3D Synthetic Aperture PIV of a Swimming Fish

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ABSTRACT

The efficiency and maneuverability of fish swimming has yet to be rivaled by manmade vehicles. Fish owe much of this locomotive success to highly three-dimensional body kinematics and wake interactions. Study of these behaviors is inherently simplified by planar measurement techniques including conventional 2D PIV. Thus, volumetric velocimetry systems are required to provide further insight into swimming hydrodynamics. In this study, Synthetic Aperture PIV (SAPIV), a new three-dimensional PIV method based on light field imaging, is applied to study swimming in 3D with minimal constraints on animal behavior. Results successfully depict all three components of the velocity field and vortex ring structures surrounding a freely swimming Giant danio (Devario aequipinnatus) during steady forward swimming and turning maneuvers.

1. INTRODUCTION

As nature’s archetypical swimmers, fish are a frequent source of inspiration for engineering design. However, the behaviors that drive biomimetic interest in fish swimming are often difficult to simplify for analysis due to complex non-planar geometries and kinematics. As a result, fish locomotion is an ideal application for high-speed 3D PIV techniques.

Three-dimensionality can be nontrivial in even the simplest swimming scenarios. For instance, stereoscopic PIV on a turning fish, a scenario often analyzed in a 2D form, revealed substantial out of plane movement extending far beyond the laser light sheet thickness [2]. Likewise, use of defocusing digital PIV (DDPIV) to capture the wake behind steady swimming bluegill sunfish and cichlid fish in a controlled flume revealed multifaceted vortex ring structures in need of further investigation and proved the need for 3D velocimetry in this application [3]. 3D PIV also enables the study of complex animal behaviors that cannot be constrained to a single plane for analysis. For instance, tomographic PIV has been used to study the feeding actions of zebrafish by tracking the fish’s prey and reconstructing the flow field as the fish reaches it [4]. This study of predator-prey behavior required very accurate near-body velocity resolution and proved the importance of masking during 3D cross-correlation when a body of arbitrary geometry is immersed in the flow.

Without the constraints of a single viewpoint and 2D light sheet, a wider range of movements in which the fish exhibits its superior maneuverability can be also captured. One area of particular interest is unsteady maneuvering, where the body kinematics are highly three-dimensional and significant time resolution is required. In order to study such behaviors, this work details the development of a 3D synthetic aperture PIV system for the study of fish swimming and its application to standard behaviors of steady swimming and turning.

2. SYNTHETIC APERTURE METHODOLOGY

Synthetic Aperture PIV is a 3D PIV technique based on light field imaging using a camera array [1]. In SAPIV, the measurement volume is illuminated with a volumetric laser light source and imaged using an array of 8-15 synchronized cameras. The cameras can be mapped to planes on a global coordinate system, following which images can be averaged at each plane location using an additive algorithm (Eqn. 1), where \( I_{SA_k} \) is the refocused image at depth \( k \), \( N \) is the number of cameras, and \( I_{FP_{ki}} \) is the transformed image from each camera \( i \) at depth \( k \).

\[
I_{SA_k} = \frac{1}{N} \sum_{i=1}^{N} I_{FP_{ki}}
\]
This averaging process effectively simulates a camera with a very narrow depth of field scanning the volume. A particle is only in focus in the planes corresponding to its location and out of focus elsewhere. Thus, refocusing can be used to generate a particle volume suitable for 3D cross-correlation.

Prior to refocusing, raw images are preprocessed to improve reconstruction and eliminate the high intensity fish body. All images intensities are rescaled to normalized grayscale values \(0 \leq I_{FP_{ki}}(x, y) \leq 1\) before beginning the preprocessing routine, which is as follows:

1. 5 x 5 median filter to remove the fish body
2. Convolution with a 3 x 3 Gaussian kernel
3. Intensity normalization over a 10 x 10 pixel window
4. Subtract sliding minimum (10 x 10 window)
5. Implementation of refocusing cost function (Eqn. 2), where \(I_{FP_{ki}}(x, y)\) is the intensity value of the pixel at location \((x, y)\), and \(m\) and \(n\) are the overall size of the image in pixels. Pixels with intensity values below the mean intensity of the preprocessed image are instead set to \(-1\).

\[
I_{FP_{ki}}(x, y) < \frac{1}{mn} \sum_{y=1}^{n} \sum_{x=1}^{m} I_{FP_{ki}}(x, y) = -1.
\]  

(2)

With implementation of the cost function, a single reconstructed particle has a 3D Gaussian intensity profile over the span of several images. The resolution in \(Z\) is determined by the optics and geometry of the camera array [1].

