Investigation of Half-Ring Vortices Generated by Half-Submerged Thin Circular Plate Using Digital Particle Image Velocimetry Method

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Abstract. A half-ring vortex near the free surface interface of water can be generated by dragging a half-submerged thin circular plate in the fluid and quickly pulling it out. This results in faster moving water in front of the plate rolling over the slower water next to the plate and creating a vortex. This vortex tends to preserve its momentum which results in the vortex continually spinning and moving in the dragging direction. To investigate the ring's motions, the Digital Particle Image Velocimetry (DPIV) method is used to study the flow of the vortex. Glitter is used as tracking particles which follow the flow of the water. The relationships between the radii of the ring and the plate as well as the dragging and vortex speeds are derived. In addition, the vortex size and speed appear not to be constant over time. It can be deduced experimentally that this half-ring vortex behaves similarly to a full vortex ring generated by the motion of a fully submerged circular plate.

1. Introduction

Ring vortices have been extensively investigated due to the simple yet elegant nature of the phenomenon. One simple way to create a vortex ring without complex apparatus is by giving a half-submerged circular plate an impulsive force and then quickly pulling the plate out of the water. The rolling of water pushed-off the front of the disc into relatively slow water on the back of the disc creates a vortex core behind the moving disc. Vortex ring generation is relatively simple when compared with monitoring and extracting useful information from the ring. Until recently, a complicated optical system was necessary in order to record the motion of the ring. The development of Digital Particle Image Velocimetry (DPIV) has made it possible to observe vortex ring behavior at a much lower instrumentation cost. This study proposes applying the DPIV method to studying of a vortex rings generated by an impulsive force to a circular plate in order to obtain vortex behavior.

2. Theory

The idea of vortex ring formation due to forced motion of partially submerged circular plates went as far back as the early 1900s when Klein proposed a thought experiment by dragging a spoon over coffee [1]. Taylor proposed the theoretical estimation of vortex rings formed in ideal fluid by dragging a fully submerged circular plate and rapidly removing it by assuming conservation of energy and constant vorticity over a vortex core [2]. The relationship of the plate radius c, the vortex radius R, the plate dragging velocity U, and the vortex translational velocity v are as follows:

$$\frac{R}{c} = \sqrt{\frac{2}{3}} \tag{1}$$

$$v = 0.436\,U. \tag{2}$$

There are a limited number of studies to confirm Taylors prediction due to difficulty in achieving the ideal experimental setup. Comparison between experimental results of a half-submerged circular plate and theoretical predictions of a fully submerged circular plate should be realizable since the conservation of energy and constant vorticity can still be applied for the half-submerged case.

The DPIV method is an optical method for instantaneous flow measurement from analyzing the displacement of seeding particles using a digital image correlation (DIC) algorithm. The fluid motion with the entrained seeding particles was recorded, with the help of computer calculation, the velocity field of the water was extracted and the related parameters were also derived.

3. Materials and Methods

The vortex ring experiment was performed in a glass tank with dimension of 50 cm × 120 cm × 50 cm and was filled with water to 45 cm in height. 1 mm thin circular plates of 6, 12, and 18 cm diameters were half-submerged, dragged by hand at various speed, and quickly pulled vertically out of the water. The half-submerged depth of the plates was chosen as it would create symmetrical vortices. Glitter with 300 μm size PVC was used as particle tracers. The digital video recorder (GoPro 4.0) with 60 fps and 1920 × 1080 pixel resolution was placed 1 m above the tank to record the motion of the plates and glitter. The recorded videos were processed with the MATLAB PIVlab toolbox [3] to calculate the velocity vector field of the surface flow and local surface vorticity.

4. Results and Discussion

From the preliminary observation, the half-ring vortex is actually a single vortex ring inverted at the water surface as can be seen in Figure 1 (a). A comparison between the raw image and the extracted velocity field and vorticity is shown in Figure 1 (b).

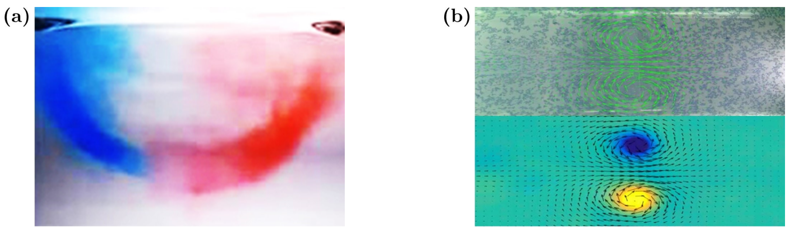

Figure 1. (a) Half-ring vortex with food coloring and (b) comparison between pre and post DPIV processing.

Figure 2 shows the extracted translational velocity and vorticity of the generated vortex ring. It should be noted that the values of translational velocity are highest in the area connecting two vortex cores as it is a combination of vortex translational and vortex core rotational velocities. The value of the vorticity is the highest in the center of the vortex core, implying the maximum rotation of velocity field in the center of the core. The upper core of the vortex exhibits positive vorticity, meaning that the core rotates counterclockwise while the lower core rotates in the clockwise direction.

