Trajectory Planning and Free Surface Deformation of a Bioinspired Flexible Propulsor at the Air-Water Interface

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Overview

Motivation

Archer fish can leap from the water to catch airborne prey (Figure 1). Notably, they produce sustained thrust throughout the duration of water exit, even when only partially submerged, and require little space for acceleration. This behavior serves as inspiration as a non-invasive alternative to existing water-exit strategies for aerial-aquatic robots [1].

Figure 1. An archer fish crossing the air-water interface (from [2]).

Approach

We manipulate a mechanical fin model to reproduce the flapping behavior of archer fish locomotion. The mechanical model accommodates varied flapping kinematics such as flapping amplitude, flapping frequency, and fin submergence depth. Force and torque data collected during fin motion are analyzed to determine what effect flapping parameters, along with fin stiffness, have on thrust production. We also measure flow patterns and surface deformations through high-speed imaging to understand the loads produced.

Previous Work

In earlier rounds of investigation, FILM collected thrust data from partially submerged flapping plates at fixed depths between 25% and 100% submergence. While this data sheds light on how thrust trends with the parameters tested, it does not account for the instantaneous vertical velocity of an organism propelling itself from the water.

Experimental Setup and Methods

Tank Overview

The experiment mechanism allows repeatable two-axis trajectory profiles. Heave motion flaps the fin in the horizontal axis, while tow motion moves the fin in the vertical axis. The system allows the adjustment of five variables: heave amplitude, heave frequency, tow speed, fin submergence depth, and fin stiffness.

Tank Redesign

The experiment mechanism was significantly redesigned in summer 2025 to improve the consistency of trajectory profiles (Figure 2). Major changes to the system included:

- Fixed-amplitude heave control
- Linear rails for heave carriage motion
- Reinforced heave carriage
- Higher-torque gearbox
- Redesigned fin bracket
- New lighting setup for surface imaging
- Codebase for control and processing

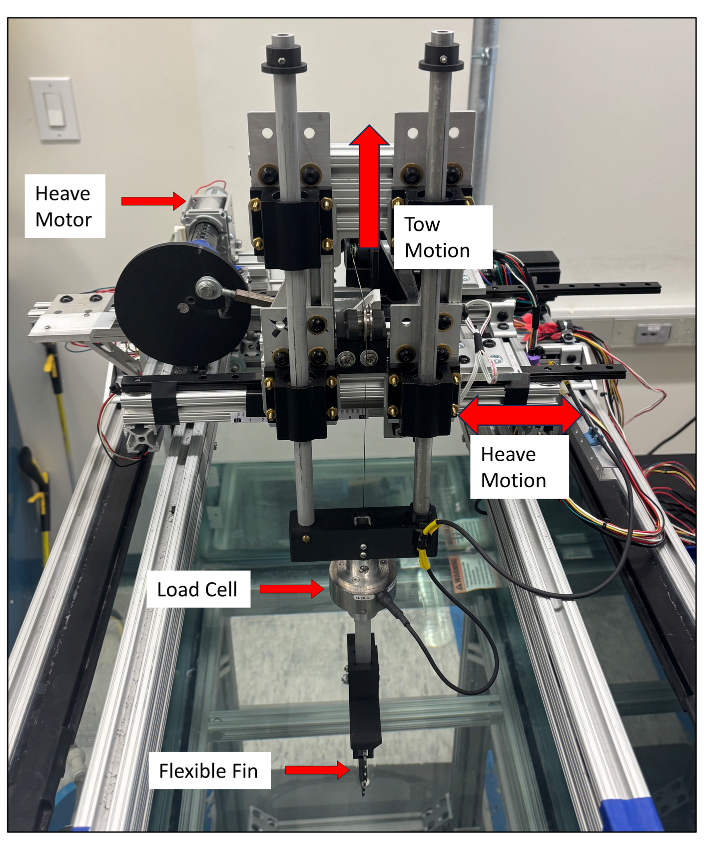

Figure 2: Tank and System Redesign

PIV Imaging

Particle Image Velocimetry (PIV) was used to image the flow patterns (Figure 3). Suspended 55µm polyamide particles were illuminated by a 532 nm laser, and their movement was captured by a 500-fps camera. Points on the fin were illumined with red light, allowing separate visual analysis of the red fin and green particles. PIV results allow us to calculate vorticity and other wake properties for comparison to the force measurements (Figure 4).

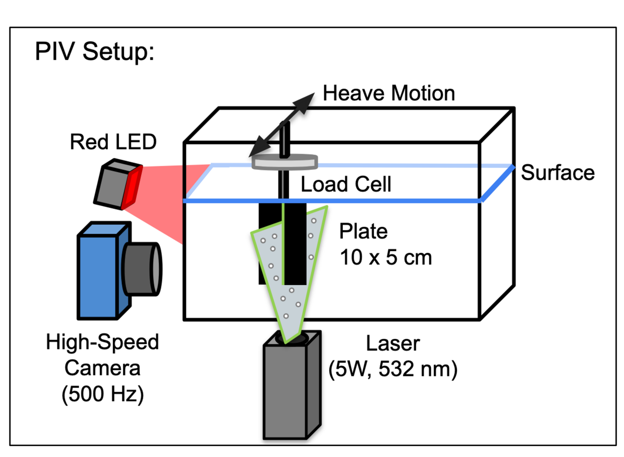

Figure 3: Experimental setup for PIV capture

Force Measurements

A six-axis load cell measured forces and torques experienced by the fin. Each trajectory required an additional trial without water in the tank to capture inertial loads. Then the inertial loads were subtracted from experimental measurements, isolating the forces solely from the fin's interaction with the fluid.

