Acoustic Levitation: A Theoretical Exploration

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Abstract

No longer confined to science fiction, acoustic levitation - the use of high and low pressure zones in standing sound waves to stabilize objects against the pull of gravity - is a real technological advancement that can be applied to various areas of science, medicine, and industry. It can be used to solve a broad range of problems and to optimize and supplement many technologies that already exist, such as human cell research. The authors conducted extensive research and concluded that with the current technology, acoustic levitation works best in a lab setting, and is not yet feasible for commercial or industrial use. With more research, however, it can be perfected and made exceedingly practical. The following paper explores in depth a theoretical experiment that could be conducted in order to acquire data about the potential and limits of acoustic levitation.

1 Introduction

For many years, scientists and other have investigated technology that can be used to defy gravity. Thanks to research that began decades ago, pressure produced by sound waves can now provide a way to levitate objects and to stabilize them against gravitational and other forces.

Though the principle of acoustic levitation arose in the 1940s, the technology of standing waves had been explored long before then. German physicist August Adolph Eduard Kundt experimented with the manipulation of sound waves to form nodes and antinodes in the mid nineteenth century. His "Kundt's Tube" is a basic model that tests for nodes in standing waves using a closed glass tube[1]. Several decades after Kundt's research, American physicist Charles Albert Rey was credited with the first successful use of an acoustic levitator.

Today, scientists all over the globe investigate and utilize acoustic levitation in the fields of medicine and technology. Physicists at Utah Valley University, for example, have used acoustic levitation for advanced cancer diagnostics by using the pressure differences within the wave to test the density of human cells[2]. With more research and experimentation, acoustic levitation will also come to revolutionize the packaging and transportation industries by making it easier to handle small, fragile objects and corrosive materials.

Acoustic levitation is a field of great opportunity, as there are many potential improvements to be made to the already developed technology. A functioning acoustic levitator will counteract the force of gravity acting upon an object, but it is also important to see how forces can be balanced in other directions as well. The experiment detailed below was designed to research these ideas by testing the strength of acoustic levitation when the standing wave was disturbed by an outside force.

2 Background

2.1 Sound Waves

Sound is a type of disturbance created by vibrations. As an object vibrates quickly, it disrupts the the particles around it and produces a wave of pressure, carrying this disturbance across space[3]. The propagation of sound relies on the movement of surrounding particles and thus, sound waves can only travel in a medium. In most cases that humans are concerned with, the medium is air. The sound waves push and pull the air molecules, which then push and pull the particles near them. Some energy is lost in this transfer so, like all waves, sound waves will not travel indefinitely. As long as people are close enough to the source, the vibrations will pass through their eardrums and produce what humans perceive as sound. Below, Equation 1 shows the relationship of the velocity of a particular kind of wave through the medium, the frequency, and the wavelength. This equation allows for physicists to calculate basic characteristics of waves in order to apply them to their research.

$$v = f\lambda \tag{1}$$

Equation 1: The Wave Equation

*The Greek letter lambda (λ) represents wavelength. The denotation (v) stands for velocity and frequency is denoted as (f).

The fact that sound is a wave is important for many reasons. As a wave, sound can be reflected. Depending on the surface, waves can be reflected back upon themselves or even directed in different directions. Sound waves through gas are longitudinal, with fronts that move parallel to the direction of motion. There are areas of compression, where the particles in the medium are closer, and areas of rarefraction, where the particles in the medium are more spread out. Most sound waves are depicted as transverse for convenience because the crests and troughs of transverse waves are easier to visualize than the compressions and rarefactions of longitudinal waves. Even though the image of a transverse wave is useful because the pressure variations of sound waves are sinusoidal, it is still important to remember that sound waves are actually longitudinal pressure waves.

