Focusing Sound Waves Using a Nonlinear Acoustic Lens

Thorsen M. Wehr
Odessa High School, Odessa, WA 99159
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ABSTRACT

Sound waves originate in a variety of applications each day such as ultrasonic toothbrushes and medical devices. In nature, nonlinear acoustic lenses are found in aquatic mammals which echolocate such as dolphins and certain whales. The purpose of this research was to engineer chains of spheres creating a nonlinear acoustic lens. Outer chains would be precompressed compared to inner chains so that an acoustic signal traveling through them had different amounts of delay through certain chains. The waves traveling through each chain met at a specific point and formed increased amplitude. A device consisting of a nonlinear acoustic lens, an impactor, a truss system to support both the lens and the impactor, and a microphone array was designed, assembled, and tested. At 10 cm from the bottom of the acoustic lens, a noticeable increase in amplitude was detected in multiple trials (Control: 2491 RA; Experimental: 4817 RA). This indicated that the precompressed chains within the nonlinear acoustic lens were affecting the relative amplitude during the experimental trials. To date, an improved acoustic lens is being developed with more adjustment and precise machining. The data supports a focusing effect and, with minor adjustments, should produce an increase in amplitude at a specific focal point.

Introduction

Sound waves originate in a variety of applications each day such as ultrasonic toothbrushes, medical ultrasound devices, and the use of echolocation in marine mammals such as dolphins and whales. No matter the organism or the device, the principle mechanics behind all sound is similar. Sound is a mechanical wave that is a wavering of pressure moving through a solid, liquid, or gas (Figure 1). The pressure alternates between zones of compression and

![Figure 1. Sound is a physical vibration alternating between zones of compression and rarefaction in a medium (such as air). The properties of waves include the wavelength ($\lambda$) which equals the phase velocity ($v$) divided by the frequency ($f$). The amplitude is the magnitude of change proportional to the change in pressure during one wavelength (Dewey, 2007).](image-url)
rarefaction; one complete alternating cycle is the wavelength. The wavelength is linked to the phase velocity, or speed of the wave in a medium, and the frequency (number of wavelengths per unit time). During the wave’s broadcast, it can be reflected, refracted, or adjusted by the material it travels within. There is a relationship between the density of the medium and the pressure created by the wave, and this relationship, affected by temperature, determines the phase velocity of sound within the material. As the sound wave travels from one medium to another, the difference in velocity is created by an acoustic lens effect.

Sound pressure can be measured in decibels (dB) which is a logarithmic unit that tells the ratio of a physical quantity (usually power or intensity) relative to a specified or implied reference level. A ratio in decibels is ten times the logarithm to base 10 of the ratio of two power quantities:  \( I (dB) = 10 \times \log_{10} \left( \frac{I}{I_0} \right) \). This means the sound level at a certain distance is in a logarithmic proportion to the sound level at a different distance, or \( I_2 = I_1 + (20 \times \log(d_1/d_2)) \), where \( I_2 \) is the sound intensity at distance \( d_2 \), and \( I_1 \) is the intensity at distance \( d_1 \) (Nave, 2011).

Sound waves are capable of creating images by non-invasively contacting the object, such as an unborn baby (ultrasound from doctor) or underwater ruins (sonar from ship). As light waves can be focused into a single point using a glass lens, in turn it occurs with sound waves as well. However, these images can be hard to focus and therefore the signals produced are murky and often show little more than grainy spots moving against a black background (Figure 2). Researcher Karpelson (2002) created a method determining an acoustic lens surface profile for a desired acoustic field. This method was applied and a logarithmic lens designed, made, and tested. The experimental data matched the theoretical computations and thus confirmed one nonlinear acoustic lens application. In 2010, CalTech researchers Spadoni and Daraio successfully focused sound waves using a nonlinear acoustic lens resulting in a pressure
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Figure 2. (A) A modern ultrasound image; it is blurry and difficult to analyze (Advanced Fertility Center of Chicago, 2009), and (B) A modern sonar image (Sawkins, 2010).

field in air with a focal point \((x_f = 9 \text{ cm}, y_f = 7 \text{ cm})\) while attaining a maximum pressure \(P_B \approx 79 \text{ Pa}\) (corresponding to 38 dB) (Spadoni & Daraio, 2010) (Figure 3).

