is sent from the Arduino through the power mosfet to the solenoid, and received through the microphone and amplifiers.

3.2 Types of Communication Protocols

There are many protocols in use today that use waves to send data. The most widespread data transfer methods involve amplitude modulation or frequency modulation to encode the data on a carrier wave. The modulation is transferred as an analog signal that can be interpreted by the receiver. An analogous method in the digital domain, frequency shift keying and amplitude shift keying, encodes the signal as a serial stream of bits in the wave. These methods, among others, work by modifying a generated waveform and can easily be implemented using a electromechanical device that could vary frequency, such as a speaker. They tend to be resistant to noise and can achieve high data rates by overlapping several waves at different frequencies. This increases the bandwidth and allows multiple data streams to be sent

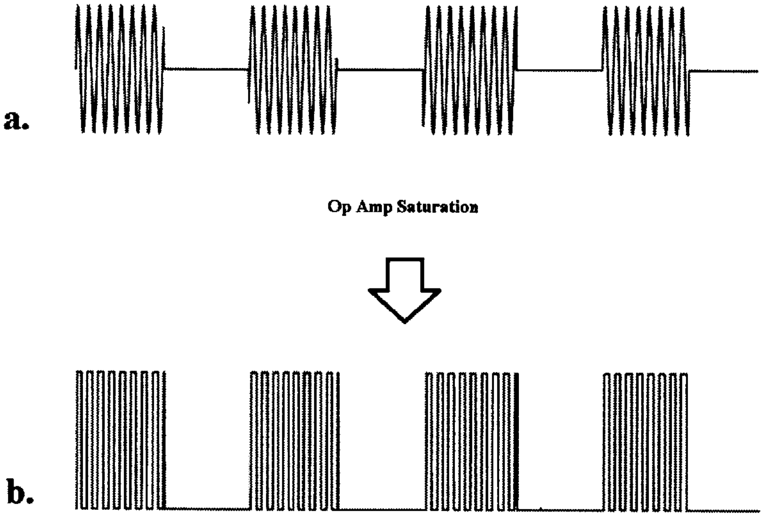


Figure 3-2: Op Amp saturation turns a sinusoidal signal into a digital square wave.

simultaneously[8]. The distance that the signal can travel is determined by the power of the source.

However, the mechanical devices produce the same tone of the same duration each time they are struck. This quality restricts the data transfer to a single frequency and does not allow any waveform manipulation. An effective communication system can still be built using these, but the data rate is limited as only one frequency band can be used for communication. This is the cost of the increased propagation distance of the mechanical devices. In the case of driving and simple sensor reading of the robot, this is a low cost tradeoff.

3.2.1 Serial Communication

The mechanical sound generation devices can be used to communicate via an amplitude keyed serial stream, where an impulse represents a binary 1 and a no impulse represents a binary 0. Timing is critical in this method, and the receiver needs to check at such an interval to capture the correct bits at the correct time. The length of each bit is determined by the duration of the click. To send a stream of data, we first send a "start" bit to indicate the beginning of a transmission. The receiver can then check for on or off signals, converting it into a stream of bits. In this case, each transmission will usually consist of 8 bits, which represents a ASCII character. If a smaller character set is needed, fewer bits can be transferred at a time to increase baud rate (characters per second).

In this communication style, the Arduino must wait for the interrupt that determines the start bit, and then poll the amplifier/digitizing circuitry at predetermined intervals. The program knows the predetermined length of the bit, and waits to poll the amplifier again until after the bit has subsided. It then waits for the next high trigger while keeping track of the time in between high bits. From this timing and the preset bit length, the program can decode the sequence of ones and zeros. Certain bytes, sets of 8 bits, are avoided for critical commands, such as bits with several trailing zeros. Noise can activate the start bit, and it is possible for noise to encode uniform ones, or uniform zeros, but it is less likely that noise will encode a uniquely timed pattern of ones and zeros. By eliminating the noise-prone bytes from the command space, the chances of receiving noise data trigging a critical command are reduced. In this scheme each character takes the same amount of time to send and gives a uniform data rate.

As seen in Fig. 3-3a, the serial signal consists of the start bit followed by a 8 bit stream of data. The combination of ones and zeros encodes the data as a unique character. The character is translated into a command by the receiver. In Fig. 3-3b the waveform of the mechanically generated serial source is shown. The receiver code records the time between the leading edge of each bit, ignoring times less than the preset width of the bit.