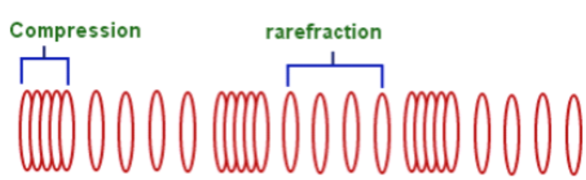

Figure 1: This diagram shows the basic components of a longitudinal wave. The

compressions and rarefractions show the wave pressure differences cause the wave to propagate through the air.[11]

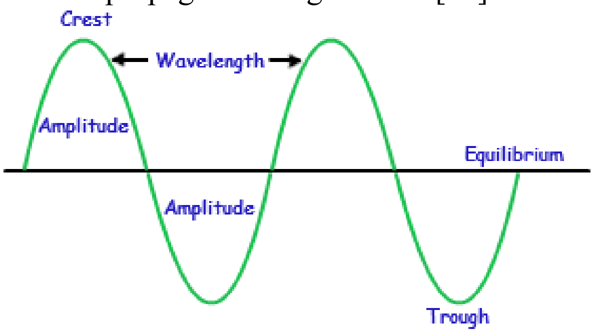

Figure 2: Transverse waves clearly show where the maximums and minimums are located, especially since they can be modeled by a sinusoidal function. Where the graph or wave crosses the x-axis is where one would place an object to levitate. These spots are the nodes of the transverse wave. [12]

2.2 Levitation

Acoustic levitation centers around the ability to create standing waves. Standing waves are formed when two waves of the same frequency interfere while traveling in exactly opposite directions. An acoustic levitator reflects a wave upon itself, so the resulting frequencies are the same while the directions are exactly opposite. The points of destructive interference along the reflected wave are called nodes. Equation 2 provides insight about the location of the nodes and distance between the transducer and the reflection needed to create a particular wavelength. At the nodes of a standing wave, there is essentially no wave movement so the pressure is very low. Directly between nodes, the standing wave reaches points of maximum displacement called antinodes. The greater the distance from the node, the greater the pressure, so these antinodes have maximum pressure[4]. This pressure is also explained because the antinodes are points of constructive interference and the wave has a lot of resonance in those areas.

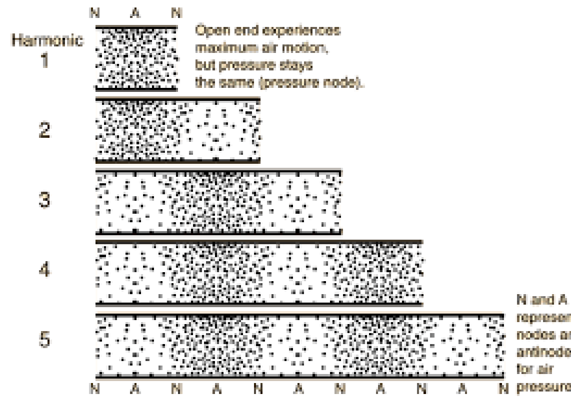

Figure 3: Longitudal Standing Waves[13]

$$L = n\frac{\lambda_n}{2} \tag{2}$$

Equation 2: Relationship Between Lambda and Length

The symbol (n) will refer to the degree of the harmonic. (L) represents the distance of the medium.

Objects tend to move from areas of high pressure to low pressure, so objects placed in the standing wave will move to the nearest node. The movement from high to low pressure is explained by the second law of thermodynamics, which explains how energy tends to flow from areas of high concentration to low concentration. Thus, the low pressure and low energy nodes are ideal places for objects in a standing wave to rest. In space, where there is negligible gravity, the objects will stay exactly at those nodes. On Earth, however, the objects will sit slightly below the nodes because equilibrium is established where the upward force from the wave is equal to the downward force from gravity.

2.3 Constraints Upon the Levitator

Several factors limit the real-world usefulness of acoustic levitation technology. Firstly, since low pressure zones exist between the nodes of standing sound waves, these zones can only measure half of the wavelength of the standing wave. Therefore, an acoustic levitator can only levitate objects with diameters smaller than that. An additional, related constraint is that only sound waves with frequencies above 20 kHz can be used to levitate macroscopic objects, so the equipment used to generate the frequency must be precise[5]. Additionally, since the pressure produced by the wave must counteract the force of gravity upon the levitated object, the levitator can only support objects that weigh less than the wave's maximum pressure. More massive objects can only be levitated by extremely loud sounds produced with immense amounts of power.