Another use for focused sound waves is sonic and ultrasonic weapons (USW) (Figure 4). These are non-lethal weapons of various types that use sound to injure or incapacitate an

Figure 3. (A) Nonlinear acoustic lens via 21 chains of 21 balls used to create focused sound (blue and red), and (B) One of many practical applications of focusing sound through an acoustic lens; the operator would not require replacement of medical components, but rather adjust the precompression on each chain to target the desired image location (Spadoni & Daraio, 2010).
Figure 4. A non-lethal ultrasonic weapon (or USW) used by the police and military for crowd control during outbreaks and riots (Fox, 2010).

opponent. The weapon runs on LPG, which mixes with oxygen to produce powerful bursts of sound. Each sound burst lasts around 300 milliseconds, and generates a convulsion that travels from the cannon at roughly six times the speed of sound (Fox, 2010). This is useful to stop riots, control crowds, and disperse people from an area. In nature, nonlinear acoustic lens are found in aquatic mammals which echolocate such as dolphins and certain whales (Figure 5). A large waxy sphere inside the forehead focuses the returning reflected beam from prey, allowing the precise location of the prey to be determined.

Figure 5. An example of a natural acoustic lens. As a dolphin uses echolocation, it transmits a wave which is later reflected back from its prey. The reflected waves pass through a large waxy portion of the forehead acting as an acoustic lens. This lens focuses the waves into a tight beam which the dolphin unknowingly uses to accurately determine the distance of the prey (Welsh Assembly Government, 2011).
The purpose of this research was to engineer chains of spheres creating a nonlinear acoustic lens. Outer chains would be precompressed compared to inner chains so that an acoustic signal traveling through them had different amounts of delay through certain chains. The waves traveling through each chain should meet at a specific point and form increased relative amplitude; at the point where all the waves meet, they would form a focal point. The focal point should form at different distances from the acoustic lens by changing the force (or pressure) on the spheres. If the outer chains are pressurized more than the inner ones, the waves should travel faster in the outer chains. If the acoustic lens is not precompressed (Control data), there should not be an increase in amplitude at a specific focal point. If the acoustic lens is precompressed (Experimental data), there should be an increase in amplitude at a specific focal point.

**Materials and Methods**

A device for focusing sound was engineered, created, and assembled. It consisted of a nonlinear acoustic lens, an impactor, a truss system to support both the lens and the impactor, and a microphone array for data collection. The truss system consisted of two rails of PVC tubing 60.0 cm long (ID 2.5 cm; OD 3.3 cm) attached over 91.4 cm long x 1.9 cm diameter all-thread (Figure 6). Two other pieces of PVC tubing 30.0 cm in length (ID 3.4 cm; OD 4.0 cm) were used over the original PVC rail pieces to produce a low-friction sliding system (Figure 6A). PVC was used because it has a very low coefficient of friction ($\mu_k<0.02$). The bottom of the all-thread was then bolted through wooden planks and tightened to stabilize the truss system. The truss system was placed on two platforms to raise the acoustic lens roughly one meter in the air.

The impactor consisted of 9 bolts (10.2 cm) going through 9 holes in a steel bar (23.5 cm long; 3.7 cm wide; 0.8 cm thick) (Figure 6B). The impacting bolts were held in place by nuts on the top and bottom of the plates on the impacting bolts (Figure 7). The nuts were used to
Figure 6. The entire truss system, (A) two rails of PVC anchored on top of all-thread with two other rails of PVC over those. The impactor (B) was attached to the outer PVC to produce a low-friction sliding system, (C) the nonlinear acoustic lens anchored to the truss system where (D) the microphone array collected the acoustic signal refracted through the nonlinear acoustic lens.

Adjust the height of each impacting bolt to ensure simultaneous impact on each of the 9 chains of the acoustic lens. Each impacting bolt was 1.8 cm from the next. The impactor plate was welded to adjustable clamps which were each attached to the larger PVC rails. The impactor (plate, impacting bolts and nuts, clamps, and PVC rails) had a mass of 1.8 kg.