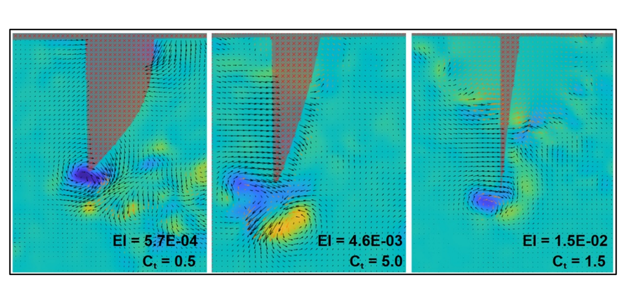

Figure 4: Vorticity results from PIV imaging

Surface Deformation Imaging

To capture surface deformations during fin movement, a separate lighting setup illuminates the air cavities from behind (Figure 5). These images allow us to measure the size of the surface disturbance, any splashing, and where the fin contacts air and water.

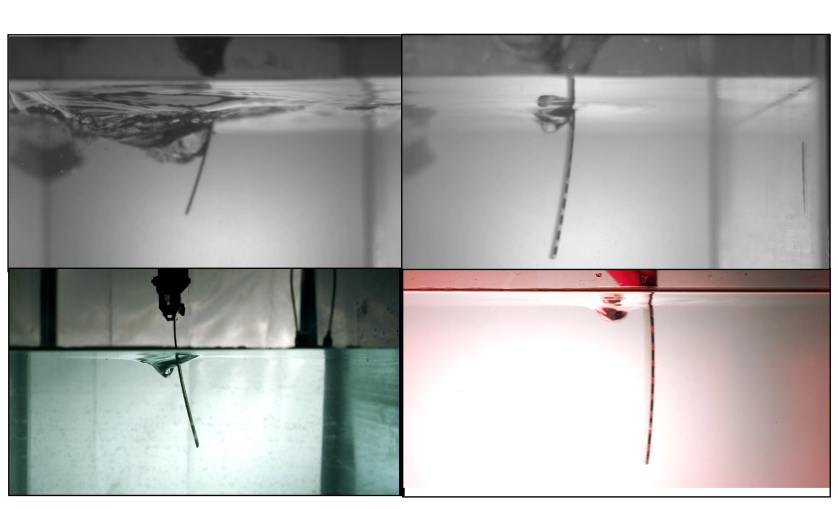

Figure 5: Air cavity lighting tests

References & Acknowledgements

[1] Sidall, Kovak (2017), *IEEE/ASME Transactions on Mechatronics*
[2] Shih, Mendelson, Techet (2017) *J. Exp. Bio.*

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Data Collection & Performance Assessment

The data collection parameter space spanned flapping amplitude, A, flapping frequency, f, fraction submerged, plate stiffness, and towing velocity, U. For statistical reliability, five replicate trials were conducted for each set of conditions.

In the data collection phase, synchronous force measurements and particle image velocimetry (PIV) data were collected to characterize the fin's propulsive performance. The measured thrust (T) can be mapped to the vortex dynamics in its wake as measured by PIV.

Amplitude (A)	1, 2, 3 (cm)
Frequency (f)	1, 2, 3 (Hz)
Fraction Submerged	25, 50, 75, 100 (%)
Plate Stiffness	5.7E-4, 4.6E-3, 1.5E-2, 3.7E-2 (N m^2)
Tow Speed (U)	0, 10 cm/s, 20 cm/s

Table 1: Summer 2025 Data Collection Parameter Space

To properly assess propulsive performance, the measured force for each trial was time-averaged over a single flapping cycle to yield the mean thrust, $\overline{T}$. The mean thrust was then normalized to calculate a dimensionless thrust coefficient, C_T which is a metric used to assess the performance across different parameters. We also considered the thrust to power input ratio, ϵ, which compares the thrust output to the average power input, to assess how efficiently mechanical energy was converted into useable thrust. Figure 6 demonstrates a specific trial case reporting C_T.

