Vortex Rings

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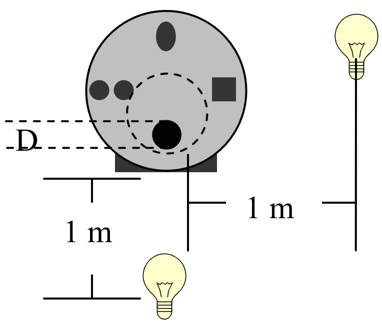
Context and Purpose:

Vortices and Vortex Rings are remarkable phenomena. Vortices are produced as a result of many objects we encounter everyday. Examples of vortices are the tip vortices created by helicopter rotors, the wake of submerged bluff bodies like bridge supports, and the tips of airplane wings. On a larger scale, weather systems like hurricanes act as sizeable vortices. These everyday vortices are commonly overlooked due to the difficulty in visualizing their spiral fluid flow. The purpose of this project was to capture a vortex ring using photography and analyze the phenomena. Many different ring geometries were experimented with ranging from squares, multiple rings, and ellipses. Non-circular geometries produce the result of axis switching due to the variable perimeter speed of the ring. Axis switching vortex rings proved to be an interesting phenomenon to observe but difficult to capture due to timing. As a result our sharpest and most striking images were of the circular vortex ring. The production of the vortex rings was done in a closed room with limited ventilation as to not disturb the ring formation. We discovered that the rings were very sensitive to temperature changes caused by the flood lights used to produce the images. This was seen by the upward lift of the ring as it propagated from the vortex generator.

Flow Apparatus:

The equipment used to create the fluid flow in the image was the vortex generator with the circular hole in front of the opening. The apparatus is shown in figure 1 below.



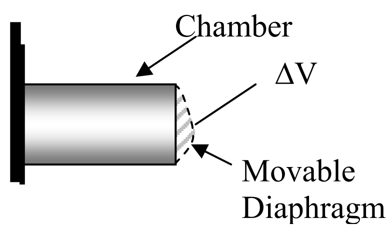


Figure 1: Vortex generator and lighting.

The diaphragm was pushed forward to displace a volume of fluid, which flowed out of the circular opening at the other end of the vortex generator. The specific criteria for vortex generation, as stated by Cantwell [1], is that a leading vortex will form in flow situations where Reynolds numbers are $\mathrm{Re} = \frac{UD}{\nu}$ >6. The exit velocity of the fluid from the orifice can be calculated using a conservation of mass approach. Since the velocities are considered low in this situation, the fluid can safely be assumed to be incompressible. Therefore, U can be calculated as a function of the time over which the diaphragm was moved, Δt=0.22 s, the displaced volume, ΔV = 3.64 L, and the exit diameter, D= 87 mm. The Reynolds number can be calculated as $\mathrm{Re} = \frac{\Delta V}{\pi \nu \Delta t \bullet D}$ = 46,080, where ν=1.51x10^{-5} m^2/s at standard temperature and pressure [2]. Another critical value in describing flow out of an orifice is a dimensionless parameter called the formation time, $T = \frac{L}{D}$, where L is the length of the cylindrical column of fluid pushed through a hole of diameter D. L can be approximated by $L = \frac{\Delta V}{\pi D^2}$, which gives a formation time of $T = \frac{\Delta V}{\pi D^3}$=1.76. Mohsemi [3] indicated that for formation times T>4 a trailing jet was formed behind the leading vortex. The trailing jet in the photograph conflicted with the prediction that there should have been no trailing jet based on the formation time. The formation time may be greater than calculated due to holes allowing fluid to be sucked into the smoke box. This was not accounted for in the conservation calculation. It should also be noted that the rings were lit from below with two 500 watt work lights. The heat created by the lights caused the air to rise, which was shown by the upward slope of the smoke's trajectory. The velocity of the smoke as it was ejected from the box was calculated to be 0.7 m/s. If the shutter speed was 1/60 s then the leading edge of the vortex moved 11.6 mm. The field of view of the image before it was cropped was around 1.5 m and the resolution was 3072 pixels wide by 2048 pixels tall. One pixel captured 0.49 mm of the vortex. The vortex moved through 24 pixels during the time that the shutter was open. This caused blurring in the direction of movement of the vortex.

