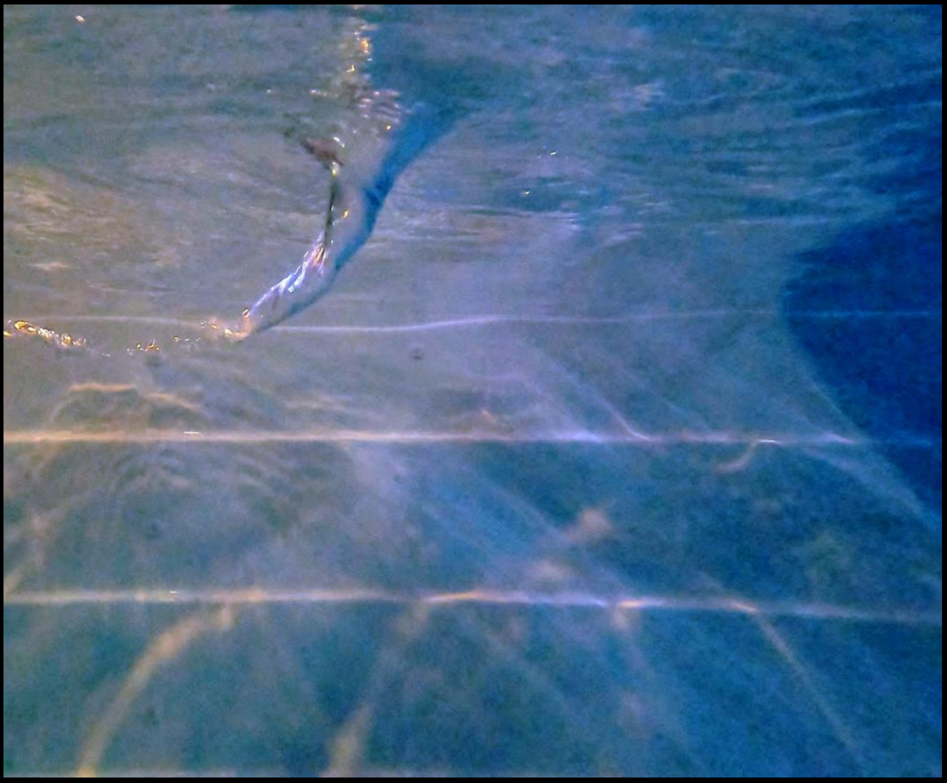
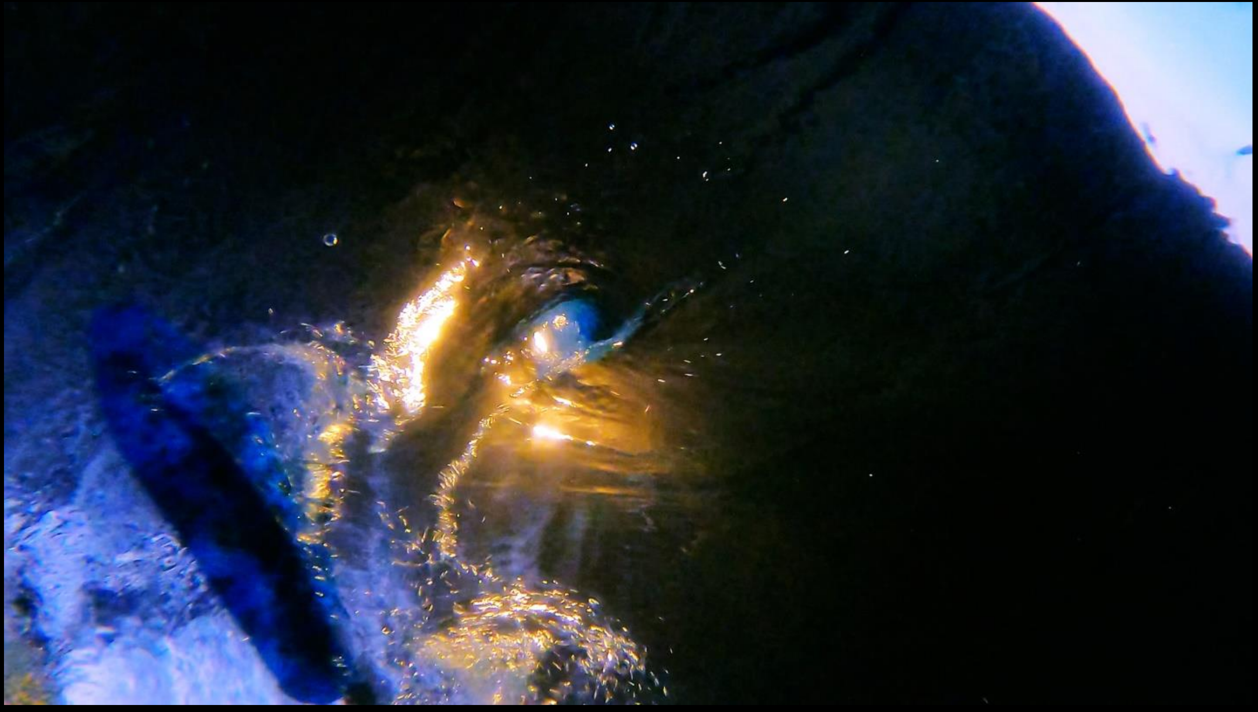