3.2.2 Pulse Width Modulation and Pulse Frequency Modulation

Another available communication method is pulse width modulation (PWM). This type of communication is commonly used in servo control, and the control of RC air planes and cars. This method works by sending a carrier square wave to the device,

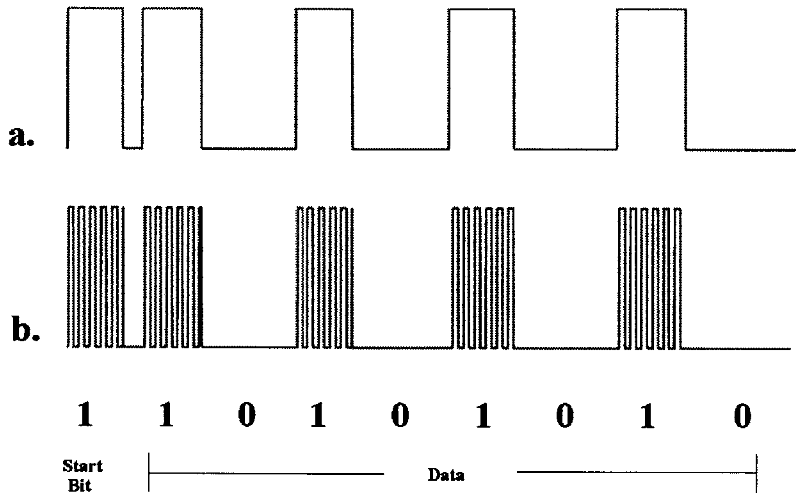


Figure 3-3: a. Serial communication scheme. b. Serial signal from a mechanically generated sound source.

and then modulating the duration of the high pulse of the wave to encode information. Most systems work by keeping the frequency of the wave constant, and varying time that the wave is held high. In the case of mechanically generated sound, the high time, the pulse width, is a constant based on the dissipation time of the vibration of the resonator. That being said, it is possible to modulate frequency of the wave, known hereafter as Pulse Frequency Modulation (PFM), and use that to transmit data in an analogous manner.

The code on the transmitting side of the has a predetermined set of values for a given pulse frequency, and drives the device at the frequency corresponding to the desired character to be sent. On the receiving end, the arduino monitors the signal from the amplifier, once the start of a transmission is signalled by a high on the square wave, the code samples the wave form and determines the pulse frequency by measuring the time until the next high pulse. This delay time is then looked up in a predetermined table and the character transmitted is determined. However, by varying the frequency, some characters are transmitted faster than others– character corresponding to the higher frequencies can be sent quicker than characters sent at a lower frequency. To deal with this, high priority or speed sensitive characters, such as ones encoding "full stop" to the controls or ones encoding sensor data, should be assigned to the higher frequencies. This allows for faster communication for critical signals at the cost of slower communication for less urgent data.