Visualization Technique:

As was mentioned before, vortex phenomena occur in many everyday activities but are rarely seen do to the inability to see the fluid flow. It was for this reason that stage fog was used in high concentration in the vortex generator chamber. The light produced by four work lights was scattered by the tiny molecules of the stage fog which is composed of a vaporized glycol-water solution. The scattering from very tiny particles (< 1/10 wavelength of light) is predominantly Rayleigh scattering. In our case the glycol particles are much larger than the wavelength of light and thus Mie scattering dominates the scattering process. Mie scattering is not strongly wavelength dependent and produces the white light seen in mist and fog. Below figure 2 is a schematic which shows Rayleigh and Mie scattering:

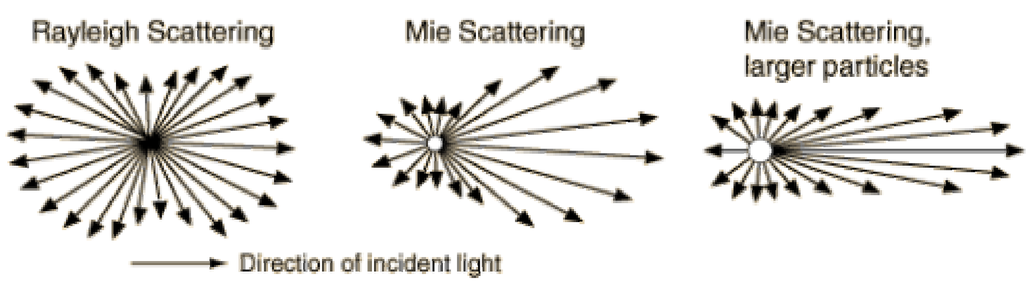


Figure 2: Rayleigh and Mie Scattering [4]

The lighting was produced by four 500 watt work lights two of which were positioned below the path of the ring and two which were at a 120 degree angle behind the camera. In addition to the work lights, the flash on the camera was used to help illuminate the ring and produce faster shutter speeds resulting in a sharper image.

Photographic Technique:

We photographed these particular vortex rings with a Canon EOS Digital Rebel camera and a Cannon Ultrasonic 28-135mm lens. The camera was the same distance away from rings as the smoke machine, which was about one meter. It was sitting about 0.5 m to the right of the machine on the same table so the rings came out eye level with the lens. This provided an ideal viewing angle on the rings allowing us to view through the ring and capture details in the trailing jet. The field of view throughout the project was between 0.3 m and 0.6 m and for these particular images it was closer to 0.3 m. The focal length was at 65mm and even with additional lighting, the flash fired. The aperture was set at f/5.0 and the shutter speed at 1/60 sec, which allowed for the maximum amount of focus with a slight blur in the smoke. The images were slightly altered in Photoshop, but since we used the black velvet background not a whole lot was changed. Tracing around the smoke and filling the rest in white/black cleaned up the folds that could be seen in the background. The brightness/contrast was tweaked slightly and the invert tool was used in the image with the white background. This made the rings and smoke trails much clearer, without disrupting or altering the flow phenomena.

What the Image Reveals:

The image captures a very developed vortex ring as well as the trailing jet and instability left behind as it translates through the air. There was much difficulty in capturing such a sharp and clear vortex ring. This image was one of the few that turned out clearly which is why it was selected. We liked the jet trial which allowed us to visualize the fluid flow after the ring had passed. What we dislike about the image is that Photoshop did not completely clean up the edges of the vortex ring and background. We would like to better understand the fluid mechanics of the fog left behind the vortex ring. We feel that this image did a great job documenting the phenomenon which we set out to capture. The aspect that we would improve on would be linking the shutter release to go off at a time the vortex is full developed in order to produce quality images more consistently. One way that the timing issue can be dealt with is by using the high speed camera to capture many frames of the vortex. This would insure that an image was captured while the vortex ring was fully developed. Another improvement would have been to increase the shutter peed in order to reduce motion blur. If this project was to be continued further I would like to capture a “leap frog” image. This is when two vortex rings separated by minimal distance fight each other for the lead by going though the center of the leading ring and then repeating.

Reference:

1) Cantwell, B. J. 1986 Viscous starting jets. J. Fluid Mech. 173, 159–189. As quoted in [5]
2) Munson, B. R., Young, D. F.,Okiishi, T. H., Fundamentals of Fluid Mechanics 4th Edition, 833.
3) Mohseni, K., Ran, H. Y. & Colonius, T. 2001 Numerical experiments on vortex ring formation. J. Fluid Mech. 430, 267–282.
4) http://hyperphysics.phy-astr.gsu.edu/Hbase/atmos/blusky.html
5) Dabiri, J. O.,Gharib, M., The role of optimal vortex formation in biological fluid transport, Proceedings of the Royal Society B 272, 1557–1560