Team Third Report (Video)

Rachel Marbaker with Corey Murphey
MCEN 5151-002 Flow Visualization
6 December 2023



Purpose and context

This image was taken for the Team Third assignment in Flow Visualization (Fall 2023, MCEN 5151) with Professor Hertzberg. The end goal for the assignment was an image that artistically demonstrated a fluid phenomenon. I filmed and photographed vortices forming behind a rowing oar and a kayak paddle. Though the oar produced interesting images, constraints of the pool setup and leverage on the oar meant that I could not replicate the force and motion of a rowing stroke which relies on full body leverage on a nearly 4-meter-long oar. In contrast, a kayak paddle is designed for upper body only leverage on a paddle blade close to the hand. The vortex shots included in the video are vortices produced by the kayak paddle.

Materials and methods

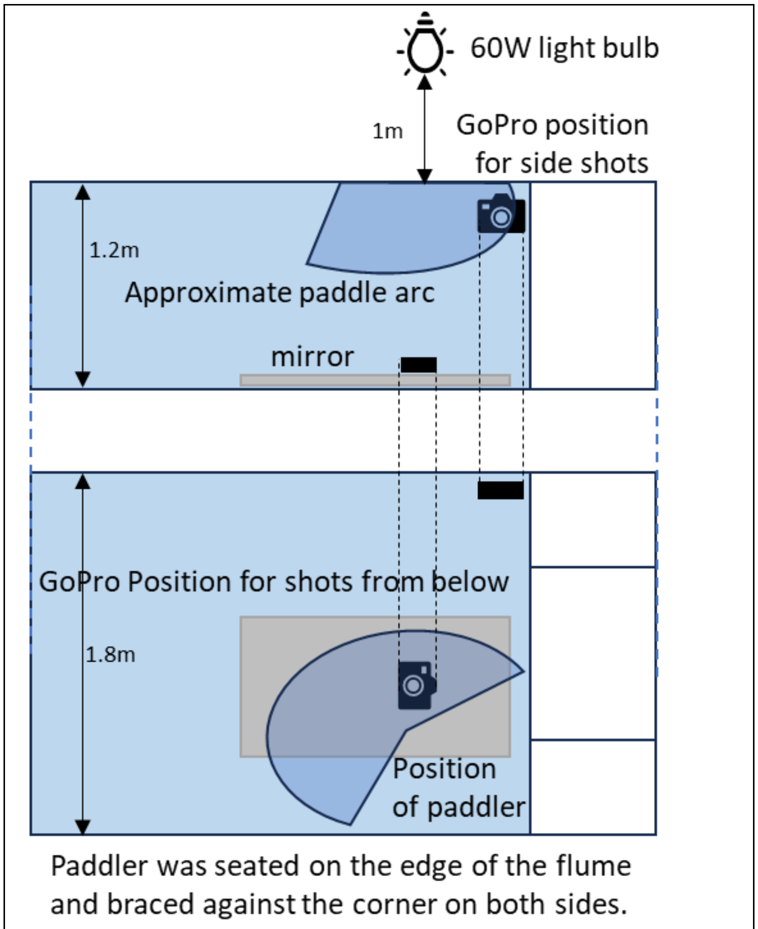


Figure 1: Set up for capturing both side shots and shots from below using the GoPro in the swimming flume. Note that a single camera was used and the duplication of cameras in the schematic is only to illustrate the camera positions in both side and top view.

