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MCEN 5051-001

Image Video #3 - Report

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The goal of this image was to dramatically capture a vortex in a way that showcased the physics present. The original intention for this project was to better understand the flow through a NACA duct by pulling it through water in a fish tank. Unfortunately, it proved very difficult to achieve reasonable dye injection and as a backup the project was switched to vortex rings. As the first pictures were taken it became evident that these rings had the potentially to look like sea creatures. This was capitalized on as the project steered towards trying to capture an image reminiscent of aquatic life.

The project was set up in a 36” x 18” x 16” fish tank. The tank was filled about 8” deep and had a light blue painted sheet of Masonite submerged as a backdrop. The light blue was selected as a natural ocean inspired color. A vortex generator was built from a small cornstarch can. The can was about 2 ¼” in diameter and 3 ½” tall. A 1” hole was cut in the plastic lid concentric on the axis of the can. The bottom of the can was cut out then a balloon stretched around the base. This setup allowed the balloon membrane to be pulled back and snapped to launch a small puff of fluid out of the hole in the lid.

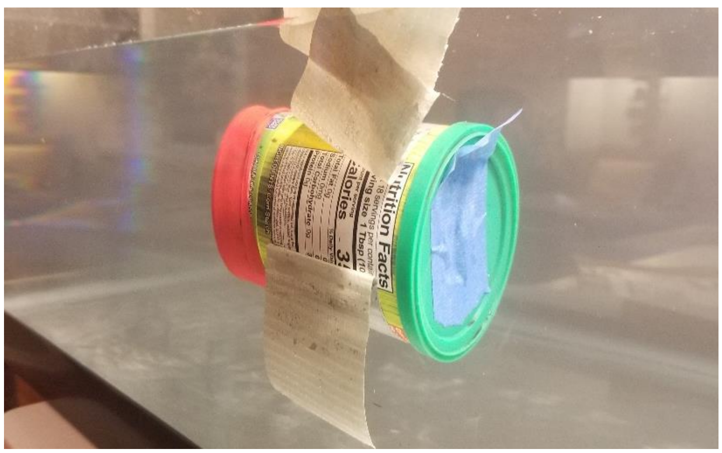

Figure 1. The vortex creating can.

Figure 1 above shows the vortex generator. A blue piece of tape seals the 1” hole in the green lid while the snappable balloon membrane can be seen on the other side in red. The can was taped to the side of the fish tank for the shooting.

The rings were captured using a continuous shooting mode at 11 shots per second. This frame rate can be combined with the field of view to determine the ring size and speed. Figure 2 below shows the ring travelling 250 pixels over the course of 360 ms. From a picture of the same scene with a ruler along the ring’s path it can be found that 1 inch corresponds to 110 pixels. Using that conversion, the ring can be clocked at 6.3 inches per second and has an outside diameter of 1.9 inches.

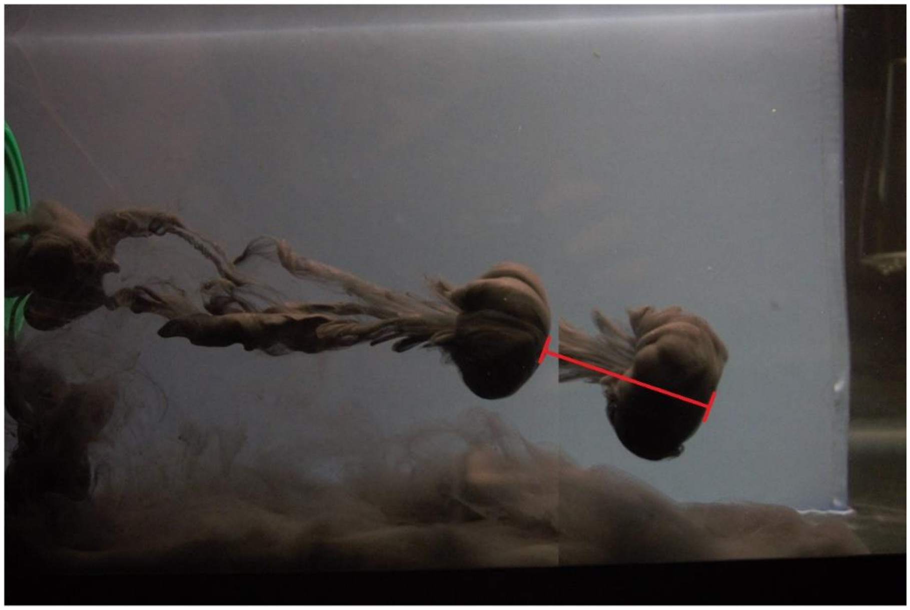

Figure 2. A composite image from 2 images taken 360ms apart. A 250px long red line measures the distance travelled by the ring.