The acoustic lens was created from 9 segments of aluminum piping 13.5 cm long (ID 1.60 cm; OD 2.10 cm); aluminum was used for its lighter density compared to other metals ($\rho = 2712$...
Figure 7. The impactor connected to the larger PVC rails by welded clamps that slid down the smaller stationary PVC to strike the acoustic lens.

kg/m$^3$) (Figure 6C). Nine aluminum segments (chains) were chosen because it was predicted that an odd number of chains would better produce the precompression ratio for each chain (Spadoni & Daraio, 2010). Each of the 9 aluminum chains were filled with a column of 9 stainless steel spheres (1.59 cm diameter). Washers (ID 1.4 cm; OD 2.0 cm) were welded to the bottom of a steel plate (23.0 cm long; 2.5 cm wide; 0.5 cm thick) which stopped the aluminum chains but allowed the bottom spheres to protrude out the end of each chain (Figure 8). This protrusion of each sphere from each aluminum chain ensured the sound wave created by the impactor did not get muffled by the diameter of the aluminum pipe.

Figure 8. The bottom of the nonlinear acoustic lens revealing the last sphere protruding from each chain.
At the top of the acoustic lens the aluminum chains seated against an aluminum plate (25.0 cm long; 2.5 cm wide; 0.3 cm thick). Nine holes were drilled and threaded (1.5 mm pitch) through the aluminum plate so nine adjusting bolts (1.2 cm diameter; 1.5 mm pitch; 1.8 cm apart) could screw into each hole (Figure 9). The adjusting bolts were hollowed out to allow for the impactor’s striking bolts to travel through and strike the top spheres in each chain simultaneously (Figure 10). A spacer washer (ID 1.4 cm; OD 1.5 cm) was placed on the top sphere in each chain so that when the adjusting bolts were tightened they seated against the washer and the sphere respectively. The top aluminum plate had a bracket created to attach to the all-thread and the bottom steel plate was welded to the all-thread truss system to ensure stability. A diagram of one chain creating the nonlinear acoustic lens is found in Figure 11 to help explain the inner mechanics of the chain.

The microphone array was created by connecting a board (70 cm) to a ring stand; the board was adjusted to raise and lower the microphone array (Figure 6D). Multiple Audio-Technica...
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Figure 10. The impactor and impacting bolts (A) sliding through the adjusting bolts (B) on top of the acoustic lens (C).

PRO-44 Cardioid condenser boundary microphones were placed in line with one another, alternating their position to overlap the range of each microphone (see Appendix A for microphone specifications). The microphones were perpendicularly positioned $X$ cm away from the bottom of the acoustic lens (where $X = 6$ cm through 92 cm; at 2 cm increments during Phase 1 and $X = 2$ through 20 cm at 1 cm increments during Phase 2 and Phase 3). Each microphone in the array was connected to an independent channel (set to 25%) on a Tascam FW-1804 digital

Figure 11. A diagram of one aluminum chain filled with nine spheres. The measurements reveal the inner mechanics of the device creating the nonlinear acoustic lens. Eight more chains 1.8 cm apart (center of sphere to center of sphere) extend toward the right.
mixing component attached via IEEE 1394-firewire (400 Mb/s transfer rate) to a laptop computer running Microsoft Windows XP OS (see Appendix B for Tascam specifications). The live audio signal was converted to electrical voltage and recorded using Cubase LE digital mixing software (Version 1.07). The independent signals were set to -30.00 dB, as well as the main output signal, so each signal would not be lost at higher amplitudes during recording.

When collecting the Control data, the chains in the nonlinear acoustic lens were not precompressed with any force (except the natural force of the weight of the 9 spheres). The impactor was raised to a height of 8 cm. To allow for consistency, a metal template 8 cm tall was placed between the impactor and the acoustic lens, then suddenly removed. During Phase 1, four independent signals were recorded at a range of 6 cm through 92 cm at 2 cm increments for a total of 696 samples. During Phase 2, three independent signals were recorded at a range of 2 cm through 30 cm at 1 cm increments for a total of 114 samples. During Phase 3, three independent signals were recorded at a range of 2 cm through 20 cm at 1 cm increments five times each for a total of 570 samples.