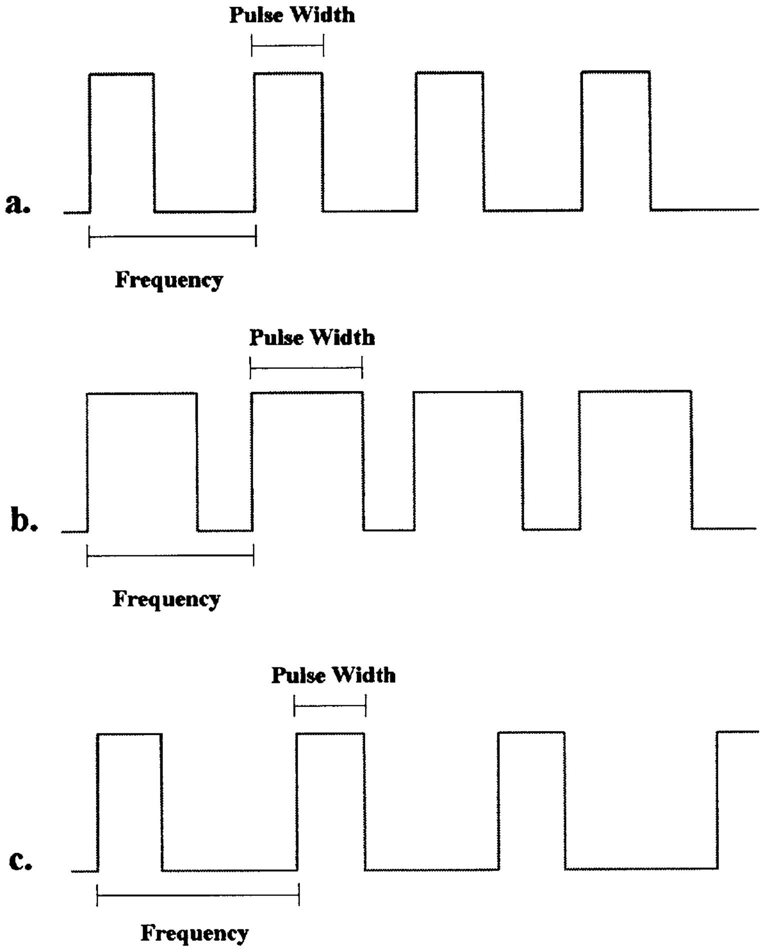


Figure 3-4: a. Regular waveform. b. Pulse width modulated waveform c. Frequency width modulated waveform. Note that the pulsing will appear as a series of square waves, as in Fig. 3-3

As seen in Fig. 3-4b, the classical pulse width modulation encodes data by changing the width of the high pulse. Due to mechanical constraints, the high pulse is constant in this system. However, data can be encoded by modulating the frequency, Fig. 3-4c.

3.2.3 Mixed Protocols

Since the hardware between the two aforementioned methods is identical, and the only difference is in software, both methods can be implemented on the same system. So long as the commands characters use to encode data don't overlap, the methods can be used concurrently, using two listeners in the code on the receiver. They can also be run non-concurrently–a unique command can be used to switch between protocols, or and a time out can be used to switch to the PFM method after a period of inactivity. By using both protocols, the system can achieve a hybrid communication to deal with the demands of the moment. For example, the PFM protocol can be used for control commands–where a small range of commands can be sent quickly, and the serial protocol can be used for sensor data transfer, where a wide range of data at reasonable speed is needed.

Chapter 4

Experimental Results

4.1 Overview

Though intuitively the sound generation of the mechanical devices was amplified in water, there is still a lot to learn about to what degree a signal could be propagated underwater. From a theoretical standpoint, data needs to be taken that can confirm or deny the theory behind the medium-dependent dissipation of the resonator. Sound propagation needs to be explored in both air and water, and the relative amplitudes at given distances needs to be investigated and compared with the model. The duration of the clicks is also dependent on the medium according to the model and data needs to be taken to confirm or deny this theory.

From an application standpoint, it is important to investigate the use of this phenomena and devices as used in a communication system. The range of the devices will be tested and the speed and fidelity of the data as a function of range and ambient noise needs to be explored.

4.2 Medium Dependent Sound Propagation

The effect of the difference of medium on sound propagation from a mechanical device is important to explore in order to understand the physical behavior of the sound in the underwater communication system. The benefits and limitations need to be understood to develop an effective communication system.

4.2.1 Pulse Waveform Analysis

The waveform of the signal at a constant distance was measured in both air and water and compared with the dissipation model. It was expected that the air waveform would be longer in duration and lower in amplitude than the water waveform at the same distance.

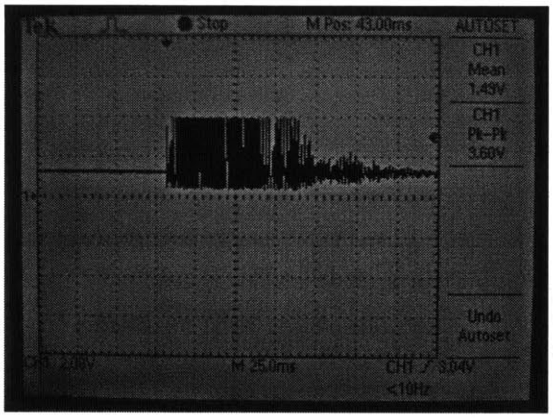


Figure 4-1: This is an image of the sound waveform at full amplification in air. Note the long duration of the pulse.

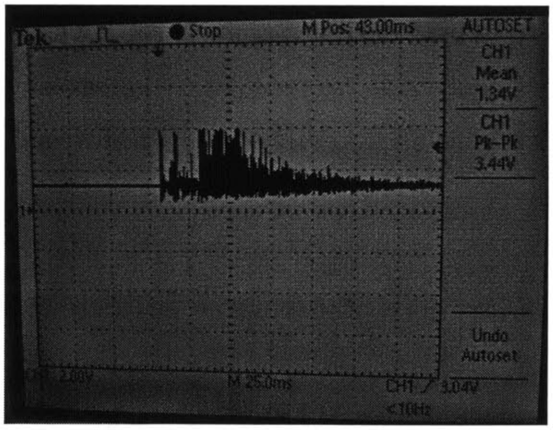


Figure 4-2: This is an image of the sound waveform at full amplification in water. Notice the initial pulse and then echoing effects.