From these numbers the Reynolds number may be approximated. Tony Maxworthy describes the Reynolds number for a vortex ring as the product of the mean ejection velocity and orifice diameter divided by the kinematic viscosity of the fluid.[3] Without an easy way to determine the mean ejection velocity it will be assumed to be similar to the ring's velocity across the tank. This indicates a Reynolds number of:

$$Re = \frac{\overline{U_M} D_M}{\nu} = \frac{0.16 \left[\frac{m}{s}\right] * 0.03\ [m]}{1.1 * 10^{-6} \left[\frac{m^2}{s}\right]^{[2]}} = 4{,}000$$

This relatively high Reynolds number for a vortex ring may help to create the interesting turbulence and twisting tails following the ring.

One of the most exciting aspects of the experiment to watch is how effortlessly the rings propagate across the entire tank. This is explained by George Batchelor in his Fluid Dynamics text where he describes how the fluid coming around the outside of the vortex travels in the same direction as the bulk ambient fluid, greatly reducing the viscous friction of the ring as it goes by.[1] This friction reduction allows the ring to travel quite far. This may be quantified to some extent by an equation laid out by Monika Nitsche in a paper about vorticity. Her equation for the propagation speed[4] is as follows:

$$U \sim \frac{\Gamma}{4\pi R}\left(\log\left(\frac{8R}{a}\right) - \frac{1}{4}\right)$$

In this case, the propagation speed, U, is related to the circulation, Γ, the radius of the vortex, R, and the thickness of the torus pipe diameter, a.[4] This equation may be rearranged to solve for the circulation as follows.

$$\mathbf{\Gamma} = 4\pi \frac{(0.02\ [m])\left(0.16\ \left[\frac{m}{s}\right]\right)}{\log\left(8 * \frac{0.02\ [m]}{0.03\ [m]}\right) - \frac{1}{4}} = \mathbf{0.08}\ \left[\frac{\boldsymbol{m^2}}{\boldsymbol{s}}\right]$$

This provides some insight as to how the speed and geometry of the vortex ring are related to each other.

For this image, the fluid flow was visualized with dye seeding. A solution was made by adding about 2 tablespoons, or 1 fluid ounce of black Pro Art Liquid Tempura paint to a 12 fluid ounce container. The rest of the container was filled with water and then aggressively agitated to mix the fluids. This solution was used to fill up the vortex generating can. This 1:11 mixture of diluted paint made for a very heavy dye which made dark rings. The tank was lit from above with a 4200 lumen, 68 watt compact fluorescent bulb. While this was a very bright bulb, it still struggled to sufficiently illuminate the rings despite being rather close the surface of the water.

Figure 3. The experimental setup showing light position, and backdrop orientation.

The image was captured on a Sony α6000 mirrorless digital camera. This camera captured a field of view just shy of 12” wide at the focal plane. The camera was about 10 inches from the rings, using a 16-50mm lens set to a focal length of 28mm. It was focused manually on a ruler held in the tank along the axis of the vortex generator. An aperture of 5.6 was selected to let lots of light in and blur the background as much as possible. To freeze the flow, a shutter speed of 1/400 was selected. The ISO was automatically selected by the camera at 3200. This resulted in an original RAW image of 6000 x 4000 pixels.

In post processing the main vortex ring was first moved up in the frame by about half an inch using Gimp. This addition space between the ring and the dye at the bottom framed the picture a little bit better. Darktable was then used to crop the image down to 4400 x 2970 pixels. The profiled denoise tool was used to reduce the noise from using a high ISO. Finally, the RGB curve was adjusted to bring out more contrast in the dark greys of the vortex. It was difficult to achieve proper contrast as the picture was initially a bit dark. A comparison between the original and edited images is below as Figure 4.

Figure 4. The initial image on the left and post processed image on the right.

I do like the results of this image. It is quite reminiscent of a strange sea creature. By pulling the rubber membrane back further on the vortex generator, a larger slug of fluid was ejected. This increased the turbulence and amount of ejected tail from the vortex which helped to create the creature shape. The most significant downfall of the image is the lack of contrast in the shadows. By the time this image was captured, the water was slightly opaque from the previous attempt's dye. Combined with the fast shutter speed the image turned out dark. Increasing the ISO was not possible given the graininess at 3,200. To improve this, a slightly lower concentration of the dye could be combined with more lighting. Additionally, less ambient room lights may have reduced the reflections in the tank glass. The size of the tank was additionally troublesome as it took about half an hour to fill from the sink. Each trial required a complete emptying and refilling with fresh water. A smaller tank would make it easier to conduct many trials and have more flexibility with colors or ring shapes.

Works Cited

[1] – Batchelor, G. K. An Introduction to Fluid Dynamics. Cambridge Univ. Press, 1994.

[2] – Engineering ToolBox, (2004). Water - Dynamic and Kinematic Viscosity. [online] Available at: https://www.engineeringtoolbox.com/water-dynamic-kinematic-viscosity-d_596.html [Accessed 20 11. 2020].

[3] – Maxworthy, T. (1977). Some experimental studies of vortex rings. Journal of Fluid Mechanics, 81(3), 465-495. doi:10.1017/S0022112077002171

[4] – Nitsche, Monika. “Vortex Dynamics.” Department of Mathematics & Statistics, The University of New Mexico. math.unm.edu/~nitsche/pubs/2006EMP.pdf.