Focusing Sound Waves Using a Two-Dimensional Non-Linear System

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Sound is logarithmic by nature; if the distance a person hears a point-sound source doubles the amplitude halves. 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. Researchers in Toronto, Canada, 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. Their data matched the theoretical computations and thus confirmed a non-linear acoustic lens application. In 2010, Caltech researchers Spadoni and Daraio successfully focused sound waves using a non-linear acoustic lens and hypothesized one of many practical applications for focusing sound as a non-invasive medical tool.

The behavior of sound waves is nearly the same throughout almost all mediums; the main difference in all waves in different mediums is the speed in which they travel. In dry air at 20° C, sound waves move at 343.2 m/s. Through steel, sound moves at approximately 6,100 m/s (about 18x faster than in air); this reveals the density of the medium. When the density of a medium is increased, the speed at which waves move through is also increased. This is the basic principal of a non-linear acoustic lens. A non-linear acoustic lens is an array of metal spheres with different forces applied to each to create a focusing affect. This works on a few principals, starting with Newton’s cradle. In a Newton’s cradle, energy is transferred from sphere to sphere effectively because of the small contact area. This same design was used for the chains in this acoustic lens. Sound waves move faster through more dense materials meaning that as more force was applied to each of these chains and then struck, the energy moving though each chain was faster than the previous chain. As the chains were transferring energy quicker than the previous chain, the sound waves coming out of the other end of the chain met up at a calculated focal point.

The purpose of this research was to engineer chains of spheres creating a nonlinear acoustic lens. Specific chains would be precompressed compared to other chains so that an acoustic signal traveling through them had different amounts of time delay through certain chains. The waves traveling through each chain met at a specific point and created increased relative amplitude; at the point where all the waves met, they would form a focal point. The focal point was created at different distances from the acoustic lens by changing the force (or pressure) on the spheres. If the acoustic lens was not precompressed (Control data), there was not an increase in amplitude at a specific focal point. When the acoustic lens was pre-compressed with calculated force ratios (Experimental data), there was an increase in amplitude at a specific focal point.

A device for focusing sound waves was engineered and assembled. It consisted of a release system, a non-linear acoustic lens, a microphone recording system for data collection, and an apparatus to keep the lens raised and to hold the release system. The release system was created from 11 guides measuring 18.7 cm long with an inner diameter of 1.54 cm with horizontal slots in them. A solenoid was attached to a piece of plastic (55.5 cm x 6.4 cm) that was able to fit through the horizontal slot in the guides. Each guide had one steel sphere resting on the plastic plate inserted through the horizontal slot. When the solenoid was activated it released a plate allowing the spheres to fall down the guides hitting the top of each ball in the acoustic lens simultaneously. The acoustic lens consisted of 11 aluminum tubes measuring 10.4 cm each. This was chosen because having an odd number of chains would produce the compression ratio for each chain. Each chain was made from one tube and a corresponding hole in an aluminum block. The block was 43.2 cm long by 5.1 cm wide by l2.7 cm tall. Each section was paired to another and filled accumulatively with 15 metal spheres 1.3 cm in diameter. The spheres protruded out each end of the each side of the chains. The tube in each chain sunk into the aluminum block 2.6 cm. This was done to ensure stability and minimize wobble from the pipe segments. The top sphere was impacted by spheres released by the release system.

There were two sets of trials to the experimentation. The Central Trials were testing the lens with a proposed focal point in the middle of the lens. The Right-Side Trials were testing the lens with a proposed focal point to the side of the lens. Also, the Central Trials used a small clamp attached to fishing line to hold the mass on the chains. The Right-Side Trials used an improved metal plate system with hooks that fit onto each chain to hold the mass. A higher ratio of mass was used for the Right-Side Trials because it was thought to have made the focusing effect more prominent and also verified the lens's capabilities. The applied force was calculated by creating a formula based on research by scientists Spadoni and Daraio at Caltech. The calculations were used to implement the force on the spheres in each chain, creating the acoustic lens effect. Once the force was applied to all chains for each set of trials, the release system spheres were set up and released with the aforementioned solenoid. Each individual microphone recording was converted into a wave file and then analyzed using Sigview version 2.6.0 signal analysis software to find the exact focal point of the sound waves. The average relative amplitude of the Control data compared to the Experimental data at the projected focal points for both the Central Trials and the Right-Side Trials were analyzed using statistical analysis (two-tailed t-test).

Central Trials Results: The data for the Control trials were measured using relative amplitude. The Control data had average relative amplitude of 4,470 with a high of 8,008 and a low of 2,862 (N=420). 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 non-linear acoustic lens (R^2=0.826). The Experimental data had average relative amplitude of 4,856 with a high of 10,566 and a low of 2,485 (N=420). 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 non-linear acoustic lens (R^2 = 0.818).

Right-Side Trials Results: The data for the Control trials were measured using relative amplitude. The Control data had average relative amplitude of 1,668,723 with a high of 3,386,844 and a low of 590,762 (N=126). 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 non-linear acoustic lens (R^2=0.984). Experimental data had average relative amplitude of 1,474,835 with a high of 3,826,445 and a low of 581,378 (N=126). 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 non-linear acoustic lens (R^2 = 0.889).

This research was considered a success because the non-linear acoustic lens produced a noticeable increase in relative amplitude at a specific focal point in both sets of trials. Using a two-tailed t-test, the difference between the Control and Experimental for Central Trials was found to be different over the 90% confidence level. The difference between the Control and Experimental for the Right-Side Trials was found to be different over the 95% confidence level. It was noted that all data points almost perfectly formed to the Control Data's trend line, while the Experimental Data was slightly higher and lower at times. This indicates the non-linear acoustic lens was affecting the relative amplitude during the Experimental trials. This is an exciting stepping-stone to practical use in the medical field such as eradicating cancer cells or military use such as non-invasive strikes.