IV III – Worthington Jets

https://vimeo.com/763408285

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Figure 1: One frame from the video showing the cavity created by a dropped golf ball

Introduction:

For this project our team decided to use the highspeed camera to try and capture a Worthington jet occurring in a bowl of water. The team consisted of Ben Carnicelli, Alex Kelling, David Milner, and Nathan Gallagher. We all ended up using different footage after experimenting with numerous setups, differing both the object being dropped into the container and the container itself. Their videos can be seen at flowvis.org. Each video shows a slightly different fluid physics model.

Flow Physics:

A Worthington jet is created when an object is dropped into a standing fluid, creating a cavity which is then refilled with surrounding water, the momentum of which creates an upward jet. A. M. Worthington published a work on this topic in 1908 in which he described the physics behind the phenomenon and named the model (Worthington, 1908). When an object impacts the surface of a liquid, the momentum of the object displaces the liquid creating a void (Bartolo D, 2006). When the object continues downwards due to gravity, the void closes due to the hydrostatic pressure of the surrounding fluid acting on the void. This is shown below

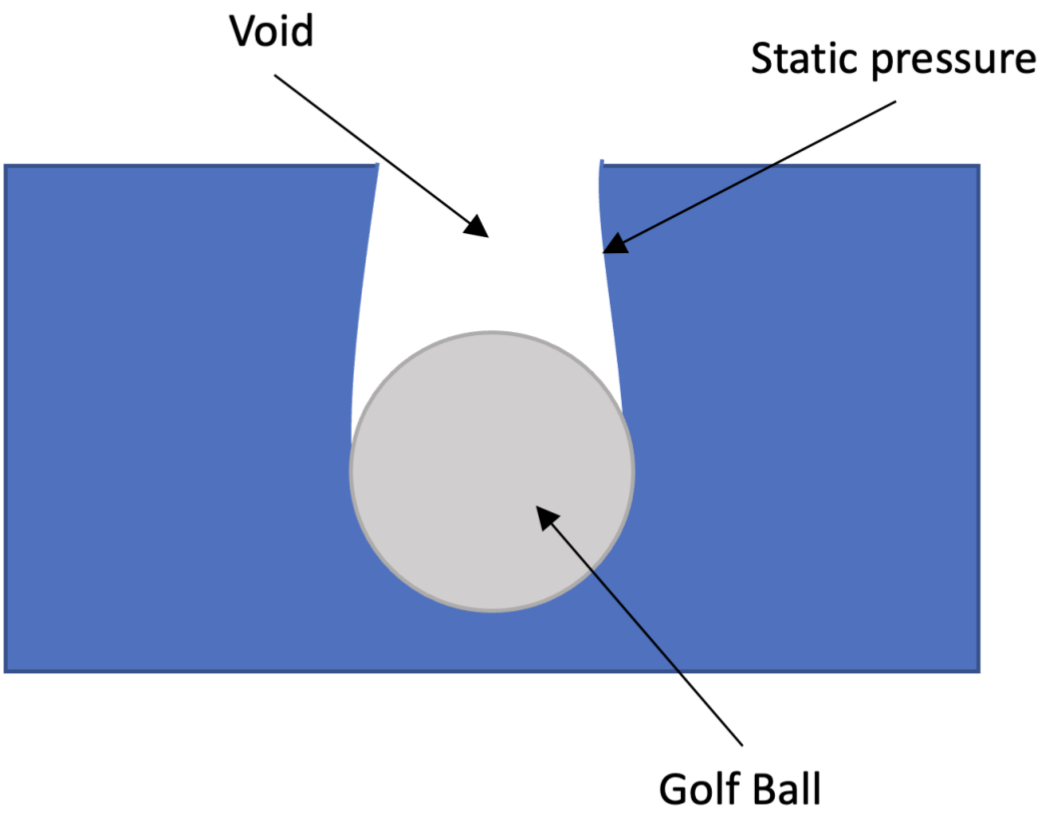


Figure 2: Diagram of the void created immediately after dropping the object into a standing fluid.

The equation for hydrostatic pressure is as follows:

$P = \rho g h$ Eqn. 1

Where P is the pressure, ρ is the density of the fluid, g is the force due to gravity, and h is the height of the fluid. Measuring height from the video, we know that the container is 3.5 inches deep and the ball hits the bottom so we can use $h = 3.5" = 0.089m$. Plugging this in we get:

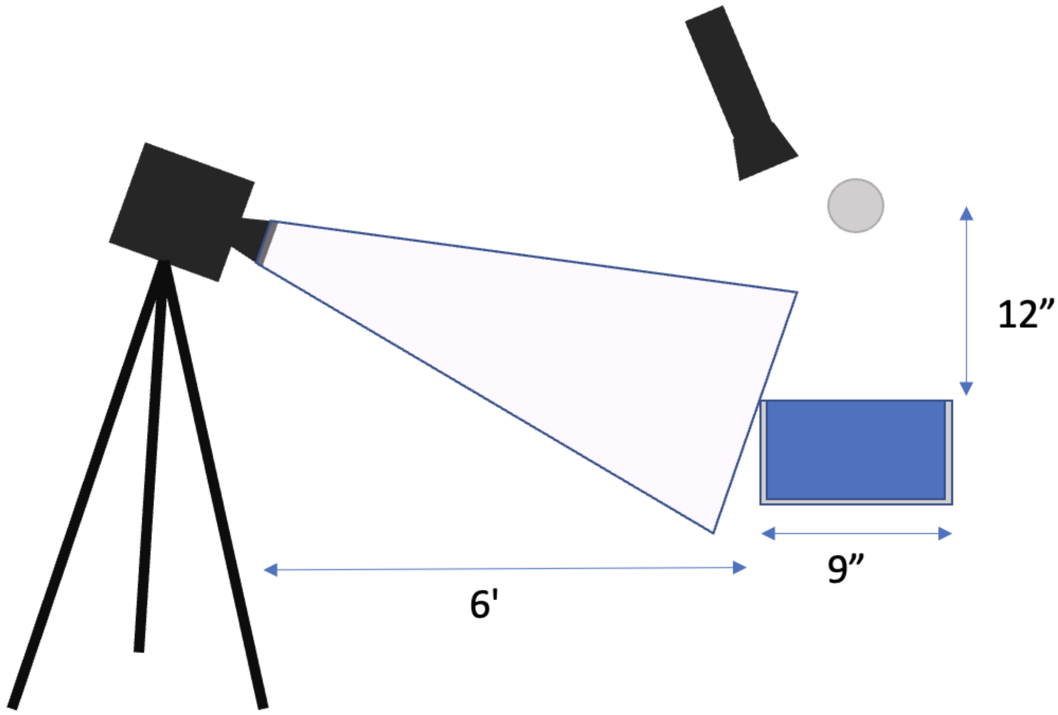
$$P = \left(1000\frac{kg}{m^3}\right)\left(9.81\frac{m}{s^2}\right)(0.089m) = 873Pa$$

This means that the void has a pressure of 873Pa acting at the bottom of it. Since this is measured in gage pressure (the pressure above atmospheric) and is acting on the atmosphere (air in the void) the fluid moves from high pressure to low pressure areas. The jet then occurs when the fluid moves to fill this void. It can be seen in the video that until 7 seconds into the video the void is increasing in volume. After this timestamp, the void starts decreasing as the ball bounces off the bottom of the bowl and moves upwards. It almost appears as though the void completes the same motion as the momentum of the water stops forcing it outwards and the statis pressure described above starts to force water back into the void. The void starts to decrease in volume starting at the bottom of the container and collapsing upwards. This makes sense because the pressure acting on the void is a function of depth so deeper points in the void have a higher pressure acting over them. Since pressure is F/A, when imagining a unit area, the force acting on a molecule of water will be higher deeper in the void and therefore accelerate normally to the voids surface faster. This explains the void collapsing from the bottom upwards in a “squeezing” motion seen in the video.

This “squeezing” motion is what creates the Worthington Jet. The bottom of the void collapses to a point and the water directly under the void is forced upwards due to the static pressure underneath it. This creates a vacuum effect, pulling water upwards with it. As this approaches the surface of the fluid, it has gained enough momentum to continue above the surface, creating the jet. It this video, the golf ball has bounced off the bottom of the container and is above the water when this happens. It can be seen that for a moment, the jet hits the bottom of the ball, levitating it for a fraction of a second as the jet creates an upwards force resisting gravity.

Experimental Set Up:

To capture this video, our team borrowed a Phantom Miro C110 high speed camera from the University of Colorado ITLL. This included all accessories needed to complete the setup such as a tripod, different lenses, and the software needed to run the camera. When setting up the camera we experimented with different lighting and distance setups before finalizing the one shown below.



In this setup we placed the tripod roughly 6 feet from the 9 inch Pyrex dish filled with water. We then used an Energizer Tac1000 flashlight to illuminate the dish from above and dropped the golf ball from roughly a foot above the water. We placed this over a piece of white paper to try and eliminate the background. The flashlight would supply roughly 1000 lumens on top of the ambient lighting in the rooms. The difficult part about this setup was coordinating the drop and the camera trigger to get the best section of film. The software on the Miro C110 lets us select which time frame around the trigger it captures so we set it to capture roughly 0.5 seconds before the trigger and 1.5 seconds after. That way we could coordinate a count down and drop the ball and trigger the camera at the same time and get enough of the drop and splash to capture the motion and get the interesting activity. Because of the frame rate of the camera these 2 seconds of real time film become over a minute when slowed down which is why the video is so long. We completed this process roughly 5 times before selecting the most interesting and clear video. We had to refill the dish a little bit after every attempt due to the splash removing some water from the dish.

Photographic Technique:

As mentioned above, the camera used to capture this footage was the Phantom Miro C110 high speed camera. This was borrowed from the ITLL. The Phantom is capable of capturing up to 52445 frames per second at a resolution of 128x8 pixels. We opted to up the resolution at the expense of frame rate and settled on 915 frames per second at 1280x1024 pixels. This allowed us to see the complexities in water such as the dimples on the golf ball affecting the surface of the water as it passes by while still slowing it down enough to see the overall fluid mechanics. Unfortunately, we did not note the metadata for the video such as the ISO, aperture, exposure, or focal length. The lens used on the camera was a 50mm lens.

The editing was completed with iMovie and consisted of some minor color correction as well as cropping, time cropping, intro slides, and music. I cropped some of the outer frame to reduce distraction and focus the frame on the center of the ball drop better.

Conclusion:

I really enjoy watching this video and wondering a little bit more about the more complicated mechanics of the fluid movement. For example, how the dimples on the golf ball affect the surface texture of the fluid as it displaces them in the splash. This is something that I would like to study deeper given more time and energy. Experimenting with the highspeed camera was really interesting and taught me a lot about shutter speed and lighting as we had to add a lot more light to the setup than I thought we would just to be able to see anything. I would like to do more with the highspeed camera in the future.

Bibliography

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