2.4 Levitator Design

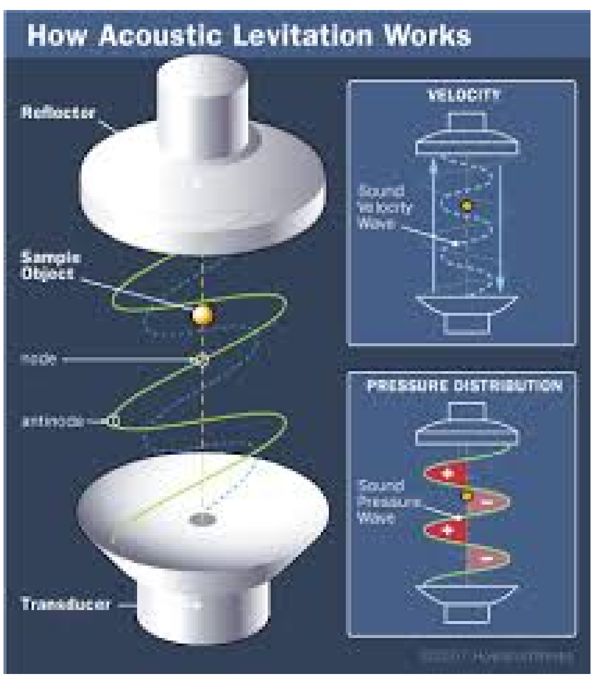

Figure 5: Basic Acoustic Levitator Setup include transducers and reflectors in order to create standing waves.[13]

When building an acoustic levitator, a transducer is needed to convert electrical energy to sound. The energy starts in a function generator. The function generator runs an electric signal to generate waveforms, which it then sends to an amplifier. The amplifier is used because the transducer alone usually cannot generate a sound strong enough.The amplifier increases the volume and thus intensity and amplitude of the sound waves. The amplified waves are then sent to the transducer. In some setups, the transducer is simply a speaker. After the sound waves are amplified and travel out of the transducer, they hit the reflector. The reflector bounces the waves back upon themselves and thus creates a standing wave by causing interference between identical waves in opposite directions. Different shapes are used to create the reflector depending on how researchers plan redirect the sound waves and create a standing wave. Curved reflectors tend to be used because they provide a more focused pressure on the levitated object. To make sure that the sound waves properly reflect back upon themselves, the reflector in the apparatus sits upon a lab jack. Adjustment of the height of the lab jack changes the distance between the reflector and the transducer.This change in separation is important because the reflector must be positioned so that it is at a distance that is a multiple of half the wavelength of the sound wave. Equation 1 and Equation 2 aid in determining the distance necessary in order to create a standing wave at any given frequencies.

3 Experimental Design

The design of this experiment focuses on testing disruptions that would occur during transportation and packaging. Braking, accelerating, and turning are all outside forces the levitator must resist to be suitable for application. Completion of the following acoustic levitation tests would answer whether this technology is suitable to optimize the efficiency of the packaging and transportation industry.

In theory, the symmetry of the low pressure zone in the node of a standing wave levitates an object perfectly in one direction: any disturbance to the levitated object along the y axis, the direction of the reflected sound waves in the levitator, should be negated by the pressure difference between the nodes and antinodes. For the acoustic levitator to be useful, however, the pressure zones must also provide stability along the x axis and protect the levitated object from the influence of strong or inconsistent forces in any direction. In order to determine how well a one-dimensional acoustic levitator actually works in two dimensions, the levitator and the object being levitated were subjected to various forces, positive and negative accelerations along the horizontal (x) and vertical (y) axes and in the xy plane.

The first test was designed to generate a disturbance along the x axis of the levitator in order to see how levitated objects responded to this force. The levitator, with a polystyrene ball levitating in the node, was placed on a level scooter and then rolled along a flat, horizontal surface. In each of the three trials conducted, the levitator traveled a consistent distance of 20 meters. The goal was also to keep velocity the same throughout all three trials, but some deviation was expected. Velocity values were determined by dividing the distance traveled by the time it took in seconds for the scooter to move from the starting point to the ending point.

