Gardner Nichols
MCEN 4151
Report: Group 1

For the first group project in the Flow Visualization class at the University of Colorado, we had the option to photograph any fluid flow phenomena, just like the “Get Wet” assignment. For this project, the group chose to photograph waves using a capillary wave generator. Due to timing, however, I worked with only one of my other three group members for this project, Janelle Montoya. The purpose of this project was to get used to working with a group in an artistic setting. We also wanted to get visually appealing and interesting pictures of the waves, but I feel this was mostly a warm up for the group.

A capillary wave generator similar to the one shown in Figure 1 was used. An acrylic container was glued to a small speaker cone via a small plastic rectangle. Figure 2 is a side view diagram of the apparatus. Rubber corks supported the container on a base plate. With a frequency playing through the speaker, the container would oscillate at the same frequency, being directly attached to the speaker cone. The water is the container is then disturbed by the container wall and a wave is created.

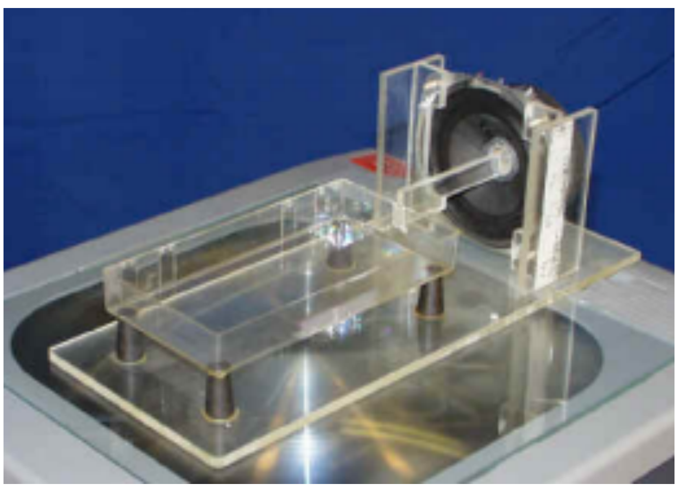

Figure 1: The Capillary Wave Generator. Image courtesy of Jean Hertzberg.

The way this apparatus functions is by moving the container back and forth in a periodic motion. The force to move the container comes from the speaker cone, which moves by playing a sound frequency. The container sits on rubber corks, so it is free to move back and forth while still being supported. The force from the speaker cone is transferred through the acrylic connector (colored red in Figure 2) to the wall of the container. The container wall then pushes on the water, however all the water in the container does not follow the same path as the container. While the container continues to move back and forth, the water, being a liquid, moves inside the container. The water is displaced vertically rather than horizontally, thus creating a wave.

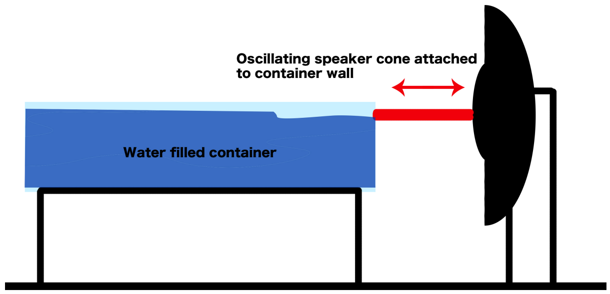

Figure 2: The speaker on the right, connected to the open container.

The reason the wave is created vertically is due to the pressure acting on a point of water. The pressure from the air above is less than the pressure from the container wall. In Equation 1, Δp is the pressure differential, T is the surface tension and R is the principal radius of the surface. Given that the water was initially still and thus had a near infinite principle radius, Equation 1 states that the pressure differential is essentially zero.

$$\Delta p = \frac{T}{R} \qquad \text{Equation (1)}$$

It is no wonder that a wave is created vertically because the vertical direction has the least pressure acting on it in this moment. The area of the container wall was roughly 1.5 square inches. It is impossible for me to figure out the force created by the speaker cone because I no longer have access to the apparatus. However, calculating the force could be done by measuring the amplitude of the electrical signal being sent to the speaker and referencing the speaker manufacturer for displacement data. The size of the water wave is proportional to the amplitude of the sound wave played through the speaker. The greater the sound amplitude, the more the speaker cone moves thus moving the container more. The greater displacement of the container creates a greater pressure differential to the air and a bigger wave is generated. With the waves now constantly being generated by the periodic motion of the speaker cone, a series of waves with the same frequency propagate through the container.

