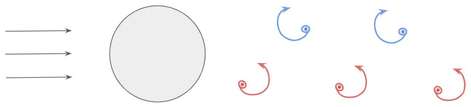
The Effects of Spanwise Stiffness on Thrust Generation in Flexible Pitching Fins

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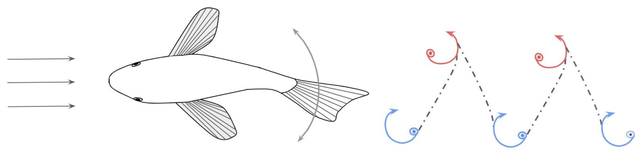
BACKGROUND

Hydrodynamic Mechanisms of Thrust Generation

- Fish generate thrust by undulating their body in a traveling wave, producing a wake.
- The trailing edge pattern forms a reverse von Kármán vortex street.



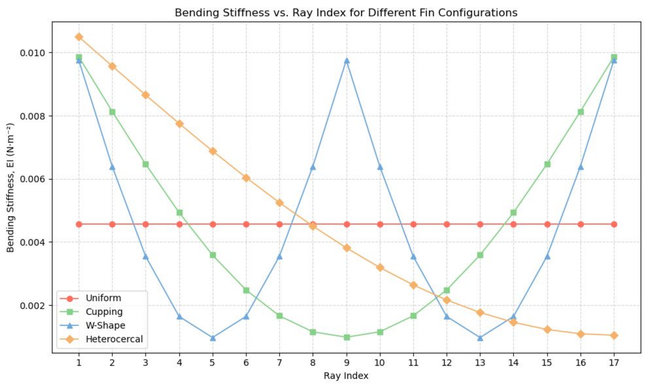
a. Karman Street of a Bluff Body.



b. Wake Generated by Swimming Fish.

Numerical Predictions of Spanwise Stiffness Effects

- Numerical studies have investigated how spanwise stiffness distributions influence fin deformation, including: uniform, cupping, W-shaped, and heterocercal configurations.
- Different configurations are shown to alter the wake structure.
- Reported performance trends are not often consistent across studies.



Normalized Stiffness for Each Ray of Each Tested Stiffness Distribution.

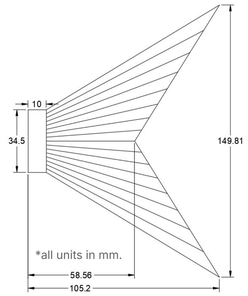
MOTIVATION

This study looks to **experimentally** evaluate the effect of spanwise stiffness distribution on thrust generation in a controlled pitching-fin system, with the aim of assessing whether bio-inspired stiffness tailoring can be leveraged to improve the performance of propulsive systems.

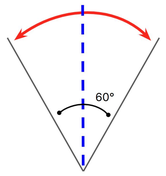
METHODS

Fin Design

- Four fin designs were additively fabricated with identical geometry and equal mean bending stiffness.
- Each fin consists of 16 spanwise rays with stiffness varied through controlled thickness.



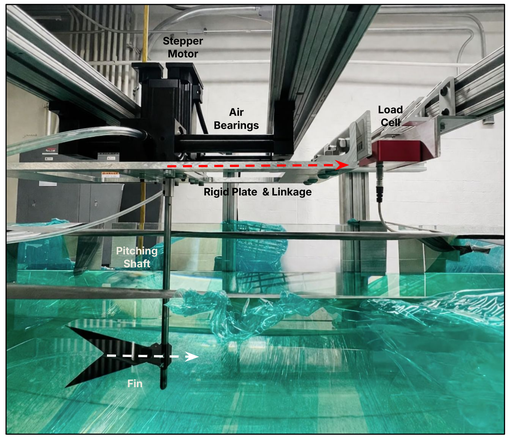
Testing Procedure

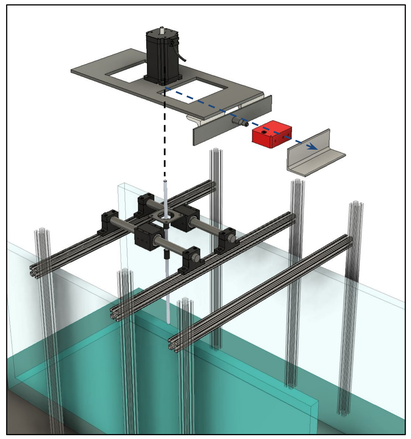


- Each fin configuration is tested three times over a flapping frequency range of 0.70–0.90 Hz.
- The fin is subjected to a prescribed pitching motion of ±30° about the neutral axis.

