Toroidal Vortices in Air

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Introduction

The purpose of this paper is to document and describe the experimental process that was followed to produce a flow visualization video titled 'Toroidal Vortices'. The original post can be found at http://www.flowvis.org/2019/09/08/matt-knickerbocker/. The toroidal vortices video was captured as a requirement for the first individual assignment of MCEN 5151 - Flow Visualization called Get Wet. The task of the assignment was to capture a photo or video of fluids that both (1) clearly demonstrate the phenomenon being observed and (2) is a good video. The intent of the video was to observe the motion and interaction of toroidal vortices using smoke as a visualization technique. The only collaboration done to produce the video was provided by J.A. 'Dino' Deane, Farrell Lowe, and Michel Stahli with the rights to use a song they composed to accompany the video.

Flow description

The apparatus used in this flow experiment involved a vortex generator, a burning incense stick, an external LED light, and a Canon EOS T7 Rebel on a tripod as shown in Figure 1 below. The vortex generator was constructed from a generic juice bottle with a circular hole cut into the bottom. A latex balloon was then stretched over the cutout hole such that a force could be applied to the balloon, causing it to act like a piston inside the bottle. A small hole was drilled into the side of the bottle so that a burning incense stick could be inserted to fill the bottle with smoke.

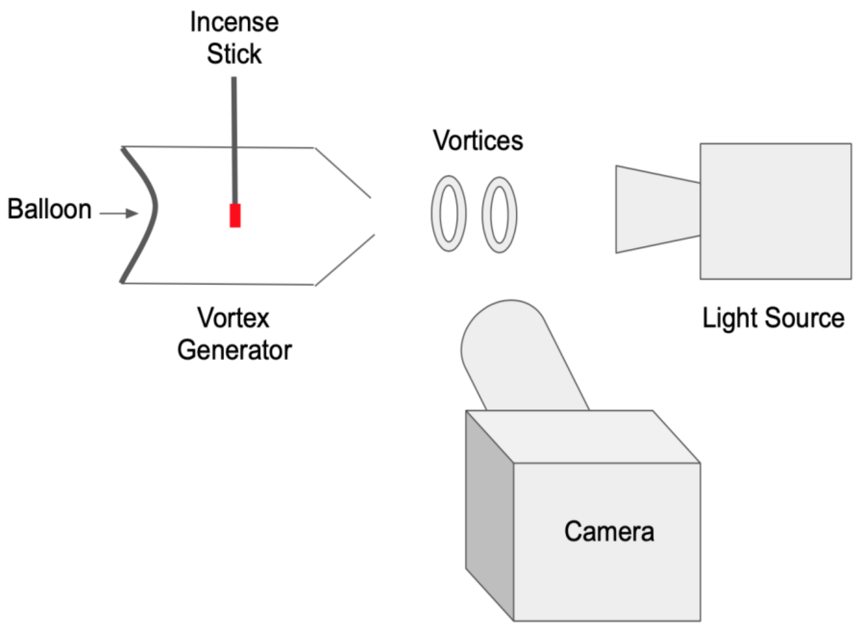

Figure 1: Experimental Setup.

The experiment was performed by allowing the vortex generator to completely fill with smoke before the balloon piston was periodically pressed into the bottle. This motion forced vortices to form at the mouth of the bottle and propagate sequentially through space. By varying the force and rate with which the balloon piston was depressed the speed, spacing, and trajectories of the vortices could be controlled. Different combinations of force and rate allowed for the production of several vortices which would interact with each other if close enough. The motions of the vortices can clearly be observed in the video as they propagate through the video frame. The scale of the vortices in the video were approximately 2 inches in diameter. The frame of the camera was placed within 5 inches of the vortex generator orifice such that the vortices were observed early in their formation, before they had time to decay. Downstream of the field of view, the vortices were observed to deform and decay as instabilities and external disturbances acted on them. An estimate of the Reynolds number of the vortices was calculated based on their density ρ, velocity u, viscosity μ, and diameter D. Based on the size of the frame and the time taken for an average vortex ring to cross the frame, the velocity was estimated to be 1 ft/s. Using these values, the Reynolds number was calculated to be approximately 2000 as shown below. This low Reynolds number indicates a laminar flow which agrees with what was observed.

$$Re_D = \frac{\rho u D}{\mu} = \frac{(0.146\ lb/ft^3)\cdot(1\ ft/s)\cdot(0.167\ ft)}{(0.0000122\ lb/s\cdot ft)} = 2000$$

The flow captured in the video is a classic example of vorticity dynamics and vortex interaction. A vortex is defined as rotational motion about some axis in a fluid. Helmholtz's third theorem states that a vortex must end at a fluid boundary or form a closed loop [1]. The case of the closed loop vortex is referred to as a vortex ring or toroidal vortex. Vortices and vortex rings are a very common fluid phenomenon that can be seen in many examples. In general, vortex rings are usually formed by a brief discharge of fluid from an orifice [2]. More specifically, the vortex rings are formed due to viscous forces acting on the fluid as it is being accelerated through the throat of the vortex generator. As the fluid moves through the throat of the bottle, there is a viscous force (friction) between the wall and the moving fluid. This viscous force causes the edges of the fluid to roll up as they are slowed by friction at the wall. The rolling motion forms a closed vortex ring since this force is acting around the circumference of the throat.