These flow images were taken inside a swimming flume (courtesy of Corey Murphey) using a GoPro Hero ### borrowed from the CU Boulder Library. The water was still, with the flume pump powered off during filming. The water was 1.2 m deep, and a sheet metal mirror was positioned on the bottom of the pool to reflect both ambient light from a door and the light from an overhead 60W bulb. The paddle was Quest KHOR kayak blade measuring 46.5 x 17.8 cm on a shaft 3 cm in diameter. The blade is curved slightly, such that the concave face of the blade faces the stern of the boat during the stroke. *Fluid data:* To protect the swimming flume, no dye or particles were added to the water, so the visualization relied on light reflected off bubbles and the deformed surface of the water. *Flow rate and geometry:* The water of the flume was still throughout filming. In a kayak, the resistance of the blade in the water is greater than the resistance of the water on the boat, so the paddler pulls the boat forward against the resistance on the paddle blade. In the flume, I was perched—stationary—on the side of the pool, pulling the oar through the water. I shortened and slowed my strokes somewhat to counter the for the lack of forward body movement as there would have been in a boat. Over the course of a stroke, the blade was in the water for 2-3 seconds and moved 1 – 1.2 meters across the water surface, for a pull velocity of 0.33 -0.6 m/s. The flume was 1.2 m deep, and approximately 1.8 m wide with deck allowing me to perch at one corner and brace against the side of the pool for leverage on the paddle. Note that because the relative speed of the water to the blade could be matched by the speed of a flow around a stationary paddle, we can use calculations based on water flowing against a stationary blade without loss of generalization.

Fluid Dynamics

We will approximate the flow rate (also the rate of the paddle passing through still water) as 0.45 m/s, noting that this assumption may be violated for three reasons: i) strokes were variable in both length and time, ii) because the rate of the paddle is not constant for the whole of the stroke, being slower immediately after the catch and accelerating through the pull, and iii) the blade follows a nonsymmetrical arcing path (see figure 2). In studies on the motion of flat plates, intended to mimic some dynamics of the rowing stroke, this acceleration has been treated as a steady increase in velocity, lasting 11% of the stroke and followed by motion at steady velocity of 0.3 m/s [2]. Although boat acceleration is well documented in the literature [3], [4], I found no data on the acceleration of the paddle over the course of the pull. Given the smaller area of the kayak paddle, we will make the simplifying assumption of constant velocity. Our velocity approximation of 0.45 m/s is reasonable given the smaller area of the paddle blade.

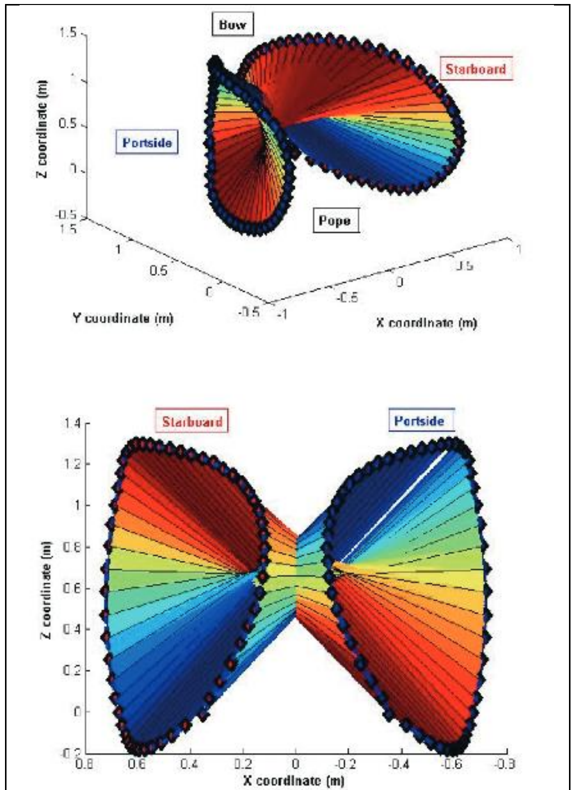


Figure 2: Profiles of optimal kayak strokes from [1]. The rainbow gradient indicates time course so that paddle stokes alternate on the port and starboard.