As seen in both waveforms, the result from the sound from the mechanical device is not clean or pure by any means. The pulse starts at saturation of the op amp, and then dissipates as expected, but many of the cycles of the waveform are missed by the amplifier and some unexpected peaks are generated when compared to the model. Most of this is caused by impurities in the sound generation. The aluminium resonator in the device, due to its shape and internal impurities does not produce a pure tone at a single frequency. Rather it produces a set of harmonics that give the resonator its timbre. Also, when the resonator is struck, it is not the only component of the device that rings. The arm of the solenoid also rings and produces its own set of frequencies. The ABS plastic also vibrates and adds noise to the overall generated sound. Thus, the final waveform produced by the device is a combination of all the resultant frequencies and this combination is what is heard as a "click" and is what is seen on the oscilloscope. However, since the microcontroller is looking for the leading edge of the pulse as a trigger this should not affect the transfer of data.

It is interesting to note the echo effect, most prevalent in the waveform of the sound in water. In Fig. 4-2 the initial pulse is seen, and then a echo pulse follows and the waveform appears to die down slowly. As expected by the model, the pulse of the sound in water is shorter in duration, but the waveform appears dissipate slower due to echoing as the original sound reverberates around the tank and is rerecorded. The echo is rather pronounced and can be discerned by the human ear. This echo causes the pulse to linger much longer than anticipated and can cause problems in data transfer if the first signal interrupts into a second pulse.

4.2.2 Propagation Distance Analysis

The device was used to generate clicks while driven at a constant interval. The microphone was placed and several distances from the device and the average peak to peak amplitude of the waveform was recorded. In this test the signal was only sent through a preamplifier to boost the signal to a readable level, and not to achieve op amp saturation. This process was completed in both air and water and the results compared on the basis on distance and amplitude of wave form.

As seen from the data, the sound propagation appears to follow the inverse square law for both air and water, though the water data is slightly noisier and follows the

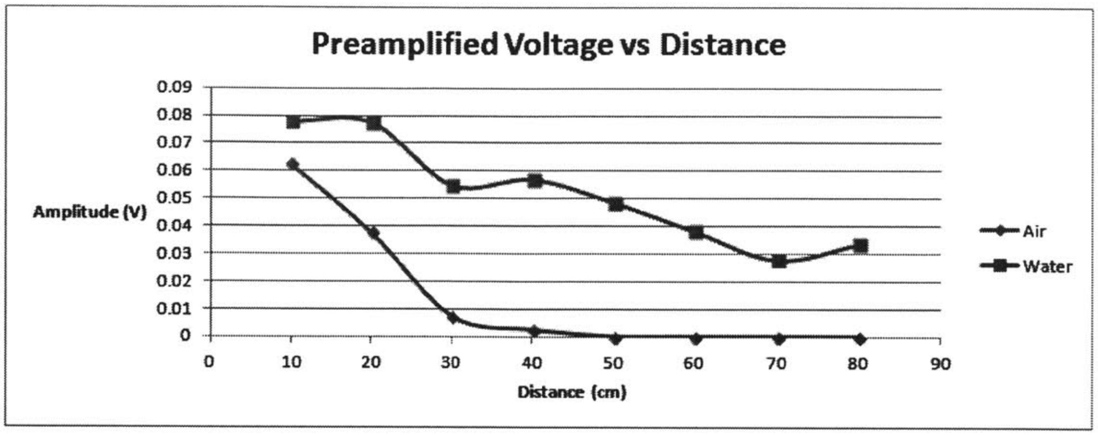


Figure 4-3: Graph of amplitude as a function of distance in water and air. Notice the increased amplitude level in water at any given distance.

trend weaker. This is likely due to the constraints of the tank and echoing. Sound bounces off the walls of the tank and is sent back in the other direction causing the propagation to deviate from inverse square. As expected by the model, the levels of sound in water are higher than the levels of air at a given distance. The signal in air is practically undetectable by 50 cm away from the source while the signal in water is still easily detectable at the full width of the tank. This supports the model that the power of sound from the mechanical device is medium-dependent.