The goal was to obtain a standing wave because they are easier to photograph. To generate a standing wave, the sound frequency was increased until several frequencies were noted as creating standing waves. The “standing wave” status was visually confirmed by Janelle before the frequency was recorded. With the container being roughly 3”x 6”, the frequencies that standing waves occurred were the various harmonics of the 6” length of the container and the 3” width of the container. A harmonic happens when exactly *n* waves can fit inside of a certain length. The fundamental frequency is the lowest harmonic as the number of waves present is one. The second harmonic would refer to a total of two complete waves in the length. Notice from Figure 3 that the wavelengths must be very precise lengths to exactly fit only completely developed waves. What I mean by this is that a wave must be executed at the wall of a container half way between the peak and trough. Figure 4 shows examples of what would lead to an incomplete wave.

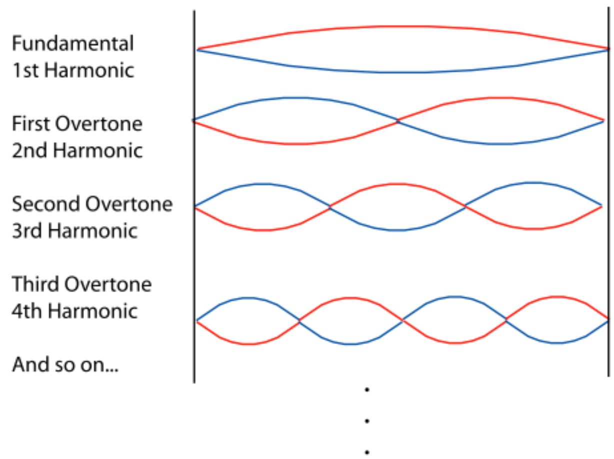

Figure 3: Standing waves as harmonics of the fundamental frequency. Image courtesy of Music Theory Online.

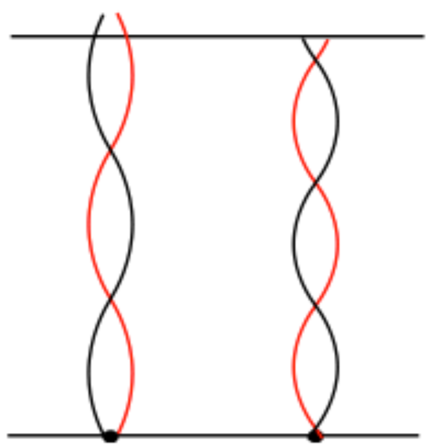

Figure 4: Examples of incomplete waves. Image courtesy of Music Theory Online.

With the container having a different length versus width, there are two sets of harmonics present. This is easily noticed when running through different frequencies because one will see standing waves form at two distinguishable frequency sets. Then, a frequency was found where the two sets intersect at roughly 82Hz. When this happens a standing wave is formed that looks like little bulbs of water with dimples rather than waves. This is what phenomena is happening in the final picture, in Figure 6 and 7. This phenomenon can be somewhat related to the Landau-Zener theory that waves exchange energy at specific locations when they cross. Although the Landau-Zener theory applies to quantum physics, the same principles can be used here. The locations where energy is transferred between waves are called "damping wells"

(Merrick, 2011). A damping well is demonstrated in Figure 5. We can see the two different sets of waves intersecting to create a well, which is exactly what is seen in the final pictures.

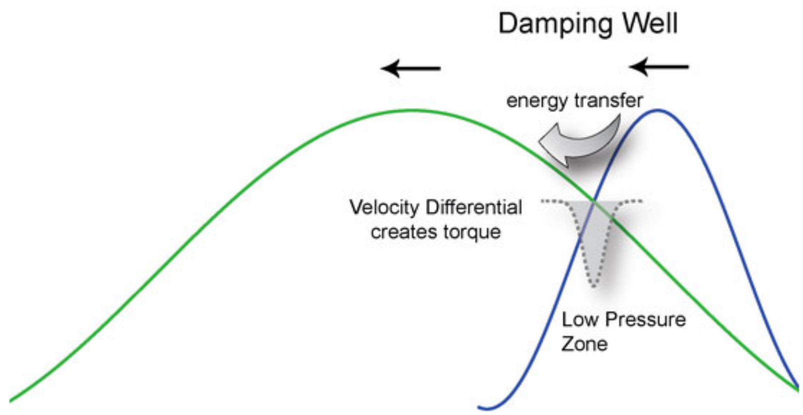

Figure 5: Damping wells are created when two waves interfere. Picture courtesy of Richard Merrick.

The energy transfer across the waves occurs across the damping well. This transfer creates a low pressure zone in the damping well, thus creating a miniature vortex (Merrick, 2011). These vortices are what creates the dimples in the water during a standing wave.

Overall, to obtain the phenomenon seen in the picture, a wave is created by the periodic movement of the container wall. This generates a set of waves with the same frequency as the container movement. Due to the container geometry, several sets of harmonic waves are created. When the sets of harmonics exist at the same frequency, they can interfere. The interference between the waves causes energy to be transferred and a low pressure area is created. The low pressure area creates a miniature vortex, which is what we see as the small dimples on the surface of the water.