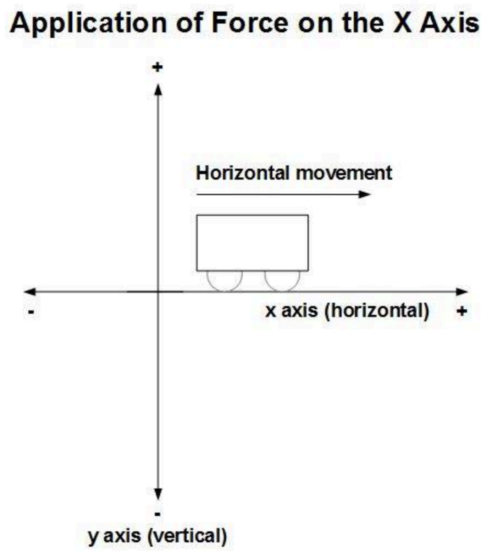

Figure 6: X Plane Experiment Set Up for the Constant Velocity: The levitator setup is placed on a cart and moved on a flat horizontal plane at a constant velocity. This is a basic test to determine whether moving a levitator in one dimension could affect the pressure differences that result in levitation.

The test for disturbance along the y axis was a variation of the horizontal disturbance test. The levitator, with a polystyrene ball levitating in the node, was to be strapped onto a trampoline. Threaded to the center of the trampoline would be a string with a loop at the end that dangles below the surface of the trampoline. The string's length would be adjusted so the bottom of the loop would be a set distance from the ground. Then, by pulling the string down to the floor, researchers could bounce the trampoline in a way such that the amplitude of the center of the trampoline would be held constant. As long as the string was pulled all the way to the ground for every bounce, each trial would have the same acceleration along the y-axis.

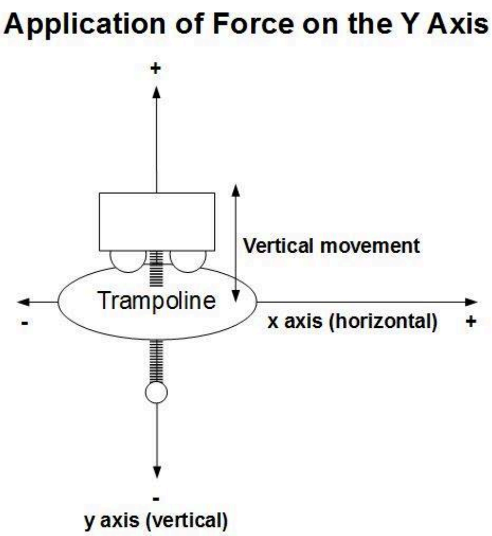

Figure 7: Y Plane Experiment Set Up for Constant Velocity: The levitator setup would be placed on top of a trampoline, with a heavy string running through the center of the trampoline and attached to the levitator. The string could be pulled and released with measured force in order to displace the levitator unit uniformly.

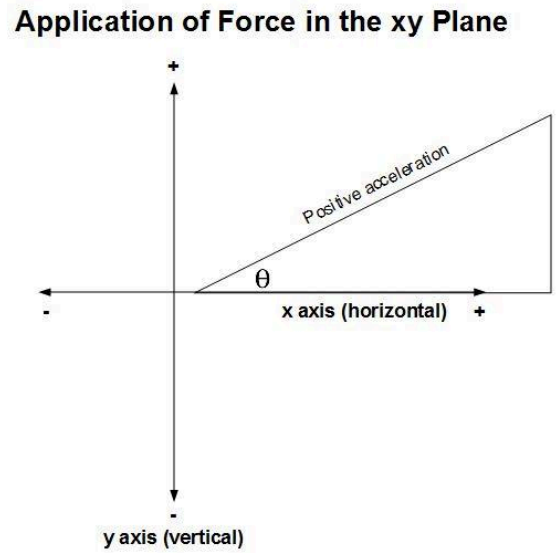

Figure 8: XY Plane Experiment Set Up for the Accelerating Trial: The cart with the levitator on it would roll down the ramp with the angle theta depicted above. The levitator would move in both the x and y directions, which combines both Test 1 and Test 2. It is expected that the polystyrene ball that is levitated would remain suspended in air.

The third test was designed to test the acoustic levitator's ability to overcome forces acting in both the x and y dimensions. The test was designed to have a single ramp of a designated angle of elevation, theta. Using the same value for theta would allow the experimenter to control the speed of the cart. The cart and levitator system would then roll down the ramp, and the trial would end when the cart reached the flat surface. The ramp forces the levitator to move in both the x and y direction. The expectation is that the polystyrene ball in the acoustic levitator would remain suspended in air the duration of the trial.