In addition to refocusing the particle images, synthetic aperture refocusing can be combined with image processing operations to reconstruct the fish body. This fish detection method is necessary to understand how body kinematics and wake structures are related. In addition, the reconstructed body can be used as a mask to improve the PIV correlation accuracy near the fish. The masking technique is based on the visual hull method for tomographic PIV [5]. Binary images of the fish body silhouette are extracted using an adaptive thresholding algorithm designed to extract both bright and dark portions of the body while minimizing coalesced particles in the thresholded images [6]. These binary masks are then refocused using a multiplicative algorithm (Eqn. 3) to determine the projection of the body at each \(z\)-depth (Fig. 1a). The volume mask is thus the stack of masks from each focal plane (Fig. 1b).

\[
I_{SA_{ki}} = \prod_{i=1}^{N} I_{FP_{ki}}
\]

(3)

**Figure 1** (a) Slices of the mask generated by the caudal fin at four different depths. The tip of the caudal fin can be seen at \(Z = -4.00\) mm, while the fork is at \(Z = 2.00\) mm and the caudal peduncle is at \(Z = 8\) mm. The body continues diagonally up the tank. (b) The volume stack of all the planar masks shows clearly the shape of the caudal fin.
3. EXPERIMENT SETUP

Experiments are performed using an array of nine 1.2 megapixel (1292 x 964 pixel) Allied Vision Manta CCD cameras running at 30 frames per second. The cameras are equipped with 35 mm lenses and positioned a distance of 635 mm from the front of a five gallon fish tank (Fig. 2). The horizontal spacing between cameras is 230 mm, and the vertical spacing is 190 mm. The tank is seeded with 50 μm polyamid particles to a seeding density $C = 230$ part/cm$^3$ and an image density $N = 0.03$ part/pixel. Illumination is provided by an Oxford Lasers Firefly 1000W volume laser with a wavelength of 808 nm. Fish are skittish in the presence of the green light typically used for PIV in water, but near-IR illumination is invisible to the fish and promotes more natural swimming behavior. Since near-IR attenuates faster than green light in water, a first surface mirror placed at the end of the tank reflects the laser beam back into the tank to provide more light. Knife-edge filters at the tank entrance are used to eliminate intensity variation at the edge of the beam and control the depth of the illuminated tank section.

With this camera arrangement, the resolvable focal plane spacing in z is 0.2 mm. Thus, to ensure sufficient particle displacement of at least a focal plane in the z direction, the interfame time between images must be kept sufficiently high. A final interfame time of $\Delta t = 0.0333$ s was implemented to enable correlation of any two images, as opposed to a frame-straddling configuration. While the interfame time is high, the laser pulse duration is kept short ($\delta t = 50$ μs) to prevent potential for motion blur.

Vector field processing is performed using a modified version of MatPIV [7] adapted for 3D cross-correlation. The velocity field is determined using a multipass normalized cross-correlation. The final interrogation window size is 64 x 64 x 16 voxels, corresponding to a resolution of 1.85 mm x 1.85 mm x 1.60 mm. After cross-correlation, the velocity field is post-processed using a signal-to-noise ratio filter based on the cross-correlation peak height and a local median filter run on 3 x 3 x 3 vector windows. Removed vectors are replaced using linear interpolation, and the velocity field is smoothed once using a 3 x 3 x 3 Gaussian kernel. As done by [1], the system was benchmarked on a vortex ring generated by a mechanical piston, and showed good agreement with 2D PIV.

The fish used in this study are Giant danio (*Devario aequipinnatus*). Giant danio, a relative of the common laboratory zebrafish, have previously been used for 2D PIV experiments [8, 9], and there is substantial planar data about their kinematic and propulsive behavior for comparison. 3D SAPIV results are shown for a fish with body length $L = 58$ mm, mass $M = 4.8$ g, and caudal fin width $W = 12$ mm. The fish is allowed to swim freely in the tank, with the cameras triggered manually when the fish passed into the field of view. Only image sequences where the fish is in good view of all the cameras were processed. Limited kinematic resolution could be obtained at 30 Hz, and there was substantial variation in the orientation and velocity of the fish, even within a single maneuver, but the fish generally swim with a Strouhal number, $St = fA/U$, where $f$ is tail beat frequency in hertz, $A$ is the wake width, approximated by the peak to peak amplitude of the tail beat, and $U$ is forward velocity, in the range of 0.25-0.4 as predicted by [10].