There wasn't a specific visualization technique used. Sunlight was used as the light source and a white background was set up around the apparatus. Janelle and I took photos at many different angles to get the best combination of light and shadows to see the waves. Red dye was even mixed into the water to help visualize the waves better, but this did not help the photographs.

I used a Tamron telephoto lens with a focal length of 70-300mm with a Canon EOS 60D DSLR camera. The camera was roughly 9 feet from the object on a tripod. The lens was set to a focal length of 300mm because I was attempting to get a lot of detail of a few waves. The original image was 5184 x 3456 pixels while the final image was 4513 x 2084 pixels. I cropped the original to get rid of some unfocused areas as well as the edge of the container in the foreground and background. An aperture of f/29 was used to get as many waves in focus as possible. A shutter speed of 1/1600 was used because the waves moved quickly, so a time resolved image need a high shutter speed. To account for the small aperture and high shutter speed, an ISO of 1000 was used. Despite the high ISO, the picture appears to be sharp, but not grainy. Photoshop was used for post processing. The output slope was increased in the "curves" function to increase the exposure and contrast. The red and blue channels were also increased and modified to have less black in them to bring out the color of the reflections on the surface.

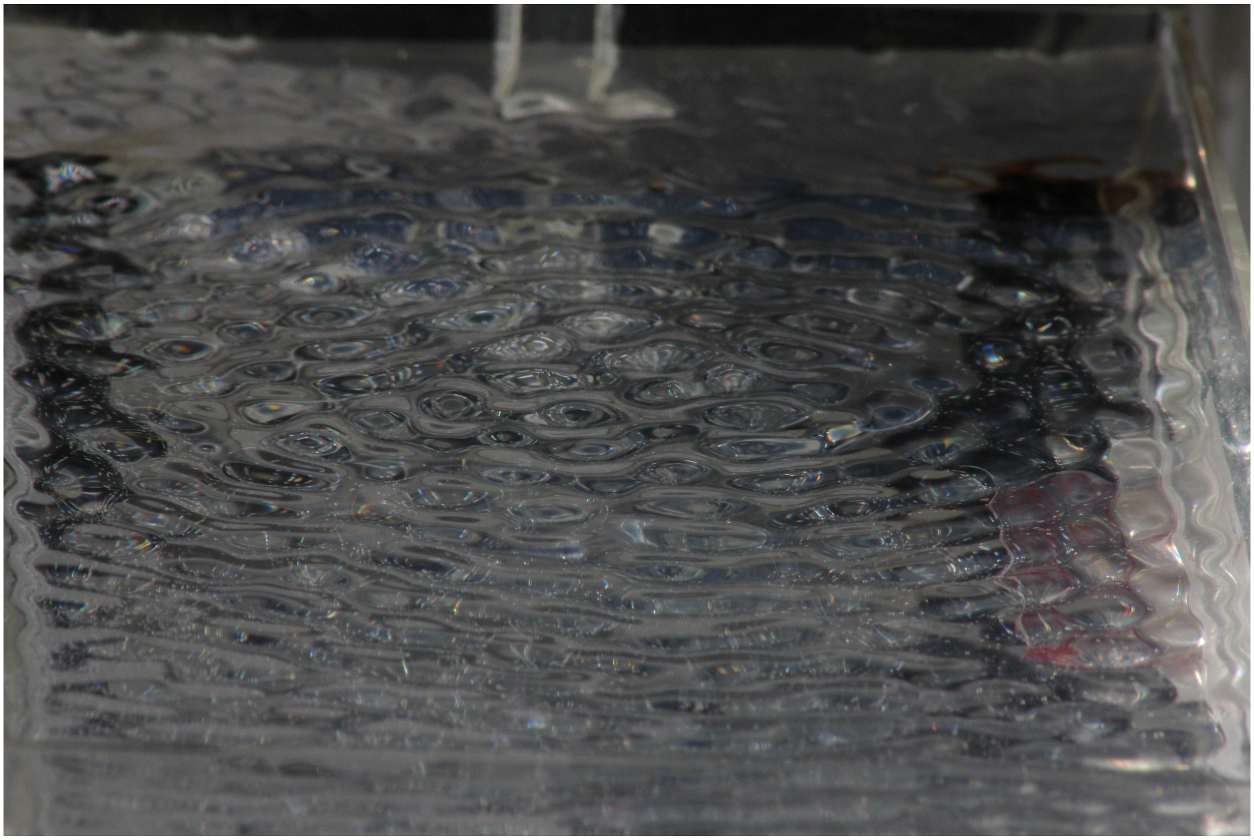

Figure 6: The original image, before any post processing.

