Vortex Rings

Vortices, and vortex rings are an amazing fluid phenomena. Vortex structures are commonly developed in the normal transactions of daily life and appear in a wide variety of fluid flows. Examples of vortex phenomena include; vortices shed off an airplane wing while the airplane is in flight, vortices left behind a baseball as it's thrown, and the vortex structures that are shed from an automobile cutting through quiescent or non-quiescent air. Large-scale vortex configurations are abundant in the ocean and the atmosphere and are now more easily seen because of the invention of the satellite. The purpose of this project entails photographing and understanding the complex elliptical vortex ring. More specifically, elliptical vortex rings are unstable as far as there configuration or geometry is concerned. Therefore, an elliptical vortex ring actually ungulates switching its major and minor axis while translating. This phenomenon is known as axis switching and is very fascinating to see. Countless engineers and various students walked by this experiment and commented on how awe struck and captivated they were by the elliptical vortex rings. The experiment was conducted in the storage room of the Integrated Teaching and Learning Laboratory at the University of Colorado at Boulder. The purpose of conducting the experiment in this room was to reduce gusts, breezes, and other air disturbances that would affect the trajectory and structure of the vortex ring. Capturing this extraordinary phenomenon proved to be very difficult, and extremely frustrating. But, the shear attractiveness and amazement of the vortex ring made it worth pursuing.

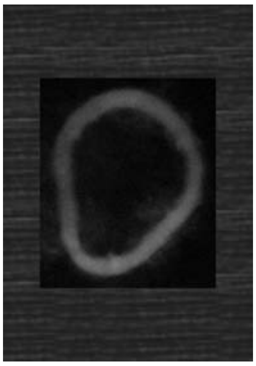

Figure 1. Elliptical Vortex Ring

The flow apparatus and setup was not too complicated, although a more robust experimental setup would definitely alleviate some inconsistencies and improve the quality of the photograph. For example, the vortex ring occasionally missed the target area. This problem was due in part to minor breezes in the room, and possibly to inconsistent squeezing of the box to generate the vortex rings. Further experimental improvements are discussed in the final paragraph. The elliptical vortex rings were created using a cardboard box with an ellipse cut out of the side. The box had the dimensions of 21.8 x 16.4 x 10.1 inches. Therefore, the approximate volume of the box was 3600 cubic inches. The size of the ellipse or orifice cut out of the box was 6.5 inches major diameter, with a 3.5 inch minor diameter. The box was then filled with stage smoke, which was produced with the Rosco model 1700 fog machine. The elliptical vortex rings were then generated by squeezing the sides of the box forcing the stage smoke through the elliptical orifice. Several different techniques for generating the vortex rings were examined, one of which included taping the box. Since the box was fairly pliable, the most reliable method for creating the best vortex rings involved squeezing both sides of the box. The white/gray stage smoke vortex rings where shot towards a black cardboard target in order to achieve a significant contrast and thus a better image. The black cardboard target was 22 by 28 inches in size, and was located approximately 40 inches high off the ground.

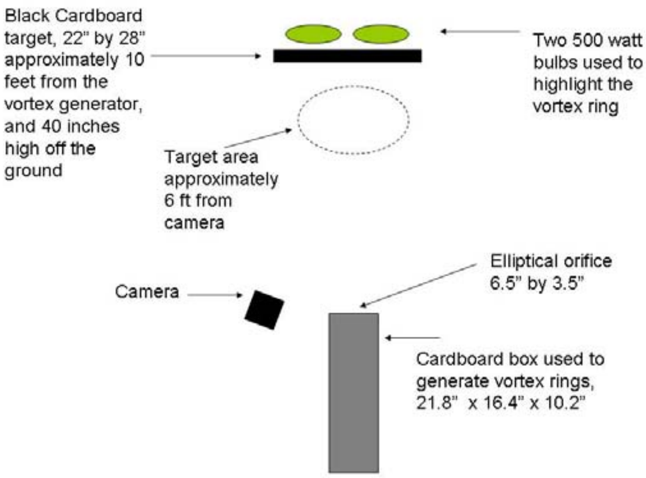

Figure 2. Experimental Setup

A few parameters that help describe the vortex ring include the Reynolds number and the Formation number. The equation for the Reynolds number is given below in equation 1.

$$N_R = \frac{u \cdot D}{\nu} = \frac{u \cdot d_h}{\nu}$$

Equation 1. Reynolds Number

Where N_R is the Reynolds number, u is the velocity of the vortex ring, d_h is a characteristic length in this case the hydraulic diameter, and v is the kinematic viscosity of air. The average velocity of the vortex rings was measured to be 4.3 ft/s. The kinematic viscosity at 70 degrees Fahrenheit is $1.64*10^{-4}$ ft^2/s (http://www.engineeringtoolbox.com/24_601.html).The equation for the hydraulic diameter is

$$d_h = 4 \cdot \frac{A}{P} \qquad \text{where } A = \pi \cdot a \cdot b \text{ and } P = \pi\left\{3(a+b) - \left[(a+3b)(3a+b)\right]^{1/2}\right\}$$