We calculate the Reynold's number for this flow using the density of water (1000 kg/m^3), the flow speed of 0.45 m/s, the characteristic length of 0.465 m[1], and the dynamic viscosity of water (0.001 kg/(m*s)). Accordingly,

$$Re = \frac{\rho\, u\, L}{\mu} = \frac{1000kg/m^3 * 0.45m/s * 0.465m}{0.001kg/(m*s)} = 2.09x10^5,$$

indicating a turbulent flow regime.

The Strouhal number, describes the oscillating flow typically characterized by vortex shedding [6]. the Strouhal number is determined using the frequency of vortex shedding (determined from the footage to be approximately 3 vortices/second, a characteristic length (in this case we will use the width of the paddle 0.178 m since vortices form on either side of the blade), and the flow velocity (0.45 m/s). Thus,

$$St = \frac{fL}{u} = \frac{3\ Hz * 0.178m}{(0.45m/s)} = 1.19,$$

[1] Characteristic length of a rectangular object is taken as the length of an ellipsoid approximation [5]. Since our paddle is already roughly an ellipsoid, we choose the length of the paddle over the width to match Re convention.

which is high compared to values reported in the literature [8], [9]. The Strouhal number is a ratio of inertial forces, comparing inertia from local acceleration to inertia from convective acceleration [10]. A high Strouhal number indicates that oscillations dominate the flow, playing a greater role in flow dynamics than the moving water [11]. This interpretation is consistent the lingering nature of the vortices in the video; while the vortices do move along the streamlines curling up again the back of the paddle, they do so slowly, lingering after the paddle has been lifted from the water.

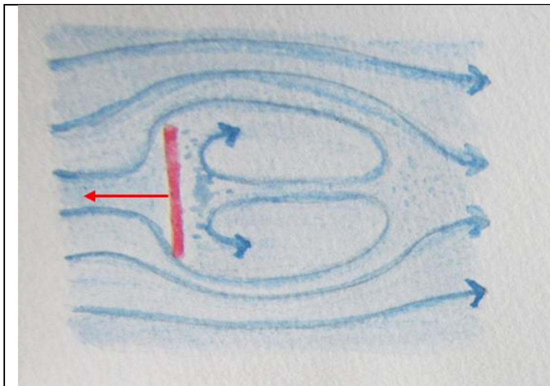


Figure 3: Illustration of vortex formation in the wake of a paddle, adapted from [7].The red arrow indicates the movement direction of the paddle

Vortices form in the wake of the paddle as the blade displaces water and the flow disrupted by the flat of the blade is pushed to either side of the flat and rejoins the flow on either side (Figure 3, adapted from [7]). Water swirls into the area where the paddle has displaced water, creating inward vorticity. A vortex forms on each side of the paddle and move together because they rotate in opposite directions. From the film, we can see that the vortices on either side do not always form at the same time, sometimes offset in time similar to vortex shedding. I attribute this asymmetry to the variables inherent in a kayak stroke including the angle of the blade at the catch and through the pull, the complex arc of the stroke, and force application on the handle varying during in magnitude and direction of the pulling force. The inertia of the fluid (tangential to the circular rotation) is balanced by the centripetal force from the vortex rotation (pulling inward toward the center point of the vortex). The vortices created by the oar are free surface vortices, where the fastest rotating fluid is closest to the center axis. This balance where the high velocity fluid is more central creates the characteristic funnel shape (figures 4, 5).

Figure 4: Vortex in the wake of a kayak paddle, the narrowest point of the vortex funnel trails after the paddle in its path.