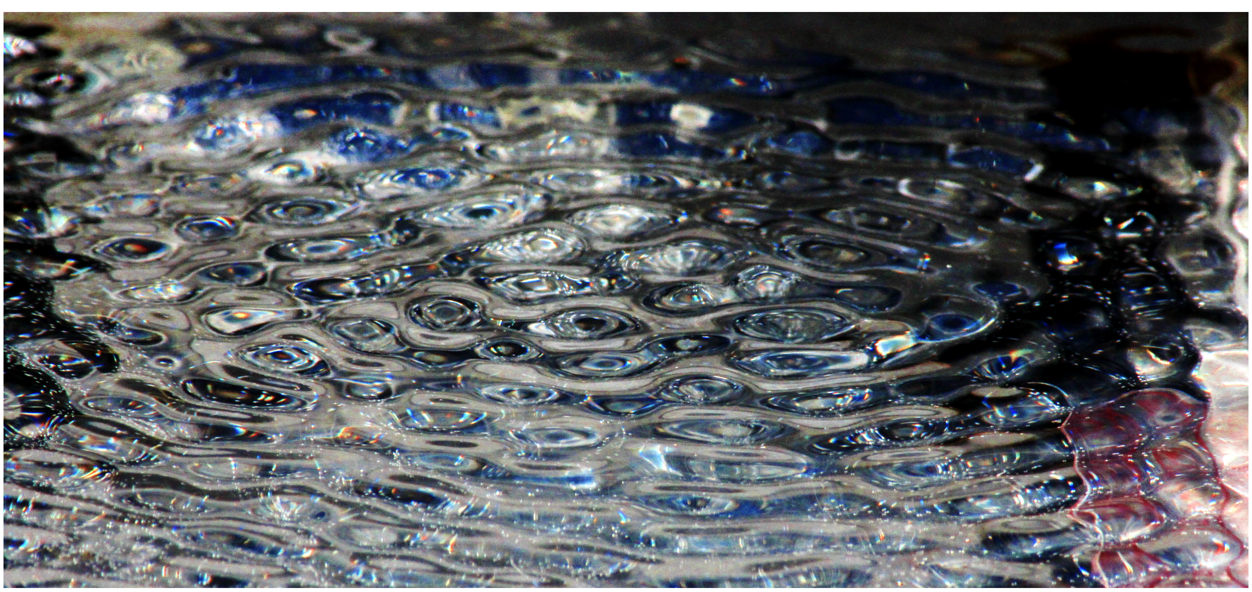

Figure 7: The final image, after editing in Photoshop.

This image reveals the interesting phenomena of what happens when two harmonic frequencies interfere in a rectangular container. I had the chance to talk about capillary waves with the owner of the apparatus, Scott Kittleman. Scott informed me that the geometry of the container greatly effects the wave formations. Had a circular container been used, rings of waves would've been produced for instance. This picture does a good job of demonstrating the energy transfer between waves with this specific geometry. I think one can easily see the damping wells described by Richard Merrick as well. I think this image fulfills the intent to get an interesting and aesthetic picture. I like the clarity of the image, but I wish I had some different lighting to get a well defined picture of a few waves. I feel as if a bunch of the waves are blending together in this image and a distracting background is created by the out of focus waves. I originally wanted to get a clear picture of a few waves without a distracting background.

To take this idea further, I taped a petri dish to a 13" speaker and filled it with water. I was able to get much larger amplitude waves and the black background gave a nice clear display of standing waves. However, when I was completely set up and ready to photograph, my camera broke again! This is the second time this semester I've had to send my camera to Canon to get repaired, so unfortunately I did not get any pictures of this set up.

My only questions on the physics were how to calculate the fundamental frequency of a container. I researched and was unable to find anything on using the container geometry to calculate the fundamental frequency. This would've been nice to know because all of the harmonics could be calculated as well.

References:

Cushman-Roisin, Benoit. "Waves." *Environmental Fluid Mechanics*. Hanover: John Wiley & Sons, 2014. Print.

Benielli, D., & Sommeria, J. (1998). Excitation and breaking of internal gravity waves by parametric instability. *Journal of Fluid Mechanics, 374*, 117-144. Retrieved from http://0-search.proquest.com.libraries.colorado.edu/docview/26877247?accountid=14503

Kenyon, Kern. "Capillary Waves Understood by an Elementary Method." *Journal of Oceanography* 54 (1998): 343-46. *Terrapub*. Web. 4 Nov. 2015. <https://www.terrapub.co.jp/journals/JO/pdf/5404/54040343.pdf>.

Merrick, Richard. "Harmonic Formation." *Interference: A Grand Scientific Musical Theory*. Richard Merrick, 2011. Print.

Schmidt-Jones, Catherine. “The Physical Basis.” Understanding Basic Music Theory. Creative Commons. Ch.3. Online.