In order to test the levitator's response to deceleration and braking, the levitator was placed on a scooter and sent down ramps of various inclines, as demonstrated by the experimental diagram. A large ramp was used to accelerate the levitator and scooter downward, while a smaller ramp, with an incline facing the opposite way, was used to decelerate the scooter and levitator. This "braking" maneuver was performed using ramps with 3 different inclines, in order to test deceleration under low, medium and high applied forces.

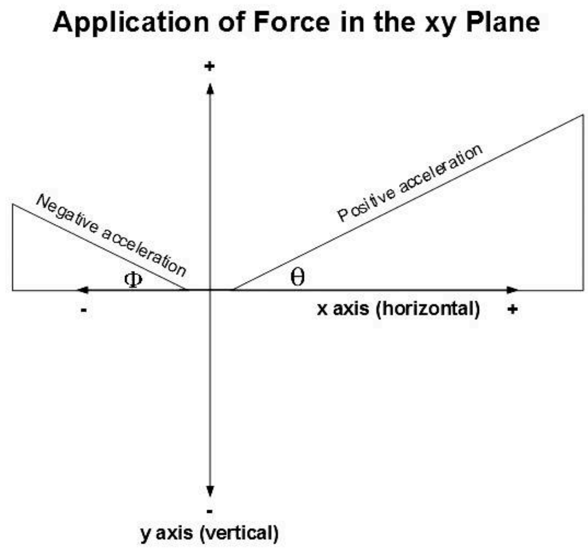

Figure 9: XY Plane Experiment Set Up for the Braking Trial: The cart with the levitator on it would roll down the ramp with the larger angle value for theta. The second ramp would slow down the cart, resulting in a disruption that simulates a break.

Although the concept of acoustic levitation is complex, it does not require many materials. A levitator depends on two parts: the reflector and the transducer. The transducer supplies the standing wave, which without, the levitator would not exist. This experiment's transducer would consist of a function generator, tweeter speakers, and an amplifier. The function generator must produce a stable standing wave or else the wave cannot be reflected. Lab jacks have the ability of raising and lowering to accommodate different experimental environments. In this case, the lab jack provides a surface to reflect the standing wave upon. The transducer and reflector run parallel and face one another. Besides the levitator itself, wooden ramps should be constructed to use for the xy disturbance and brake trials. For all trials except the y axis test, the levitator should be placed on a square cart with wheels. The cart allows the levitator to travel distances smoothly and consistently. Polystyrene balls can be placed in the node of the standing wave. Many of these materials can be substituted for others that serve the same purposes.

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4 Results and Discussion

Based on research and experimentation with the equipment, it was concluded more research needs to be conducted before acoustic levitation can be fully utilized for scientific, medicinal, and commercial use. It is hard to use older models of function generators because they do not keep a steady frequency. Also, the speakers needed to handle the high frequencies desired for levitation can be costly. Unfortunately this means that it is currently expensive to levitate objects without the most current technology. It was also concluded that despite the research needed to move forward, there are many areas of science and industry that can benefit from acoustic levitation, including transportation and packaging.

4.1 Potential Improvements to Acoustic Levitation Technology

The design and execution of the above experiment could have been improved drastically through the use of newer and better acoustic levitation technology. Recent developments in precise laser measurement could have been used to measure the exact displacement of the polystyrene balls in the acoustic levitator during each test, providing more accurate data than qualitative observations and imperfect manual measurements would have.

Furthermore, some sophisticated acoustic levitators use curved reflectors as opposed to flat ones, in order to funnel the sound waves and make their path of motion more precise. In this experiment, such curved structures would have provided a stronger, more consistent standing wave than the flat lab jack would have, making the tests easier to perform and the data collected more exact.

A particular challenge encountered in the experiment was the emission pattern of the tweeter. Acoustic levitation works best when the sound waves are emitted from the transducer in a cone or a funnel shape, so that the waves are directed towards a central point and exert a stronger pressure force upon the object to be levitated. In the above experiment, however, the slightly rounded tweeter emitted sound waves in a dome shape. This weakened the pressure force applied by the tweeter, making it impossible to levitate any objects. An improved technology would include tweeters with less rounded, more funneled shapes in order to better channel the sound waves.

