# Vortex Rings

**Team Image 1, MCEN 4151, Flow Visualization**

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## Introduction

This image of vortex rings is for the first team assignment in Flow Visualization. I worked with Kristopher Tierney, Lael Siler, and Mark Voll to produce images of vortex rings in the air. Our group chose to image vortex rings because our professor told us that they are difficult to capture clearly, and we wanted to see if we could create better vortex ring images than groups in years past. Artistically, I enjoyed seeing the rotational motion within the vortex rings. I attempted to capture the rotational motion on video, but the quality was low and they would have required extensive post processing. Instead of a video, I used a still image to show the circulation and wake of the vortex rings.

## Experiment and Flow Description

To image this smoke ring, a cardboard box (about 35 cm by 13 cm by 20 cm) was placed on a table with a black backdrop behind it. A small hole about the size of a soda can (5 cm in diameter) was cut in the smallest side of the box, and the box was then filled with stage fog from a fog machine. When the larger sides of the box were compressed, vortex rings were emitted from the circular hole. Many images were taken with the box pointing in several different directions. For this image, the box was oriented with the hole pointed towards the ceiling to see if gravity caused the vortex rings to behave differently. However, there was no noticeable change in the ring behavior. The air in the room needed to be still to create a good vortex ring, so the door to the room was closed and all of the air vents in the room were covered. Soft and diffuse natural light illumined the vortex rings from the windows opposite the table. The camera was positioned slightly off center from the box between the table and the window. At this angle, the vortex rings were lit well with the light from the windows. The camera was raised about half a meter above the table to capture the vortex rings just after they left the cardboard box. The camera was hand held instead of used with a tripod, because there only tripod available was being used by one of my partners. A top view of the experimental set up is shown below in Figure 1.

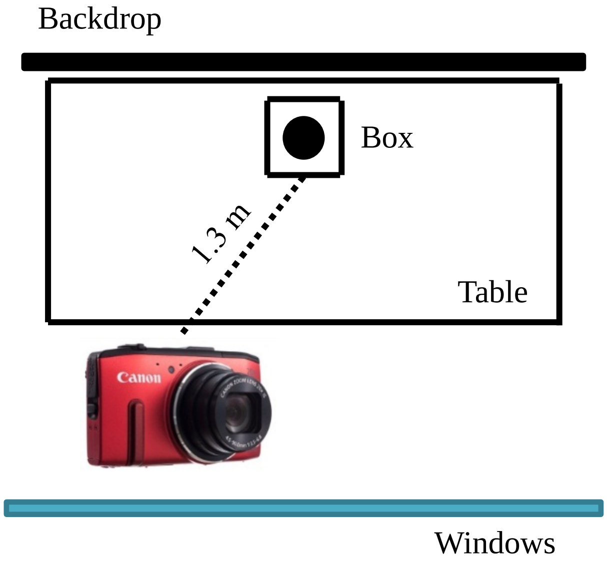

Figure 1: Top View of Experiment

The dynamics of vortex rings in air are determined by the velocity and viscosity of the air. Compressing the cardboard box creates a pressure wave that forces the air out of the hole in the top of the box. For any given cross section of air that passes over the edge of the hole, friction slows down the air particles that are closest to the edge of the hole. The particles that are father from the edges are less affected, because the viscosity (friction between air particles) is low. The farther the particles are from the wall, the more they resemble free flowing air. This results in a velocity profile for any given cross section within the vortex ring as it leaves the box. See Figure 2 below. The different velocity layers introduce shear forces on the air particles, which cause the particles to rotate about a centerline or vortex core. This rotation is called vorticity. Once the air has left the cardboard box, each cross section maintains this rotational motion, so the air forms a rotating vortex core in a ring that propagates forward.

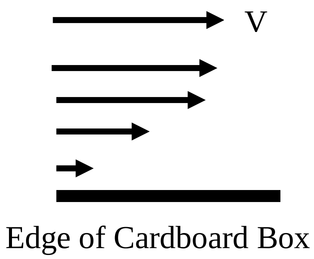

**Figure 2: Velocity Profile of a Vortex Ring Cross Section**

Several videos were taken of the vortex rings throughout the experiment, and the velocity of the vortex ring was estimated from these videos to be 0.28 m/sec as it propagated through the air. This velocity can be used to estimate the motion blur and the Reynolds number for the vortex ring. Motion blur can be estimated with the following formula.

$$motion\ blur = \frac{(shutter\ speed)(velocity)(height\ of\ image\ )}{field\ of\ view}$$

Substituting values in yields:

$$motion\ blur = \frac{\left(\frac{1}{320} sec\right)(0.28\ m/sec)(4000\ px)}{0.23\ m} = 15\ px$$

Therefore, the vortex ring has about 15 pixels of motion blur. This can be seen in the image, because the wake of the ring, which is moving slower, is clearer than the ring itself.