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**Figure 2** Schematic of the experiment setup. An array of ten CCD cameras views a ten gallon tank from the side. A portion of the tank is illuminated by a laser light volume.
4. RESULTS AND DISCUSSION

SAPIV was first used to visualize the simplest swimming scenario possible: steady, low-speed forward swimming. In this case, the fish swims at a mean body velocity of 1 L/s, with $St = 0.34$. Survey images from the center camera of the array show that the direction of fish motion is aligned with the z-axis of the tank (Fig. 3).

![Figure 3](image)

Figure 3 Raw images from the center camera of the SAPIV array show the fish steadily swimming straight back into the tank.

After the fish has passed through the majority of the measurement depth ($t = 0.000$ s), a single vortex ring can be seen coming off of the caudal fin (Fig. 4). The peak velocity observed in the ring is 0.56 L/s, found in the center axial jet of the ring. For comparison, the peak near-body transverse velocity observed using 2D PIV was 0.39 L/s [8]. The peak magnitude of vorticity in an x-y plane is 10.7 s$^{-1}$ and the peak vorticity in an x-z plane is 9.9 s$^{-1}$. The ring diameters, measured as the distance between the two vortex cores in each slice, are 11.1 mm in x-y and 11.7 mm in x-z. These results show that for forward swimming the vortex ring shed off the caudal fin is very close to axisymmetric. This supports the vortex ring model commonly used to extract thrust forces from fish PIV in 2D [9].

![Figure 4](image)

Figure 4 Flow behind a fish swimming at a steady velocity through the tank. (a) Isovorticity contour at 5 s$^{-1}$ reveals a single vortex ring coming off of the caudal fin. (b) Velocity vectors in the vortex ring show the thrust coming off of the caudal fin at the center jet of the ring. Every third vector in x is shown for clarity.
The wake structures from steady swimming can be compared to those observed during a turning maneuver. During the turning sequence, the fish executes a 75° turn over the span of approximately 0.60 s. The resultant wake differs substantially from forward swimming in form (Fig. 4). The shape of the isovorticity contour is elongated and fills the space that the caudal fin sweeps through during the turn. Furthermore, the wake extends beyond the measurement volume, and thus the full geometry of the vortex loop cannot be determined.

Figure 4 (a) Vortex loop shed during a 75° turn. At the conclusion of the turn, the body is roughly aligned with the x-y plane, with only the caudal fin remaining within the field of view. The fish sheds an asymmetric loop with a wider core that extends beyond the measurement volume. (b) Slices of velocity and vorticity reveal a wide region of axial thrust and higher vorticity magnitudes than steady low-speed swimming.

The strength of the wake recorded behind the turning fish varies substantially from the forward case as well. The peak velocity within the wake of the turning fish is 1.15 L/s, faster than that recorded during forward swimming. In any x-y plane, the peak vorticity is 19.9 s⁻¹, while in any x-z plane the peak vorticity is 17.0 s⁻¹. These values are very close to the peak vorticity magnitude (20.0 s⁻¹) observed by [8] during a 60° turn. The ring diameter measured in the x-y plane is 11.3 mm, close to the values observed during forward swimming, suggesting that this feature is controlled by the caudal fin geometry, not the maneuver.

5. CONCLUSIONS

Synthetic Aperture PIV has been successfully implemented to reconstruct the fish body and the vortical structures in its wake. Results show good agreement with previous 2D and 3D PIV on similar fish and confirm the applicability of a vortex ring model during forward swimming. Clear differences between forward swimming and turning can be seen in the shape of the wake, the peak flow vorticity, and the magnitude of the thrust jet in the center of the vortex loop. Future work will implement this technique with high-speed cameras, and thus extend the study to more complex behaviors such as fast-starting and rapid maneuvering. Further attention will also be paid to developing models for extracting forces from volumetric PIV datasets that accurately incorporate the full three-dimensional shape of the flow features observed.

ACKNOWLEDGMENT
The authors would like to thank Juliana Wu for her assistance with the handling and care of the Giant danio.
REFERENCES