$$C_T = \frac{\overline{T}}{4\rho bLf^2A^2} \qquad \epsilon = \frac{\overline{T}}{\frac{1}{\tau}\int_0^\tau F_x(\tau)U_x(\tau)d\tau}$$

where, $\overline{T} = \frac{1}{\tau}\int_0^\tau F_y(\tau)d\tau.$

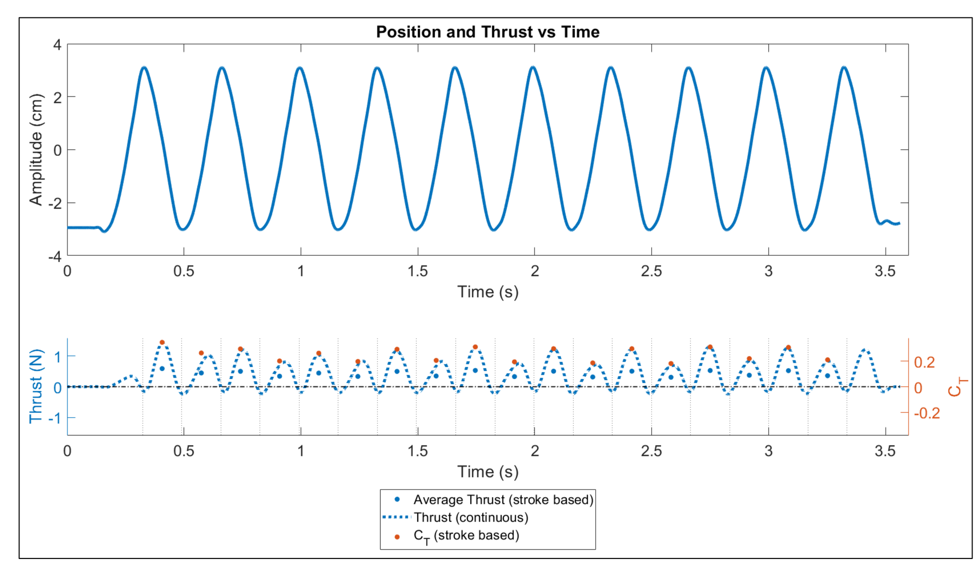

Figure 6: Averaged position and thrust report from a 1/8" plate with a 3 cm amplitude and 3 Hz frequency, fully submerged with no vertical tow

Surface Deformation Characterization

Comparison of free surface deformations and their corresponding thrust profiles will reveal if parameter combinations that minimize surface disturbances perform more desirably. Air cavities are of particular interest as thrust is expected to decrease as more water is displaced (Figure 7). Additionally, air cavity closure may generate forces that are currently not examined in higher resolution. The flexibility of the fin is a major factor of interest in surface deformation cases (Figure 8).

Figure 7: Air cavity footage with background subtracted

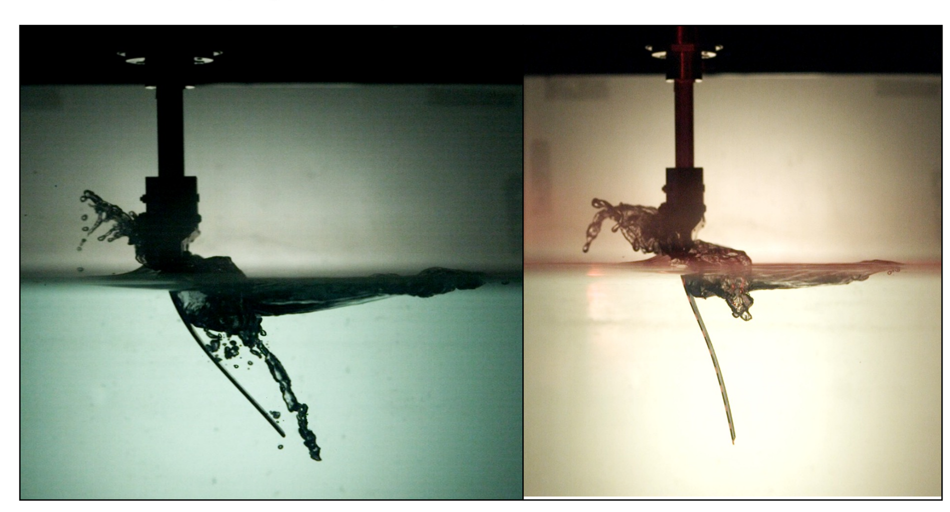

Figure 8: Surface deformation at 3 cm amplitude, 3 Hz frequency, and full submergence for 1/16" thickness (left) and 1/32" thickness (right)

Conclusion & Future Work

Conclusion

Preliminary results display that there is significant variety in surface deformation and propulsion produced between parameter sets. Further exploration of results is necessary to deduce specific patterns and characteristics of propulsive performance and surface deformation.

Future Work

Research upon surface deformation will be continued through data collection and air cavity analysis. Furthermore, additional experiments will be conducted to investigate the effects of three-dimensionality on partially submerged propulsive performance. A three-dimensional setup will need to be constructed and validated to accommodate additional cameras in the test tank area.

Trajectory Planning

Trajectory planning will center around further data analysis to understand the fin and flapping parameters that result in optimal performance with tow enabled. Trajectory planning will then be mapped out to experiment with predicted cases and parameters of optimal performance. For example, parameters could be changed throughout a trial, such as increasing frequency and decreasing amplitude as the fin exits the water. Additionally, through implementation of a variable amplitude servo into the mechanism, more precise trajectory trials will be tested at specific amplitudes. Data will then be collected and analyzed for comparison to predicted performance.