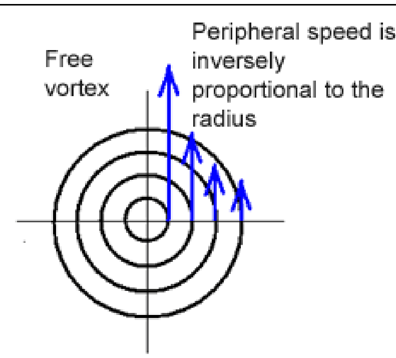


Figure 5: Vortex velocity profile showing faster rotation at the center of the vortex. Figure from [12]

Imaging technique

A GoPro HERO9 placed in a watertight case was used to capture all video. The camera was set to record at a frame rate of 60fps, the actual frame rate was 59.94 fps. The frame was 3840 x 2160 px. The camera settings are described in Table 1.

Table 1. Camera settings

Camera settings	**GoPro HERO9 Black**
Focal length	3 mm (35 mm equivalent = 15 mm)
Lens	Wide angle lens
Sensor size	11.04 mm (1/2.3 in)
Field of View	Angle of view 123 deg Field of View 2.9 m [13]
Depth of field	0.61 m with [near limit, far limit] = [0.7,1.31]. Calculated using [14]
Aperture	f/ 2.5 (max)
Exposure time	1/60 s
ISO	2560
Pixels	3840 x 2160 px
Sensor size	23.5 x 15.6 mm
Video settings	
Playback speed	Between 0.25x and 1x; varies through the video
Camera mode	Activity mode; 2.7K video at 60fps
Edited video	1920 x 1080 px; 59.94 fps;

The primary light in the video is the 60W bulb centered above the flume and 1m above the surface of the water. In both the side shot and below shot positions, the camera is approximately 0.9 – 1.2 m from the paddle blade and the resulting vortices. The wide-angle lens and this distance resulted in a wide field of view (2.9 m) and a high span depth of view (0.61 m). The GoPro HERO9 included preset camera modes that could not be altered. For this reason, I was forced to choose between high resolution (2.7k at 60fps) and high frame rate (1080 at 240fps). I ultimately selected the higher resolution with lower frame rate, which becomes obvious when the video is played back slowly. However, the complex lighting of the flow (dependent on reflection and refraction of light on the water) and contrasts and boundaries of the vortices were more difficult to identify in the lower resolution footage.

The slow frame rate resulted in some motion blur and thus lacked spatial resolution. The lack of contrast between the flow structures and the background, the light filtering through the disturbed water surface, and the caustics visible on the background all impair the spatial clarity of the vortices. The most notable motion blur is along the deepest parts of the vortex structure. For the sample still included as figure 4, the motion is blurred over about 30 px of an image that was 1920 px wide. Approximating the diameter of the vortex at the surface to be about 15 cm and corresponding to 250 px, we can calculate that the flow moved about 2 cm during the 1/60 exposure which corresponds to a velocity of 120 cm/s, indicating a very fast rotation in the narrow trailing funnel.

In post processing, the footage was cropped to remove my foot braced against the side of the pool. I also deepened the shadows, increased the highlights, and increased the blue gain to focus the image on the vortices in the foreground rather than on the background caustics or on the paddle itself. All post processing was done in DaVinci Resolve. The music added to the video was titled Resistance, accessed via YouTube from PopVibes, and licensed under Creative Commons (https://www.youtube.com/watch?v=NfERNzkdxZ4).

Image reflection

Though I am not sure I got what I wanted, I did get something cool. Working in DaVinci resolve, I was able to practice stringing together short, active shots. This more dynamic approach, combined with the two differing camera angles allowed me to try a different style of video (in strong contrast to the simple slowness of my previous video submission). I am pleased with the power captured in the swirling water and at the complexity of such a familiar flow.