The Reynolds number of a flow is defined as a ratio of the inertial forces to the viscous forces in a fluid, and it influences the stability of the vortex ring as it propagates forward. To estimate the Reynolds number, assume that the stage fog has negligible effect on the dynamics of the air. Let that the density of air at 20 degrees C be 1.184 $kg/m^3$ and the dynamic viscosity of air be $1.84 * 10^{-5}\ Pa * sec$.[1] The characteristic diameter is taken to be 0.03 m, which is the estimated thickness of the vortex ring.

$$Re = \frac{(density)(velocity)(diameter)}{dynamic\ viscosity} = \frac{(1184\ kg/m^3)(0.28\ m/sec)(0.03\ m)}{1.84 * 10^{-5}\ Pa * sec}$$

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[1] "Wolfram Alpha." Wolfram Alpha LLC—A Wolfram Research Company, Web. 08 Mar. 2014.

$$Re = 5.4 * 10^5$$

Vortex rings have been shown to be turbulent when they shed large amounts of fluid into their wake.[2] Given that the vortex ring in this image is shedding fluid into its wake and that the Reynolds number is on the order of $10^5$, it is concluded that this vortex ring is also turbulent. This conclusion is consistent with the findings of Maxworthy in 1972, which state that vortex rings with initial Reynolds numbers greater than about $2 * 10^4$, become turbulent immediately after their formation. [3]

## Visualization Technique

The vortex rings were visualized by stage fog, which is a suspension of water droplets and glycerin in the air. The water droplets reflect the light towards the viewer, and the glycerin slows the evaporation of the water into the air. Stage fog is approximately 70% water and 30% glycerin,[4] and it is aerosolized with a stage fog generator. The black backdrop provided contrast to the light vortex rings. The vortex rings were lit with natural light coming from a bank of large window behind the camera. It was cloudy and snowing on the day of the experiment, so the natural light was soft, uniform, and cooler in color. No flash was used. As a team, we considered using additional light, but ultimately decided to use only natural light. We worried that the light from additional lamps would cast a different and unnatural color on the vortex rings.

## Photographic Technique

The image was taken with a Canon PowerShot SX280 HS Digital Camera with 12.1 megapixels. The camera lens has a 4.5 - 90.0 mm focal length and a 20 times optical zoom with image stabilization. It can produce an aperture between 1:3.5 and 1:6.8, and the camera supports an ISO from 80 to 6400.

The original image was 4000 by 3000 pixels with a bit depth of 24. The field of view in the image is about 23 cm vertically and 13 cm horizontally. The lens was about 1.3 m from the vortex ring. Because the natural light from the windows behind the camera was not very bright, the ISO was set high at 3200. Any higher ISO produced very grainy images. The focal length was 10 mm, and the F Number was 4. This aperture was chosen to be as wide as possible to allow more light to enter the lens and lighten the image. Since the vortex rings were moving quickly, the chosen shutter speed of 1/320 seconds was a compromise between eliminating motion blur and having a brighter image.

In post processing with Adobe Photoshop CS6, I rotated the entire image 90 degrees clockwise, because I liked the composition better when it was rotated. I also wanted to make the background blacker to contrast with the light colored vortex ring, so I used the curves tool to oversaturate the blacks. This operation gave the vortex ring a bluish tint, which did not look natural; therefore, I converted the colors to grayscale with the Desaturate Tool. Desaturating the

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[2] Weigand, A., and M. Gharib. "Turbulent Vortex Ring/Free Surface Interaction." *Journal of Fluids Engineering* 117.3 (1995): 374-81. Print.

[3] T. Maxworthy (1972). The structure and stability of vortex rings. Journal of Fluid Mechanics, 51, pp 15-32 doi:10.1017/S0022112072001041

[4] Helmenstine, Anne Marie, Ph.D. "Atomized Glycol Fog." *About.com Chemistry*. Web. 08 Mar. 2014.

image also helped enhance the contrast in the ring. Finally, the image was cropped to improve the composition resulting in an image size of 2555 by 3000 pixels. See the original image below in Figure 3.

Figure 3: Original Image

## Image Results

This image highlights the detail flow in the wake behind the turbulent vortex ring. The vorticity core can also be seen in the ring. While I was hoping to capture more details of the flow around the core, I like this image overall. The dark background provides excellent contrast, and the texture in the wake is beautiful. Our group was able to capture successfully several images similar to this one that accurately show the flow in a vortex ring. The lighting for this image was difficult, and many of the images were dark and grainy from the high ISO. In the future, I would like to make a similar image with more light (either natural or artificial). Vortex rings are ideally suited for video, and if I learn how to edit videos, I would like to capture these vortex rings on video.

## References

[1] "Wolfram Alpha." Wolfram Alpha LLC—A Wolfram Research Company, Web. 08 Mar. 2014.

[2] Weigand, A., and M. Gharib. "Turbulent Vortex Ring/Free Surface Interaction." *Journal of Fluids Engineering* 117.3 (1995): 374-81. Print.

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