4.3 Communication

Though the ability to induce a response in the microphone from a distance using sound is interesting to study, the usefulness is minimal if it is unable to transmit data reliably. This section analyses the two communication protocols outlined in Chapter 3 in terms of speed and reliability.

For both communication methods, the devices were tested at a variety of bit rates underwater. A series of several characters across the span of the character set was transmitted repeatedly and the number of incorrect or lost bits was recorded. Both protocols were tested in this manner and the results compared.

As seen in Fig. 4-4, both protocols have trouble interpreting bits at shorter bit

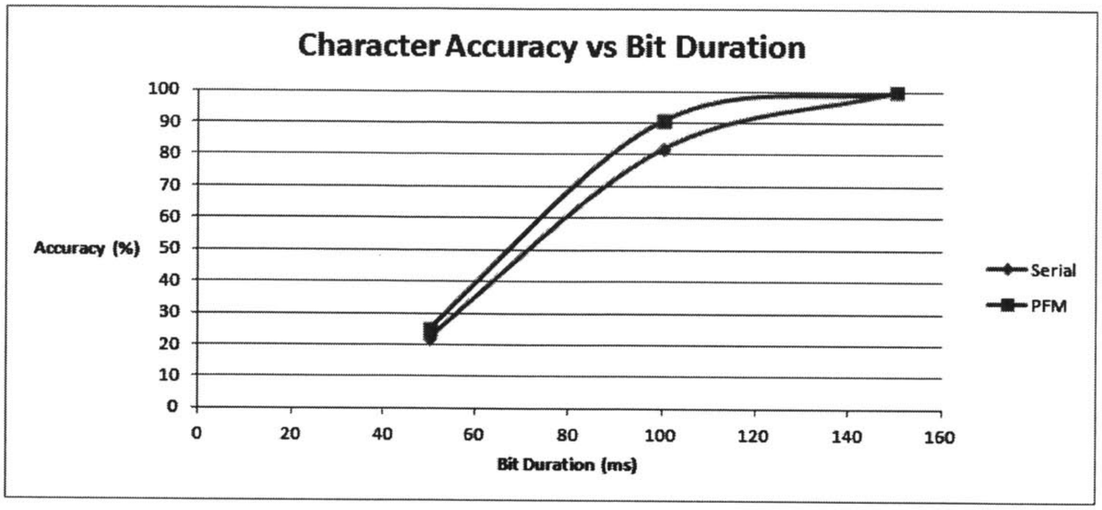
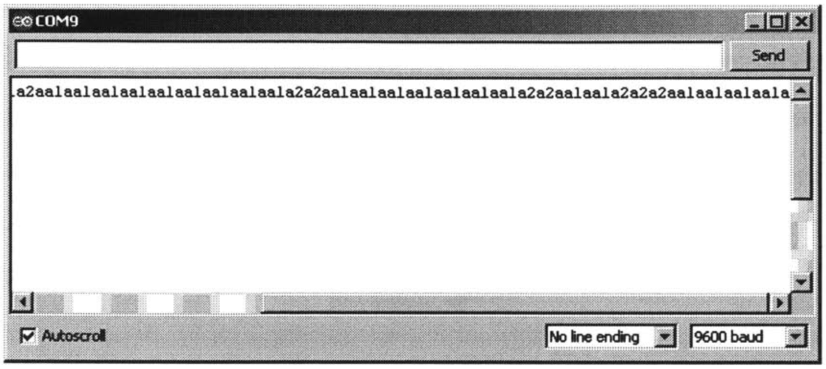


Figure 4-4: Character as a function of bit duration. Notice lost bits at shorter durations. Both protocols achieve virtually 100 percent accuracy at a duration of 150 milliseconds.

times. This is due to the overlap of the echo of the previous bit overlapping into the second bit time region. As seen in Fig. 4-2, the signal is still strong after 50 milliseconds and this is confirmed by the exact error seen in Fig. 4-5. The microcontroller confuses the echo of an old bit with a new bit, resulting in a common error giving the character for the fastest pulsed frequency, 'a'. As the delay between bits is increased and the echo has time to dissipate, the protocols get more and more accurate. At 150ms delay, the protocols are able to effectively receive the correct signal from the source, Fig. 4-4. In Fig. 4-2, the pulse is almost completely dissipated at 150 milliseconds.