When collecting the Experimental data during Phase 1 (Spring Scale Method), the chains in the nonlinear acoustic lens were precompressed with a ratio created from the research of Spadoni & Daraio (Figure 12). Determining the force needed for each chain of spheres, a force curve was obtained from Spadoni’s and Daraio’s research (using 21 chains) (Figure 12A). Observing their force curve and superimposing data from this research (using 9 chains), the chains were set in pairs from outermost to innermost at 14.0 N, 6.0 N, 1.5 N, 0.5 N, and 0 N (middle chain) (Figure 12B). The applied force from the adjusting bolt onto each chain of spheres was calculated using the torque of the bolt and the torque on the wrench: \( \tau_{\text{bolt}} = \tau_{\text{wrench}} \). Reverse calculations revealed that an applied force of 14.0 N from the bolt needed an input force of 0.3 N on the wrench (see
Figure 12. Determining the force (N) needed for each chain of balls. (A) Force curve obtained from Spadoni’s and Daraio’s research (using 21 chains); outermost chains with high amount of force relative to middle chains with little force, (B) Force curve calculated for this research (using 9 chains), (C) Data from this research superimposed with Spadoni’s and Daraio’s data indicating that even though the number of chains varies, the force curve was replicated (Spadoni and Daraio, 2010).

Appendix C for calculations) (Figure 9). Data from this research was superimposed with Spadoni’s and Daraio’s data indicating that even though the number of chains varied, the force curve was replicated (Figure 12C). A spring scale was attached to the wrench to verify the input force. Once the chains were precompressed, the impactor was again raised to a height of 8 cm using the metal template, and then suddenly removed. The independent signals were recorded at a ranges indicated previously for Phase 1. A decibel meter was used to determine the intensity of the sound wave produced by the acoustic lens at the minimum, maximum, and average distance for each Phase.

After reviewing the data from the Spring Scale Method of applied force adjustment, it was determined a more accurate applied force method was needed to be developed. To determine a more precise force, the top plate of the acoustic lens with adjusting bolt was removed and clamped to a ring stand. One sphere was placed on its spacer washer and positioned directly under the top plate and adjusting bolt, but on top of a mass scale (Figure 13). The top plate
rested almost touching the sphere, but did not add any mass to the system. The mass scale was turned on and the sphere and spacer washer was zeroed. The adjusting bolt was then screwed into the hole in the top plate and turned by 16

Because the scale had a maximum mass (2000 g), data was recorded until the scale reached its maximum. Using the formula \( F=ma \), the mass was converted into force. The data obtained was inputted into a spreadsheet to derive a power law trend line which fit the data (Figure 14A).

Figure 14. (A) A plot of the revolutions the adjusting bolt was turned to produce the force applied. Once the force meter was maximized, a power law equation was derived to be able to dial the adjusting bolt to any desired force, and (B) A diagram of the adjusting bolt and the revolutions (turns) used to determine the force applied \( (F_0) \) to the chain of spheres inside.
The equation \( y = 39.50x^{2.691} \) was used to calculate the applied force the adjusting bolt provided on the acoustic lens’ adjusting bolt (Figure 14B). It was exciting to reveal that there was a significant correlation between the number of revolutions turned on the adjusting bolt and the force applied to the spheres in the chains \( (R^2 = .981) \). Hertzian contact stress equation calculated the stress development of the spherical masses. As the force between the spheres increased, the area where they were in contact also increased. This area was calculated by applying known variables within the equation such as the force applied and the compiled variable \( K_a \): 

\[
A = K_a^{3/2} F
\]

where \( K_a \) uses specific numerical values such as Poisson’s ratio, the modulus of elasticity, the diameter of the sphere, and the material of which the spheres were made (Appendix D). Like in the Spring Scale Method; the forces applied to each chain were set in pairs from outermost to innermost at 14.0 N, 6.0 N, 1.5 N, 0.5 N, and 0 N (middle chain). This method was entitled the Rotational Method (Figure 15).

After the Control and Experimental data were recorded, the channels were mixed simultaneously from Cubase LE (at -30 dB) and exported to SigView32 signal analyzing software (Version 2.2.5) to find the positive and negative values of the relative amplitude produced by the impactor on the chains in the acoustic lens (Figure 16). These values were used

![Figure 15. Rotational method of adjusting the force applied to produce the precompression force on each chain.](image-url)
to find the average relative amplitude at each distance away from the bottom of the acoustic lens. This was placed into a graph and a logarithmic curve was used to find an $R^2$ value between amplitude and distance. If an increase in relative amplitude was discovered, the data from those locations in the Experimental data would be statistically analyzed using a two-tailed t-test (test that compares two sets of data) to the Control data.

**Results**

**Phase 1 (Spring Scale Method)**

The decibel meter from 6 cm away from the end of the nonlinear acoustic lens had an average pressure of 78.9 dB (high: 81.2 dB; low: 77.6 dB). The decibel meter from 92 cm away from the end of the acoustic lens had an average pressure of 64.3 dB (high: 70.0 dB; low: 59.8 dB).