The symbol A is the area of an ellipse, P designates the wetted perimeter, a represents the major axis of the ellipse, and b symbolizes the minor axis. The equation for the perimeter is a first order approximation (notice that when $b = a$, $P = 2\pi r$ as expected). Again, the major and minor axis of the ellipse were 6.5 inches and 3.5 inches respectively. Using these formulas, the hydraulic diameter turns out to have a value of 8.03 inches. With these values, the Reynolds number is then calculated to be 17,626. A Reynolds number of this magnitude is considered to be turbulent. Another important aspect to classifying a vortex ring is the formation number. According to Gharib et al , " The formation number is indicative of the time at which a vortex ring acquires its maximal circulation"[1]. In other words, there is a certain time at which a vortex ring attains its maximal circulation, and any further discharge of fluid from the orifice will not increase the vortex ring circulation. The formation number is defined in equation 2, where d_h is the hydraulic diameter, and L_m is usually defined as the length of the column of fluid pushed out of an orifice by a piston. Using a piston to push a column of fluid out of an orifice is another common technique of generating vortex rings.

$$T^* = \frac{L_m}{d_h}$$

Equation 2. Formation Number

As seen in Figure 2 (the experimental setup), the length of the vortex generating box is approximately 21.8 inches. Since the elliptical vortex rings were generated by squeezing the center of the box, L_m can be approximated as half of the length of the box. Taking this value for L_m and the hydraulic diameter calculated before, the formation number comes out to be 1.36. Gharib et al found that vortex rings generated by a piston generally had a formation number of approximately four [1]. But, the paper does mention that non-uniform velocity profiles may decrease the formation number significantly. Gharib et al states that, "In the case of a parabolic velocity profile of the discharged flow, for example, the formation number decreases by a factor as large as four" [1]. The elliptical orifice definitely generates a non-uniform velocity profile that is parabolic in nature. Furthermore, the general formation number of four applied to laminar vortex rings. The calculation for these vortex rings seemed to show that the flow was turbulent.

As mentioned before, vortices and vortex structures are common in fluid flows. Although, often times vortex phenomenon remains unseen even though it appears in the everyday circumstances of automobile and airplane motion. Thus, stage smoke was used to visualize the elliptical vortex rings. This type of visualization technique is considered to be a Mie scattering technique because the small smoke particles that construct the vortex ring are used to scatter light. In order to take advantage of the Mie scattering, two 500 watt light bulbs were used. Several different locations for the shop lights were examined. In the end, these light bulbs were placed above the target area (see Figure 2. Experimental Setup) because this location seemed to highlight the vortex rings the best as they moved into the target area. The lights were tilted slightly downward to illuminate the rings as they approached the target.

Below is a list of important geometrical and camera parameters that help describe how the picture was taken.

- Size of field of view – Using the size of the cardboard target, an estimation for the size of field of view in the final picture is approximately 11 by 10 inches
- Distance from object to lens – The distance from the vortex ring to the camera was about 6 to 6.5 feet. Because the vortex rings were difficult to photograph, the camera was focused to approximately 3 meters or 6 ft. A picture was then taken when the vortex ring entered the target area.
- Lens focal length and other lens specs – The pictures were taken at and f-number of 4.8, and a focal length of 16.2 mm.
- Type of camera – The camera is a Canon A70, with a lens focal length between 5.4 and 16.2 mm. The aperture on the lens is 1: 2.8 – 4.8. The Canon A70 has a times 3.8 zoom. But, 3.0 of the zoom is optical, the rest is a digital zoom.
- Exposure Specifications –
  - Shutter speed – 1/30th of a second
  - Aperture - 3.375
- Photoshop processing – An original picture was given. The final picture was cropped to cut out the background. A textured artistic background was then given to try to highlight, or enhance the vortex ring.

In the end, the best aspect of trying to photograph a vortex ring, is actually getting to see a vortex ring. What this image reveals is a complex yet amazing phenomena in which the elliptical vortex ring ungulates as it progresses or translates forward. This photograph catches the vortex ring as the sides of the ring begin to move forward propelling itself through the air. Unfortunately, the vortex ring proved to be very hard to photograph. This picture contains several artifacts that detract from the beauty of the vortex ring. These artifacts include; motion blur, a lack of definition of the vortex ring perhaps due to focus, and a deficiency in contrast which would help separate the white/gray vortex ring from the background. Improvements in these areas could be the next step to capturing a more visually pleasing photograph. A more sophisticated method for lighting up or highlighting the vortex ring would be a vast improvement. A strobe of flash would probably work best to highlight the vortex ring in a dark room, but moderate to significant work would have to be done in order to time the flash, with the picture right as the vortex ring moves into the target area. Infrared photo-eyes could be used the initiate the sequence as the vortex ring passes through the infrared beam, but I'm not sure if the smoke vortex ring would be enough to break the beam and set off the flash or camera. If the smoke vortex ring were able to break the infrared beam, then complex equipment would be needed to commence the picture and the flash simultaneously. I believe a more complicated set up that involved a considerable amount of time is needed to get a better, more visually pleasing image of the vortex ring.