The above analysis indicates that a 150 millisecond bit duration is the fastest time that will give us accurate character transmission. Using this delay, it is important to understand which protocol is appropriate for which application.

As seen in Fig. 4-6, the PFM protocol baud rate decreases as an inverse function of character set while the serial protocol decreases as a logarithmic function. There is a breakeven point at 15 characters. Below this, the PFM protocol is preferred, as it can communicate those 15 bits at a faster rate than the serial protocol. This is ideal for driving the robot as 15 characters is enough to control many aspects such as



```
.a2aalaalaalaalaalaalaalaala2a2aalaalaalaalaalaala2a2aalaala2a2a2aalaalaalaala
```

Figure 4-5: Sample of characters received by PFM at 50ms bit duration. Noticed how the sensed bits are errored as at 'a's rather than the correct '1'

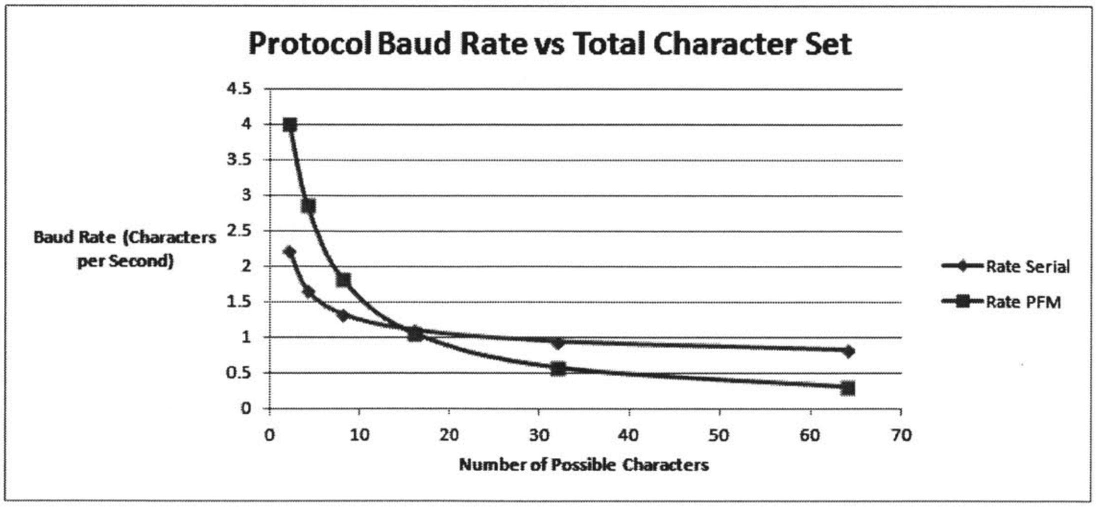


Figure 4-6: waveform in air

direction, speed, or other specialised control functions. Above 15 characters the serial protocol is optimal, as it can send a wider range of characters faster than the PFM. The serial protocol can send characters from the full ASCII set in 1500 ms. This is ideal for sending data from a sensor, as the character width is needed to encapsulate the range of possible readings.

Chapter 5

Conclusion

5.1 Overview

This thesis explored the issues in developing a communication system for a small underwater robot. The solution implemented all the design considerations for the communication device– wireless, long range, compact, and robust. By exploiting the ability of the mechanical device to increase power with intermittancy, it works at long ranges underwater and can be robust, though at the cost of speed. It does not need line of sight to work and the device itself is small enough to be fitted on a small robot. This proof of concept features advantages over other communication styles, but further development is needed and issues must be addressed before it can become a working prototype and product.

5.2 Future Work

Though a significant amount of development on this unique communication style was achieved during the course of this thesis, there is much more work to be done to improve the functionality of the system. The major limitation of mechanical communication device is speed. Though the current system may work for driving a robot and simple data transfer, a faster system is needed for the concept to reach its true potential. The mechanical features of the device can be altered to decrease the ring time of the resonator and different materials could be explored to find one with optimal characteristics. Another way to increase the data rate would be to increase the bandwidth of the device. Several resonators at different frequencies could be added to transfer data simultaneously. A tone decoder or band pass filter can be used on the receiving end to differential between frequencies.