The data for the Control trials was measured using relative amplitude. The Control data had average relative amplitude of 3205 with a high of 7735 and a low of 1739 ($N=696$). Placing the data within a logarithmic curve revealed a significant correlation between the relative amplitude and the distance the microphone array was from the end of the nonlinear acoustic lens ($R^2 =$
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0.943) (Figure 17). \( R^2 \) is just a correlation between the X and Y axis, where 1 would be a 100% correlation and 0 would be completely random.

The data for the Experimental trials was measured using relative amplitude as well. The Experimental data had average relative amplitude of 3387 with a high of 8052 and a low of 1841 (N=696). Placing the data within a logarithmic curve revealed a significant correlation between the relative amplitude and the distance the microphone array was from the end of the nonlinear acoustic lens (\( R^2 = 0.884 \)) (Figure 18).

After comparing the Experimental data to the Control data, a noticeable increase in relative amplitude was apparent at 26 cm (Control: 4232; Experimental: 5505). When comparing the

![Figure 17. The Control data during Phase 1 revealing the relative amplitude compared to the distance (cm) the trial was recorded from the nonlinear acoustic lens. A logarithmic trend line reveals the consistency of the data (\( R^2 = 0.943 \)).](image-url)
Figure 18. The Experimental data revealing the relative amplitude compared to the distance (cm) the trial was recorded from the nonlinear acoustic lens. A logarithmic trend line reveals the consistency of the data ($R^2 = 0.884$). At 26 cm away from the bottom of the acoustic lens, a noticeable increase in amplitude is discovered compared to the Control data (noted yellow).

Experimental and Control data at this point, it was found they were statistically different at the 90% confidence level (two-tailed t-test; $t$-value = ±1.89; df = 8; $p < 0.1$). When the segment of data was isolated from both the Control data and the Experimental data around the suspected focus point of sound (24 – 28 cm), the Control and Experimental data were relatively the same amplitude except at 26 cm.

**Phase 2 (Rotational Method; Initial Trials)**

The decibel meter from 2 cm away from the end of the nonlinear acoustic lens had an average pressure of 73.5 dB (high: 74.7 dB; low: 72.6 dB). The decibel meter from 20 cm away from the end of the acoustic lens had an average pressure of 68.6 dB (high: 72.9 dB; low: 66.3 dB).
The data for the Control trials was measured using relative amplitude. The Control data had average relative amplitude of 3341 with a high of 6744 and a low of 2277 (N=114). Placing the data within a logarithmic curve revealed a significant correlation between the relative amplitude and the distance the microphone array was from the end of the nonlinear acoustic lens ($R^2 = 0.814$) (Figure 19).

The data for the Experimental trials was measured using relative amplitude as well. The Experimental data had average relative amplitude of 3512 with a high of 5546 and a low of 2454 (N=114). Placing the data within a logarithmic curve revealed a significant correlation between the relative amplitude and the distance the microphone array was from the end of the nonlinear acoustic lens ($R^2 = 0.388$) (Figure 20).

Figure 19. The Control data using the rotational method, revealing the relative amplitude compared to the distance (cm) the trial was recorded from the nonlinear acoustic lens. A logarithmic trend line revealing the consistency of the data ($R^2 = 0.814$).
Figure 20. The Experimental data revealing the relative amplitude compared to the distance (cm) the trial was recorded from the nonlinear acoustic lens. A logarithmic trend line reveals the consistency of the data ($R^2 = 0.388$). At 10 cm away from the bottom of the acoustic lens, a noticeable increase in amplitude was discovered compared to the Control data (noted yellow).

After comparing the Experimental data to the Control data (Rotational Method), a noticeable increase in relative amplitude was apparent at approximately 11 cm (Control: 2491; Experimental: 4817). When comparing the Experimental and Control data at this point, it was found they were statistically different at the 95% confidence level (two-tailed t-test; $t$-value = ±10.77; $df = 2$; $p < 0.05$).