Once the vortex ring is formed, it will propagate through space along the direction of its central axis. This propagation is caused by the self-induced velocity of the ring due to its rotational motion. This self-induced velocity is described by the Biot-Savart Law as shown in Equation (1) below where $V$is velocity, $\Gamma$is circulation, $dl$is a segment of the vortex line, and r is the distance between the vortex line segment and the point where the velocity is being induced.

$$dV = \frac{\Gamma}{4\pi}\frac{dl \times r}{\left|r^3\right|} \qquad (1)$$

This induced velocity explains the motion of the vortex ring as well as the vortex interaction that is observed when two vortices are near one another. An applied example of vorticity in fluids is that of the formation of wing tip vortices on the wings of an airplane in flight. This vortex caused by the flow of air around the tip of the wing is characterized by a core region of concentrated vorticity and a region outside the core that is dominated by the remainder of the wing wake [3]. The wingtip vortex creates an effect called downwash where the flow field behind the wing is deflected due to the induced velocity. Another applied example of vorticity in fluids is seen within the motion of blood inside the mitral valve of the human heart. It has been shown that vortical motions of blood inside the heart allow the mitral valve to act passively, that is to open and close purely due to the forces induced by the surrounding blood motion [4].

Flow Visualization Technique

As mentioned above, the flow visualization technique used in this experiment was smoke produced from a burning incense stick. With the vortex generator filled with smoke, the motion of each vortex was visible as it propagated. The visible ash particles in the smoke made the rotational motion clearly visible. The incense sticks were manufactured by the Bhakta Incense company. In order to reduce external noise that might affect or distort the vortices, the experiment was carried out in a small closet with the door closed, along with the ventilation system being turned off. In an effort to enhance the visibility of the vortices, an LED lighting source was positioned perpendicular to the camera frame such that the light was in line with the vortices as shown in the apparatus diagram in Figure 1.

Photographic Technique

The camera used to produce the video was a Canon EOS T7 Rebel DSLR mounted on a tripod. The video was shot at 60 frames per second with a resolution of 1280 x 720 pixels. The resolution was not modified between the original and final video. The chosen frame rate was the highest available and was selected to provide the most detail as well as the ability to slow down the play rate. The field of view was roughly 6 inches by 6 inches with the camera lens positioned about 12 inches from the vortices.

The scale of the vortices was approximately 2 - 3 inches in diameter, so this field of view provided adequate detail without being too close. The lens used was a Canon 18-55 mm zoom lens with an aperture range of 1:3.5-5.6. The exposure was produced using an aperture value of f/5.6, an ISO of 6400, and a shutter speed of 1/125 in order to obtain the 60 frames per second.

Minimal post-processing of the video was performed, and screenshots of the original and final video can be seen below in Figures 2 and 3, respectively. The white balance along with the contrast were slightly adjusted in order to darken the background and to enhance the detail of the vortices. The play rate of the video was reduced to 40% of the original speed such that the motion of the vortices could more clearly be seen since they were moving rather quickly. Additionally, a music track called ‘Her Touch Diary’ by J.A. ‘Dino’ Deane, Farrell Lowe, and Michel Stahli was added to the video. Documentation proving that the rights to use the music was obtained can be found in the ‘Music Rights Documentation’ file that was submitted along with this report. All of these edits were performed through the use of Apple’s iMovie program.

Figure 2: Screenshot of Original Video.

Figure 3: Screenshot of Final Video.

Conclusion

The video of the toroidal vortices reveals the vorticity dynamics of fluids and how individual vortices interact with each other. The video also highlights the beauty of fluids in motion, specifically rotational motion. I personally enjoy how visible the rotational motion is within the vortices as they move across the frame. Additionally, I think the video does a good job of depicting the interactions between individual vortices as well as highlighting the dissipative nature of the rings as they breakdown. If I were to attempt to improve the video, I would utilize a larger field of view or move the camera by hand such that each vortex ring could be seen for a longer duration. This would allow for more development and interactions between the vortices to be visible. Something else that could be improved is the consistency of smoke distribution across each vortex ring. The video shows that a larger concentration of smoke appears around the bottom half of the vortices compared to the top. While this effect is not undesirable aesthetically, it does act to disrupt the visibility of the underlying physics. Perhaps performing the experiment with a larger smoke concentration in the vortex generator could help resolve this effect. Overall, I am very happy with the result of this experiment and I surpassed my own expectations.

References

[1] Kundu, P. K., Cohen, I. M. “Fluid Dynamics”, 4th Edition, Academic Press, 2008.

[2] Glezer, Ari. “The formation of vortex rings”. Physics of Fluids 31, pp. 3532-3542 (1988). doi:10.1063/1.866920

[3] Devenport, W., Rife, M., Liapis, S., & Follin, G. “The structure and development of a wing-tip vortex”. Journal of Fluid Mechanics, 312, 67-106 (1996). doi:10.1017/S0022112096001929

[4] Reul, H., Talukder, N., Muller, E.W. “Fluid mechanics of the natural mitral valve”. Journal of Biomechanics. Volume 14, Issue 5, 361-372 (1981). doi: 10.1016/0021-9290(81)90046-4