Another issue is noise filtering. Currently there are three sources of noise. First, ambient noise form the environment. Second, noise from impurities in the sound generation. Lastly, echoing of the sound pulse can cause erroneous signalling. The ambient noise problem can be addressed by implementing a band pass filter and selecting frequencies uncommon in the ambient spectrum. This will diminish the amplitude of non-signal sounds and amplify the real signal, effectively filtering out noise. This same method will also filter out impurities from the sound generation, but that means all the energy inputted into the device is not used in the signal, and an efficiency loss occurs. If a better shape for the resonator is chosen, the fundamental frequency could be more pronounced and the device could be more efficient.

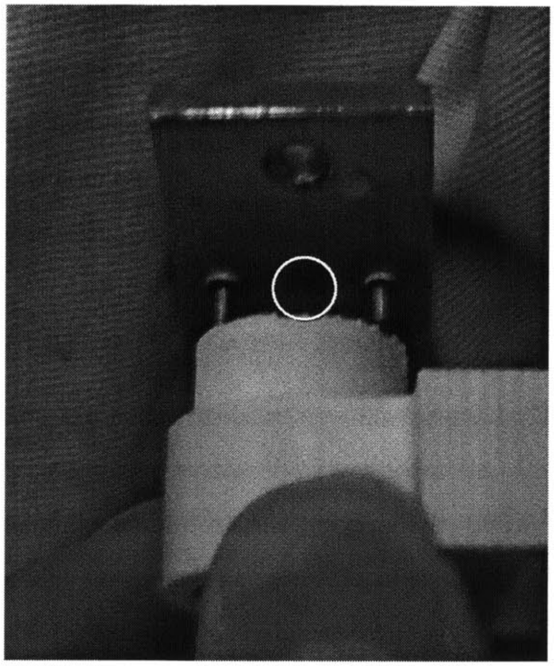


Figure 5-1: Wear on the Mechanical Sound Generator

The longevity of the device was something not considered in this thesis, but something that would need to be improved. Even after the short run time, the resonator experienced some mechanical wear as the solenoid hit it repeatedly, see Fig. 5-1. A harder material could be used for the resonator to help this.

5.3 Applications

The work on this thesis was particularly suited for small robotics communication. This robots perform a many tasks, from ship hull inspection and piping inspection to data collection in underwater locales. This communication system could be used, as it was designed, for the many robots in these niches and allow for effective and compact communication.

The concept of mechanically generated sound as a communicator could be also applied to sensors in a piping system or along underwater bridge supports. By clicking on the steel pipe or truss, the sensors could be communicated with wirelessly and could provide data from sources incommunicable by conventional methods.

In the field of actuation, the same concept used in creating a compact, higher power source by storing up energy can be used. A compact, high power actuator could store energy in a spring driven by a motor or solenoid and then release it in a high force, high power motion. This could be useful when size is a critical consideration, but high power is also needed, such as a small biomemetic jumping robot.

Though this thesis explored and developed a specific solution for a specific problem, the concepts explored could be utilized in applications beyond the scope of the original use.

Appendix A

Arduino Code

A.1 PFM Receive

```
int led = 13;
char bbuf;
unsigned long time;
unsigned long hittime;
unsigned long oldhittime;
unsigned long delayvalue=0;
int timing=100;

void setup() {
  pinMode(12,INPUT);
  pinMode(led, OUTPUT);
  Serial.begin(9600);
  Serial.print("serial initiated");
}

void loop() {

  listenPWM();
```

```
}

void listenPWM(){

  //check for start bit

  if (digitalRead(12)==1){
    oldhittime=hittime;
    hittime=micros();
    charFromPWM();

    //wait until last signal has dissipated
    delay(150);

  }
}

void charFromPWM(){
  //calculate delayvalue and use lookup table to get char
  //15 character set, 0-9 and 5 letters
  // conversion between millis() from signal generator
  delayvalue=2*((hittime-oldhittime));
  delayvalue= (delayvalue+50000)/100000-2;

  //lookup table for characters
  switch (delayvalue){
  case 1:
    bbuf='a';
    break;
  case 2:
    bbuf='b';
```

```
  break;
case 3:
  bbuf='c';
  break;
case 4:
  bbuf='d';
  break;
case 5:
  bbuf='e';
  break;
case 6:
  bbuf='1';
  break;
case 7:
  bbuf='2';
  break;
case 8:
  bbuf='3';
  break;
case 9:
  bbuf='4';
  break;
case 10:
  bbuf='5';
  break;
case 11:
  bbuf='6';
  break;
case 12:
  bbuf='7';
  break;
case 13:
```

```
    bbuf='8';
    break;
  case 14:
    bbuf='9';
    break;
  case 15:
    bbuf='0';
    break;
  default:
    // if nothing matches, do nothing
    ;
  }
  Serial.print(bbuf);
}
```