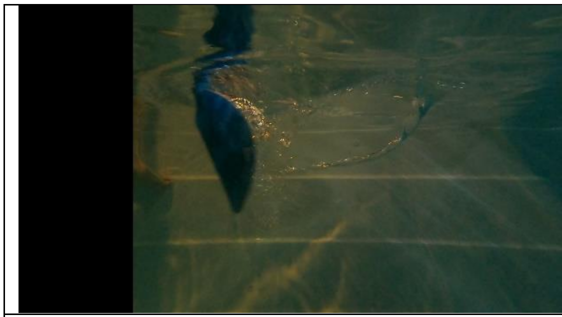
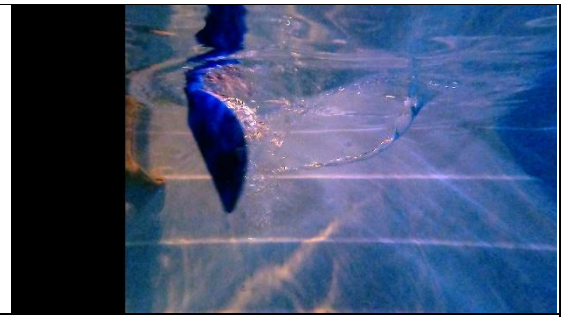
	

Figure 6	
Unedited photo	Edited photo
Dimensions: 3840 x 2160	Dimensions: 1940 x 1080
	

Citations:

[1] C. L. López, "Quantitative analysis of kayak paddling technique: definition of an optimal stroke profile".

[2] E. J. Grift, N. B. Vijayaragavan, M. J. Tummers, and J. Westerweel, "Drag force on an accelerating submerged plate," *J. Fluid Mech.*, vol. 866, pp. 369–398, May 2019, doi: 10.1017/jfm.2019.102.

[3] M. Li, "The Progress of Biomechanical Researches in Kayaking," *Yangtze Med.*, vol. 01, no. 01, Art. no. 01, 2017, doi: 10.4236/ym.2017.11004.

[4] J. Baker, "BIOMECHANICS OF PADDLING," *ISBS - Conf. Proc. Arch.*, 2012, Accessed: Dec. 05, 2023. [Online]. Available: https://ojs.ub.uni-konstanz.de/cpa/article/view/5171

[5] "Reynolds number," *Wikipedia*. Oct. 26, 2023. Accessed: Dec. 06, 2023. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Reynolds_number&oldid=1182043522

[6] "Strouhal number," *Wikipedia*. Oct. 26, 2023. Accessed: Dec. 06, 2023. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Strouhal_number&oldid=1181912760

[7] mglessmer, “Visualizing flow around a paddle,” Adventures in Oceanography and Teaching. Accessed: Dec. 06, 2023. [Online]. Available: https://mirjamglessmer.com/2015/07/03/visualizing-flow-around-a-paddle/

[8] I. Afgan, S. Benhamadouche, X. Han, P. Sagaut, and D. Laurence, “Flow over a flat plate with uniform inlet and incident coherent gusts,” *J. Fluid Mech.*, vol. 720, pp. 457–485, Apr. 2013, doi: 10.1017/jfm.2013.25.

[9] F. Auteri, M. Belan, G. Gibertini, and D. Grassi, “Normal flat plates in tandem: An experimental investigation,” *J. Wind Eng. Ind. Aerodyn.*, vol. 96, no. 6, pp. 872–879, Jun. 2008, doi: 10.1016/j.jweia.2007.06.014.

[10] “Strouhal Number - an overview | ScienceDirect Topics.” Accessed: Dec. 06, 2023. [Online]. Available: https://www.sciencedirect.com/topics/engineering/strouhal-number

[11] N. D. Katopodes, “Chapter 5 - Viscous Fluid Flow,” in *Free-Surface Flow*, N. D. Katopodes, Ed., Butterworth-Heinemann, 2019, pp. 324–426. doi: 10.1016/B978-0-12-815489-2.00005-8.

[12] “JSME Fluids Engineering Division,” JSME Fluids Engineering Division. Accessed: Dec. 06, 2023. [Online]. Available: http://www.jsme-fed.org/

[13] “Camera Field of View - Part 2- Chart.” Accessed: Nov. 10, 2023. [Online]. Available: https://www.scantips.com/lights/fieldofview2.html

[14] “Depth of Field (DoF) calculator,” PhotoPills. Accessed: Dec. 06, 2023. [Online]. Available: https://www.photopills.com/calculators/dof