Most importantly, however, the experiment would have been more successful with newer, more user friendly methods of generating the necessary frequency and amplitude. The function generator initially used in the acoustic levitator setup was old and no longer functioning at optimal levels, making it difficult to generate a smooth sine wave of optimal wavelength and frequency with the required power input. Eventually, the authors received a new function generator, but it too produced incorrect frequencies which made the experiment impossible to conduct accurately. An improved function generator, or a digital sound file or other alternative method of generating the necessary sound wave, would have made the process of building and configuring the acoustic levitator much smoother.

5 Conclusions

5.1 Findings

Since time constraints and issues with the acquisition and function of equipment made it impossible to build the acoustic levitator, the experiment could not be carried out. Though the initial question remains unanswered, the process of failing to conduct the experiment demonstrates that acoustic levitation technology must be improved before it can be widely used.

5.2 Recommendations for Future Work

Based on the research and planning that went into this project, the best next step in developing acoustic levitation is to establish which types of materials and models of equipment are best to build an acoustic levitator. The major problem the authors encountered was the inability to build a physical model to test their experimental procedures. The authors began with a function generator that could not provide a stable standing wave, which was followed by another generator that appeared to be providing faulty information. Also, the tweeter speakers experimented with were the wrong shape to create a uniform standing wave that funneled properly. As more research is conducted on what is specifically needed to use the technology, it will become easier to master the fundamentals of acoustic levitation.

5.3 Applications of Acoustic Levitation

Though the focus of the proposed experiment was acoustic levitation in transportation, the experimental and practical uses of acoustic levitation also extend to the fields of medicine and scientific research. Acoustic levitation has already been proven to be an asset to biomedical engineers and scientists researching tissues, cells and other organic samples. Researchers at Utah Valley University, for example, acoustically levitated cells in order to test their density and rigidity, possible indicators of cancer[6]. This innovative approach to early cancer diagnostics is non-invasive, uses only a small sample from the patient, and does not involve the dangerous radiation and chemicals typically associated with cancer diagnostics and treatments.

There is also great potential for use of acoustic levitation on human patients, especially in the case of severe burn victims, who recover more quickly when their affected body parts are elevated but who may not be able to handle bulky straps or other devices that touch burnt skin directly. In this case, acoustic levitation provides a more comfortable and sterile healing environment than do technologies currently in use. This is not feasible with current technology, however, because a standing wave with enough amplitude and wavelength to hold a human being might produce an unsafe pressure difference[7]. However, with further development of the technology, levitation of human beings is very possible. There have already been experiments levitating small animals such as insects, tadpoles, and small fish. The insects were not adversely affected by the levitation, and the fish were only harmed because they did not have enough water while they were being lifted[8]. Thus, it is likely that human levitation will be possible with more testing and a few alterations to current acoustic levitation setups.

Acoustic levitation might also be an effective means of storing, transporting and using chemicals too dangerous for standard containers or human contact. It could also be very useful to materials engineers because some substances crystallize prematurely when they come in contact with a container. Scientists at China's Northwestern Polytechnical University demonstrated that acoustic levitators could suspend droplets of mercury, iridium and other room-temperature liquids for prolonged periods of time, making it possible to work with these substances in a convenient, controlled way[9]. Currently, researchers dealing with these sensitive materials have to spend an extravagant amount of money to send their experiments into space[10]. With further development, acoustic levitation could revolutionize lab safety, transport, and the way people manage sensitive experiments.

Acoustic levitation even has applications beyond planet earth, as it may become a valuable tool for astronauts conducting research in the microgravity of outer space. Though the technology would not be useful in the vacuum of space since the sound waves would have no medium through which to travel, it could be utilized on the International Space Station and other spacecraft. It would minimize the hassle of handling small quantities of dangerous materials in an enclosed environment, and would help astronauts mimic earth, outer space, and other conditions in one laboratory. Additionally, acoustic levitation's ability to overcome gravity would actually allow researchers to mimic space-like conditions on earth, reducing the need for experiments to be sent out into space.

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