A.2 PFM Send

```
int led = 13;
int charnumber;
int data;
int i=0;
int message[]= {
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15};

void setup() {
  pinMode(2,INPUT);
  pinMode(led, OUTPUT);
  pinMode(9, OUTPUT);
  Serial.begin(9600);
  Serial.print("serial initiated");
}
```

```
void loop() {

  //change char number argument controls the character sent the character sent
  // send data only when you receive data:
  if (Serial.available() > 0) {
    // read the incoming byte:
    charnumber = Serial.read();
    sendPFM(charnumber);
  }

}

void sendPFM(int i){

  digitalWrite(9,HIGH);
  digitalWrite(led,HIGH);
  delay(20);
  digitalWrite(9,LOW);
  digitalWrite(led,LOW);

  // i is used as a selector for the character to be send
  delay(message[i]*50-130);
  //i++;
  //if (i>=15){i=0;}
  //Serial.println(i);

}
```

A.3 Serial Receive

```
int led = 13;
char buffer;
char bbuf;
int bufcnt=0;
unsigned long time;
unsigned long hittime;
unsigned long oldhittime;
unsigned long delayvalue=10;
int timing=100;

void setup() {
  pinMode(12,INPUT);
  pinMode(led, OUTPUT);
  Serial.begin(9600);
}

void loop() {

  listenSerial();
}

void listenSerial(){
  //Get series of 8 bits and decode as a char. Can change number of bits
  //ollect based on the char set. This uses the full char set of 256 characters.

  if (digitalRead(12)==1){   //wait for high value on pin 12, indicates start bit
    oldhittime=hittime;
    hittime=micros();

    // conversion between millis() from signal generator
```

```
  delayvalue=2*((hittime-oldhittime));
  //conversion to single digit*100 ms
  delayvalue= (delayvalue+50000)/100000-2;

  if (delayvalue<8){
    //recieve 8-bit char
    while (delayvalue> 1){
      digitalWrite(led,LOW);
      //  Serial.print("0");
      bbuf<<=1;                        // add to char buffer
      bbuf+=0;
      delayvalue--;
      bufcnt++;
      if (bufcnt>=8){
        delayvalue=0;
      }
      Serial.print("0");
    }
    if (bufcnt<8){
      digitalWrite(led, HIGH);
      //Serial.print("1");
      bbuf<<=1;                        // add to char buffer
      bbuf+=1;
      bufcnt++;
      Serial.print("1");
    }
  }

  //wait until last signal has dissipated
  delay(150);

}
```

```
  if (bufcnt>=8){
    bufcnt=0;          //release char buffer with recieved character
    buffer=bbuf;
    ////   Serial.println(bbuf,BIN);
    Serial.println("");
    hittime=0;
    //   Serial.print(bbuf);
    bbuf=0;
  }

}
```

A.4 Serial Send

```
int led = 13;
char buffer;
int charnumber;
int data;
int i=0;

void setup() {
  pinMode(2,INPUT);
  pinMode(led, OUTPUT);
  pinMode(9, OUTPUT);
  Serial.begin(9600);
  Serial.print("serial initiated");
}

void loop() {

  //change char number argument controls the character sent the character sent
  // send data only when you receive data:
```

```
  if (Serial.available() > 0) {
    // read the incoming byte:
    charnumber = Serial.read();
    sendPFM(charnumber);
  }

}

void sendPFM(char bbuf){
  //start bit
  digitalWrite(9,HIGH);
  digitalWrite(led,HIGH);
  delay(20);
  digitalWrite(9,LOW);
  digitalWrite(led,LOW);
  delay(150);

  //data bits
 for (i=8, i>0, i--){
//selector for hig bits
 if (bbuf-2^i!=bbuf){
     digitalWrite(9,HIGH);
  digitalWrite(led,HIGH);
  delay(20);
  digitalWrite(9,LOW);
  digitalWrite(led,LOW);
 }
 //otherwise send nothing
 delay(150);
}

  //stop bit
```

```
  digitalWrite(9,HIGH);
  digitalWrite(led,HIGH);
  delay(20);
  digitalWrite(9,LOW);
  digitalWrite(led,LOW);
  delay(150);
}
```

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