**Phase 3 (Rotational Method; Multiple Trials)**

The decibel meter from 2 cm away from the end of the nonlinear acoustic lens had an average pressure of 73.5 dB while the decibel meter from 20 cm away from the end of the acoustic lens
had an average pressure of 68.6 dB. The data for the Control trials was measured using relative amplitude. The Control data had average relative amplitude of 4266 with a high of 5492 and a low of 3111 (N=570). Placing the data within a logarithmic curve revealed a significant correlation between the relative amplitude and the distance the microphone array was from the end of the nonlinear acoustic lens (R² = 0.835) (Figure 21).

The data for the Experimental trials was measured using relative amplitude as well. The Experimental data had average relative amplitude of 3738 with a high of 6046 and a low of 2122 (N=570). Placing the data within a logarithmic curve revealed a significant correlation between

![Figure 21. The Control data using the rotational method, revealing the relative amplitude compared to the distance (cm) the trial was recorded from the nonlinear acoustic lens. A logarithmic trend line revealing the consistency of the data (R² = 0.835). Error bars were calculated using the standard deviation of each set of ten data points for every distance.](image-url)
the relative amplitude and the distance the microphone array was from the end of the nonlinear acoustic lens ($R^2 = 0.673$) (Figure 22).

After comparing the Experimental data to the Control data (Rotational Method), another noticeable increase in relative amplitude was apparent at approximately 10 cm (Control: 4140; Experimental: 5049). When comparing the Experimental and Control data at this point, it was found they were statistically different at the 95% confidence level (two-tailed t-test; $t$-value = $\pm 2.176$; df = 18; $p < 0.05$).

![Figure 22. The Experimental data revealing the relative amplitude compared to the distance (cm) the trial was recorded from the nonlinear acoustic lens. A logarithmic trend line reveals the consistency of the data ($R^2 = 0.673$). At 10 cm away from the bottom of the acoustic lens, a noticeable increase in amplitude is discovered compared to the Control data (noted in yellow). Error bars were calculated using the standard deviation of each set of five data points for each distance.](image-url)
Discussion

This research was considered successful since the nonlinear acoustic lens was engineered, created, and provided considerable initial results. Both the Control and Experimental data produced valid logarithmic trend lines (Phase 1; $R^2 = 0.943$; $R^2 = 0.884$ respectively/ Phase 2; $R^2 = 0.814$; $R^2 = 0.388$; Phase 3; $R^2 = 0.835$; $R^2 = 0.673$). It was noted that all data points almost perfectly form to the Control data’s trend line, while the Experimental data is slightly higher and lower at times. Notice in Phase 1 that the Control data had a much greater $R^2$ value than the Experimental data, and this is thought to be because of the force put on the spheres. Because the force applied was not very accurate, the energy exerted was not focused properly causing varied relative amplitude (lowering the $R^2$ value in the Experimental data). In Phase 2, the Control also had a larger $R^2$ value than the Experimental data. This was again thought to be from the applied force on each chain system. However, the sound was much more effectively focused than Phase 1 and caused larger amplitude around 10 cm. Since the same amplitude was seen again in Phase 3 and at that same distance away from the acoustic lens (10 cm), it is assumed that these spikes in amplitude were caused by the new method of applying the force to each chain effectively. This indicates the nonlinear acoustic lens is affecting the relative amplitude during the Experimental trials in all three Phases of experimentation (Figure 23).

Regarding the noticeable focal point at 26 cm (Phase 1), it is uncertain if this is due to the precompressed nonlinear acoustic lens or not, but it was a hopeful beginning. Spadoni’s & Daraio’s research found a focal point at $x_f = 9$ cm, however their research also contained 21 spheres in 21 chains. Also, Spadoni’s & Daraio’s research revealed a pressure of $p_B \approx 79$ Pa corresponding to approximately 38 dB. The 9-chain system used during this research did not calculate a direct sound pressure level (Pa), but did reveal a sound level of 66 dB at the assumed
Figure 23. The Control data and Experimental data from Phase 3 shown simultaneously. It is uncertain why the data is lower for the Experimental for most data points, but it is thought to be from the acoustic lens not being focused at all the points besides 10cm, thus lowering the amplitude.

focus point in each phase. Although this value is higher, it did indicate that the method used and the acoustic lens may have been functioning correctly. However, it was thought the force applied with the wrench and force meter was too high and unreliable. The force meter was a fairly simple spring scale that returned variable results each time it was used, therefore the Rotational Method was devised.