Experimental Setup & Force Measurement System

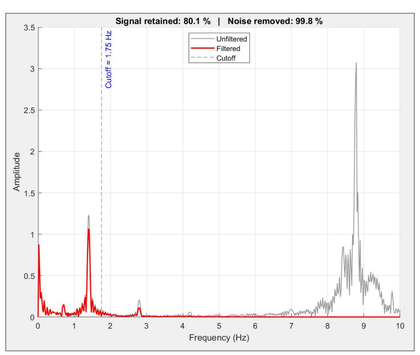
- Fin samples are rigidly mounted to an shaft and stepper motor system.
- A low-friction air-bearing assembly constrains the system to a single axial degree of freedom, allowing the generated thrust to be measured by a load cell.



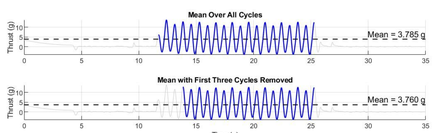


Setup and Organization of the Force Measurement System.

Data Processing & Validation



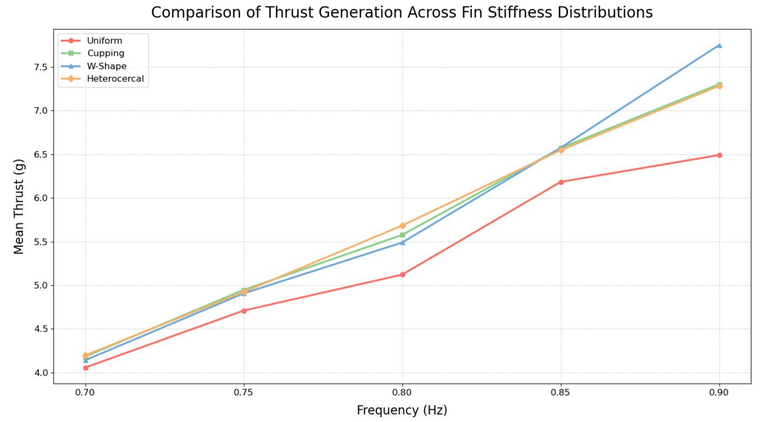
Validation of Noise Reduction via FFT.



Comparison of Cycle Averaging for Mean Thrust.

- Trials are ensemble-averaged before a low-pass filter is applied to remove high-frequency noise.
- All pitching cycles, including transients, are retained to calculate the final mean thrust.
- Maximum experimental uncertainty is found to be 0.0479 g.

RESULTS



Mean Thrust vs. Frequency (Hz) for Each Fin Configuration.

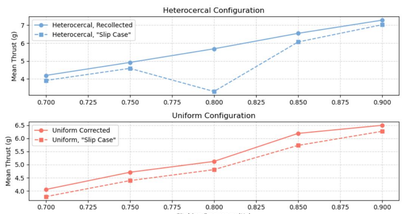
Low-Frequency Regime (0.70-0.80 Hz)

- All fin configurations produce similar thrust with differences comparable to the experimental uncertainty, indicating limited deformation effects.

High-Frequency Regime (0.85-0.90 Hz)

- All variable-stiffness fins outperform the uniform case.
- Maximum thrust spread is 25× larger than experimental uncertainty.
- W-shaped configuration consistently generates the highest thrust, producing 1.26 g more thrust than the uniform case at 0.95 Hz.

The Occurrence of "Slip Cases"



- Slip between the fin–shaft interface was observed as a confounding factor.
- A correction factor derived from corrected heterocercal measurements was applied to adjust affected datasets.

Mean Thrust Under Slip Conditions.

CONCLUSIONS & FUTURE WORK

- Results support the use of spanwise stiffness gradients as a passive strategy for improving propulsive performance.
- Further testing should be conducted to eliminate slip uncertainty, while incorporating power and flow measurements to better assess efficiency and behavior at broader operating conditions.

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