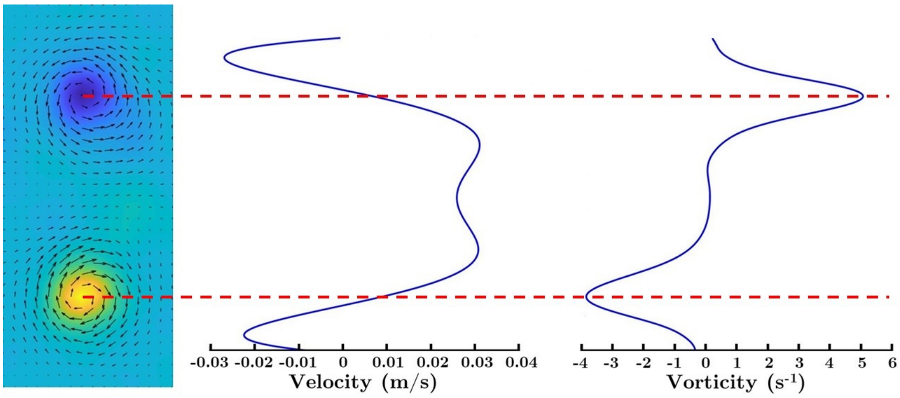

Figure 2. Translation velocity and vorticity profiles of a half-ring vortex generated by dragging a 12 cm diameter plate with 4.41 cm/s speed from the DPIV technique.

The relationship between plate radius and vortex ring radius is plotted in Figure 3 (a). Although there were only three different circular plate sizes, the experiment was conducted with the plates being dragged at varying speeds with the results showing a consistent relationship. From the plot, the R/c ratio was found to be 0.750 which is 8.1% off from the Taylor prediction. The relationship between average speeds of plate dragging and initial vortex speed is plotted in Figure 3 (b). From the graph the slope between v and U is 0.415 which is 4.81% off of the Taylor prediction.

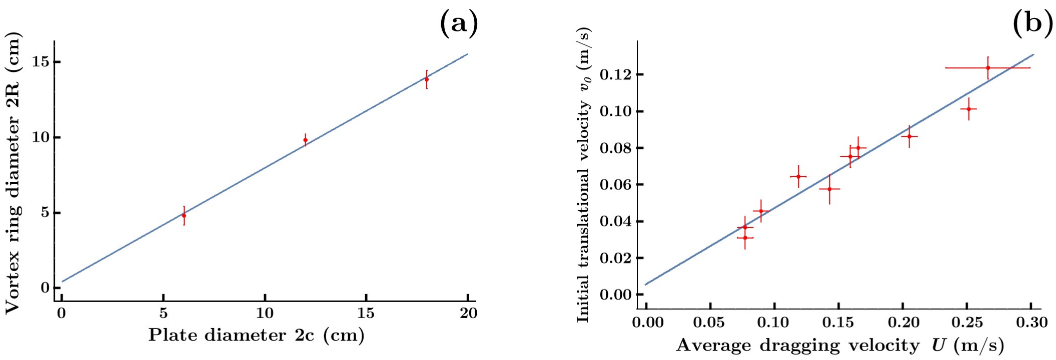

Figure 3. Relationship between (a) the thin circular plate diameter and initial vortex size and (b) the average speed of plate dragging and initial vortex speed when a 12 cm diameter plate is used.

Although the observed values of vortex size and speed agree with the theoretical predictions, they only do so at the beginning of the vortex formation. As shown in Figure 4 (b), as the vortex travels along the water tank, the translational velocity of the vortex decreases. The diameter or the size of the vortex also increases, as illustrated in Figure 4 (c). Note that the vortex ring undergoes small radius fluctuation while increasing its size. This observation is in accordance with that of the experimental study of the full of vortex ring [4], in which the vortex entrains more mass as it travels. Since the momentum is conserved, the vortex then slows down.

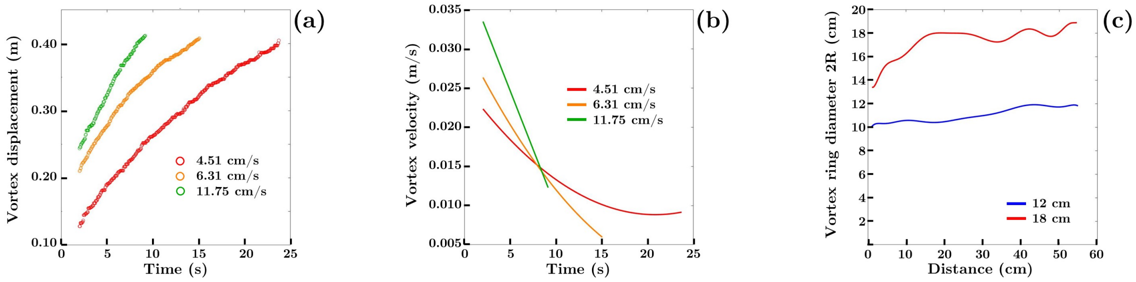

Figure 4. (a) Tracked vortex core position as a function of time at various 12 cm diameter plate dragging speed, (b) vortex core translation speed derived from differentiating vortex position with respect to time and (c) vortex ring diameter as function of traveling distance for circular plate of 12 cm and 18 cm diameters.

5. Conclusion

In the study, the half- ring vortex was generated by giving an forward impulsive force to half-submerged thin circular plate and then rapidly pull it out. The energy given by the plate transfer into the vortex energy and the vortex continues to travel for a long distance. The behavior of the vortex of investigated using DPIV technique, which shows that the vortex attains more volume as it travels, resulting in slowing down of the vortex. The result of the study shows power of relatively inexpensive DPIV technique in deriving important vortex parameters such as translational velocity and vorticity.

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