After the impactor was engineered, it had a relatively higher mass than what was found in Spadoni’s & Daraio’s research; the mass of the impactor in their research was the same as one chain of spheres (21). In this experiment, the mass of the impactor was 1.8 kg and one chain of spheres was 149 g. At this point it is uncertain if the extra mass had an effect on the data, but a
possible future improvement could be either changing the mass of the impactor to 149 g or modifying the existing impactor to deliver a force of 1.46 N (149 g) on impact.

A future improvement for this research would be to take a solid cylinder of aluminum and machine ideal holding cells which fit the steel spheres perfectly (Figure 25). The spacing between each chain of spheres could be better controlled as well as the height of each chain relative to all other chains. The end spheres protruding from the bottom of the aluminum cylinder would also be uniform. The top of the cylinder would still house threaded adjusting bolts, and together might create an ideal non-linear acoustic lens. The adjusting bolts will be extended to allow for more pressure to strike each sphere as well as have more precise adjustments so that simultaneous impact would be ensured. Finally, more trials will be run on specific areas instead

Figure 25. A diagram of a future acoustic lens, a cylinder. (A) The top of the acoustic lens showing the adjusting bolts and the hypothesized force for each with key. (B) The new acoustic lens form the side showing the spheres in each channel with the end sticking out. (C) The side of the acoustic lens showing the impacting bolts and adjusting bolts with four PVC sliding rails (three are shown, another one would be in front of the spheres).
of few trials at longer distances because it is apparent that the focal point is located between 5 cm and 12 cm away from the acoustic lens at the current applied force ratios.

In conclusion, the engineering of the nonlinear acoustic lens, impactor, and analyzing system was accomplished. The data supports a focusing effect and with minor adjustments, should produce an increase in amplitude at a specific focal point. It is predicted that this increase in amplitude could be considerably higher than any other data point at a specific distance from the acoustic lens.
Acknowledgements

I would like to thank Dr. Daraio for her technical assistance and clarification of her research at CalTech. I would like to thank Jeff Wehr for financial and scientific support, and access to materials in the laboratory. I would like to thank Gary Smith for assisting in metal and wood working for the truss system, the acoustic lens, and the impactor. I would also like to thank Julie Wehr for helpful thinking and support. I would like to thank the Odessa School District for laboratory supplies.
References and Literature Cited


# APPENDIX A. Audio-Technica PRO-44 cardioid condenser boundary microphone specifications (Audio-Technica, 2011)

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<th>SPECIFICATIONS</th>
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<tr>
<td>ELEMENT</td>
<td>Fixed-charge back plate, permanently polarized condenser</td>
</tr>
<tr>
<td>POLAR PATTERN</td>
<td>Half-cardioid (cardioid in hemisphere above mounting surface)</td>
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<tr>
<td>FREQUENCY RESPONSE</td>
<td>70-16,000 Hz</td>
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<td>OPEN CIRCUIT SENSITIVITY</td>
<td>-25 dB (66.2 mV) re 1V at 1 Pa</td>
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<td>IMPEDANCE</td>
<td>100 ohms</td>
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<td>MAXIMUM INPUT SOUND LEVEL</td>
<td>114 dB SPL, 1 kHz at 1% T.H.D.</td>
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<td>DYNAMIC RANGE (TYPICAL)</td>
<td>86 dB, 1 kHz at Max SPL</td>
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<tr>
<td>SIGNAL-TO-NOISE RATIO</td>
<td>66 dB, 1 kHz at 1 Pa</td>
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<tr>
<td>PHANTOM POWER REQUIREMENTS</td>
<td>9-52V, 2 mA typical</td>
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<td>WEIGHT</td>
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<td>DIMENSIONS</td>
<td>2.87” (73.0 mm) maximum width, 3.56” (90.5 mm) maximum length, 0.59” (15.0 mm) height</td>
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<td>OUTPUT CONNECTOR</td>
<td>TB3M-type</td>
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<tr>
<td>CABLE</td>
<td>25’ (7.6 m) long, with TA3F and XLRM-type connectors</td>
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APPENDIX B. Tascam FW-1804 Digital PC Audio Interface (Tascam TEAC Professional, 2005).

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FW-1804 SPECIFICATIONS
- 18-in/12-out audio interface
- Records at up to 96kHz/24-bit
- Four balanced XLR / 1/4" TRS mic/line inputs with phantom power
- Four balanced 1/4" TRS line inputs
- 1/4" TRS insert jacks for channels 1-4
- S/PDIF and ADAT digital input and output
- Word clock in and out
- Balanced 1/4" TRS monitor outputs
- Headphone output with level control
- Two MIDI inputs and four MIDI outputs
- Assignable footswitch jack
- Includes GigaStudio 3 LE
- Includes Steinberg Cubase LE 48-track 96kHz workstation software
- Dimensions: 15"W x 3.75"H x 14.5"D
- Weight: 12.6 lbs.
- Compatible with the latest Intel Macs

FW-1804 supports the following applications:
- Ableton Live 8.04 and higher
- Cubase 3.02 and higher
- Nuendo 3.02 and higher
- Logic Pro
- Final Cut Pro
- Digital Performer 5 and higher

Driver Compatibility Chart

- Windows XP
- Windows XP 64-bit
**APPENDIX C.** Calculations for determining the applied force of the adjusting bolt and the input force on the wrench.

<table>
<thead>
<tr>
<th>Force Out (N)</th>
<th>Pressure (psi)</th>
<th>Pressure (kPa)</th>
<th>Pressure (kPa) Adjusted</th>
<th>% Increase</th>
<th>Force In (N)</th>
<th>Pitch (m)</th>
<th>Plug Diameter (m)</th>
<th>Radius Plug (m)</th>
<th>Radius Wrench (m)</th>
<th>Torque on Wrench (N*m)</th>
<th>Torque on Bolt (N*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.0</td>
<td>18.0</td>
<td>123.8</td>
<td>123.8</td>
<td>100</td>
<td>0.258</td>
<td>0.0015</td>
<td>0.012</td>
<td>0.006</td>
<td>0.13</td>
<td>0.0336</td>
<td>0.0336</td>
</tr>
</tbody>
</table>

*An Excel spreadsheet calculating the applied force of the adjusting bolt and the needed input force provided by the wrench. Using reverse calculations, knowing the applied force of the bolt (Force Out) determines the torque on the bolt since torque = force * distance:

\[ \tau_{\text{bolt}} = F_{\text{bolt}} \times (d_{\text{bolt}} \times K_T) \]

...where \( d_{\text{bolt}} \) is the bolt diameter and \( K_T \) is the torque coefficient for non-plated steel.

Next, the torque of the bolt should roughly equal the torque by the wrench where:

\[ \tau_{\text{bolt}} \approx \tau_{\text{wrench}} \quad \text{... or} \quad [F_{\text{bolt}} \times (d_{\text{bolt}} \times K_T)] \approx [F_{\text{wrench}} \times d_{\text{wrench}}] \]

...knowing the radius at where the force meter was positioned on the wrench (\( d = 13.0 \) cm) calculations were made to determine the force needed by the wrench.
APPENDIX D. Calculations for determining the Hertzian Contact Area between the steel spheres at a particular applied force ($F$) (Phases 2 and 3).

<table>
<thead>
<tr>
<th>Pressure (Pa)</th>
<th>Force (N)</th>
<th>Contact Area (mm$^2$)</th>
<th>$K_a$</th>
<th>$\nu_1$</th>
<th>$\nu_2$</th>
<th>$E_1$ (Pa)</th>
<th>$E_2$ (Pa)</th>
<th>$d_1$ (m)</th>
<th>$d_2$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0E+16</td>
<td>0.5</td>
<td>0.00330862</td>
<td>4.1686E-09</td>
<td>0.305</td>
<td>0.305</td>
<td>1.93E+11</td>
<td>1.93E+11</td>
<td>0.015875</td>
<td>0.015875</td>
</tr>
</tbody>
</table>

* An Excel spreadsheet calculating the Hertzian Contact Area between the steel spheres using Poisson’s ratio, Modulus of Elasticity, composition of the spheres, and the diameter of the spheres. The Hertzian Contact Area between the spheres can be calculated by:

$$A = K_a^{3/2} \sqrt{F}$$

…where $K_a$ is a variable compiling the properties of the spheres:

$$K_a = [(3/8 \times (1 - (\nu_1^2)) / E_1 + (1 - (\nu_2^2)) / E_2) / (1 / d_1) + (1 / d_2)]^{1/3}$$

…and the values for $\nu_1$, $\nu_2$, $E_1$, $E_2$, $d_1$, and $d_2$ are found in the above spreadsheet. The amount of force ($F$) was calculated from Figure 14.