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Numerical Study of Overlap-and-Fling Swimming in a Marine Pteropod (Sea Butterfly)

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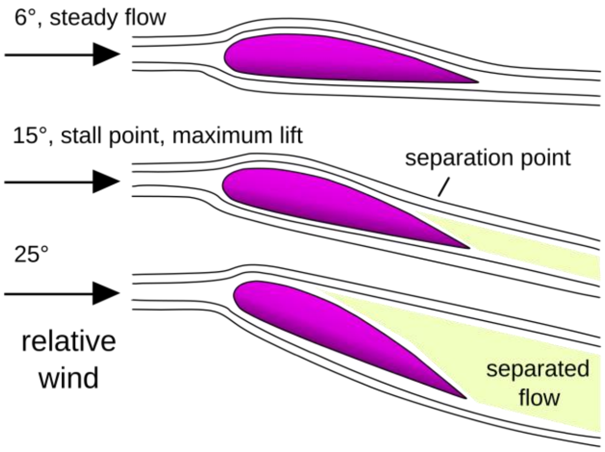
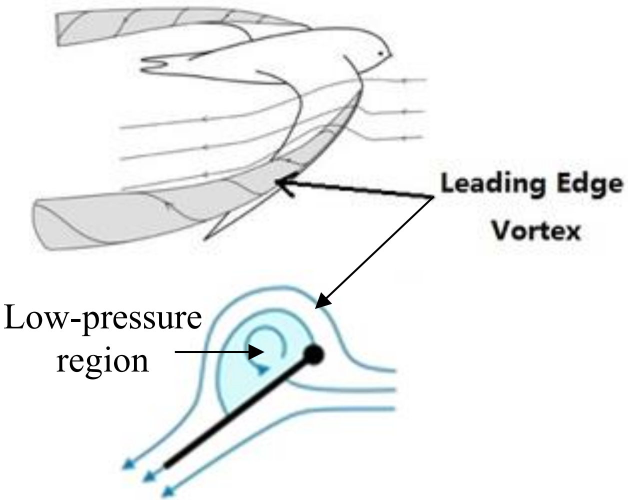
Introduction: Lift Mechanisms Across Species



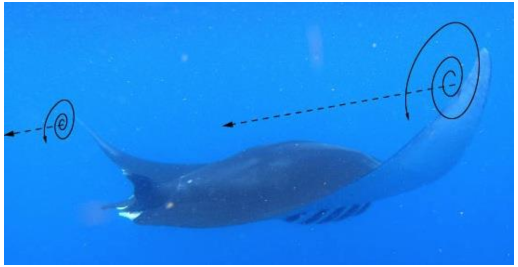
[1]

Stall at high angle of attack

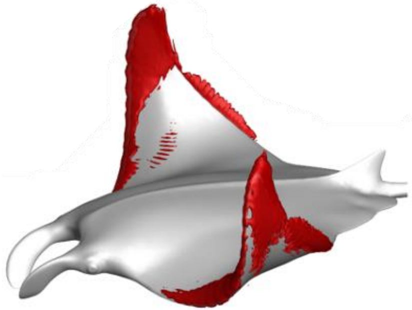


[2]

Leading edge vortex (LEV) delays stall at high angle of attack



[3]



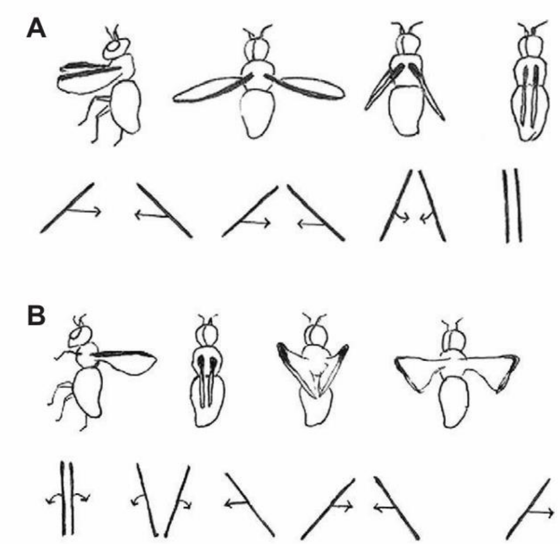
[4]

Aquatic animals use LEV-like flows for thrust

Introduction: Challenge for Tiny Animals

For tiny animals, Reynolds number Re ↓, viscous effect ↑

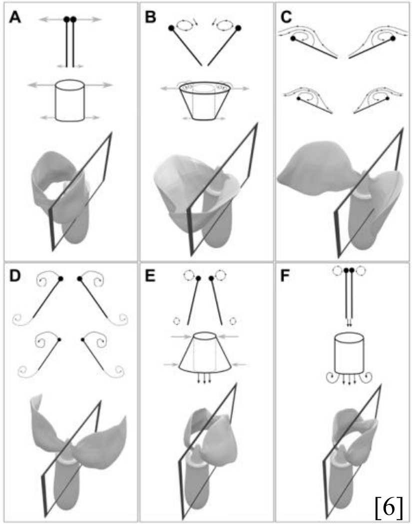
Clap-and-fling motion



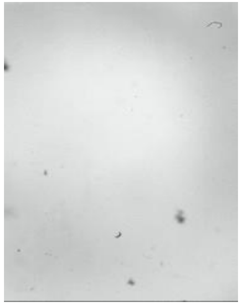
[5]

Introduction: Sea Butterfly

Overlap-and-fling motion



Camera at right of animal



Camera at back of animal

The sea butterfly has a **higher average density** than the surrounding water. To avoid sinking, it must swim efficiently.

Objective: Use CFD to uncover the underlying flow mechanisms behind its propulsion

Methodology: Fluid–Structure Interaction (FSI) Framework

Fluid Solver
Lattice Boltzmann method (LBM)
- Eulerian grid
- Efficient for complex solid boundary

Force at fluid node →

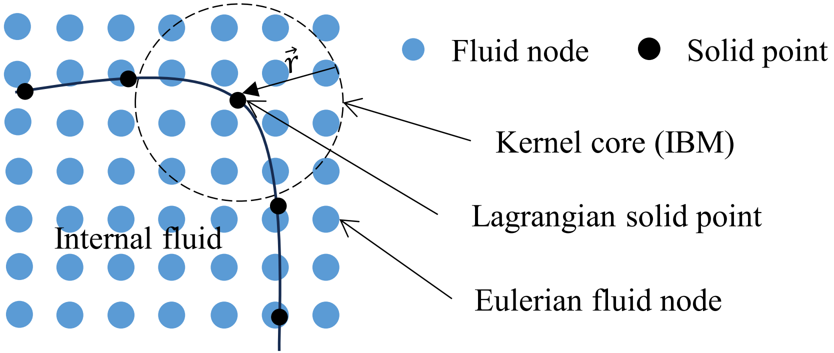
← Force field at fluid node

Coupling Module (FSI)
Immersed Boundary Method (IBM)
- Interpolate and distribute variables via delta kernel
- Internal mass elimination using Lagrangian point approximation (LPA) [7]

Force at solid point →

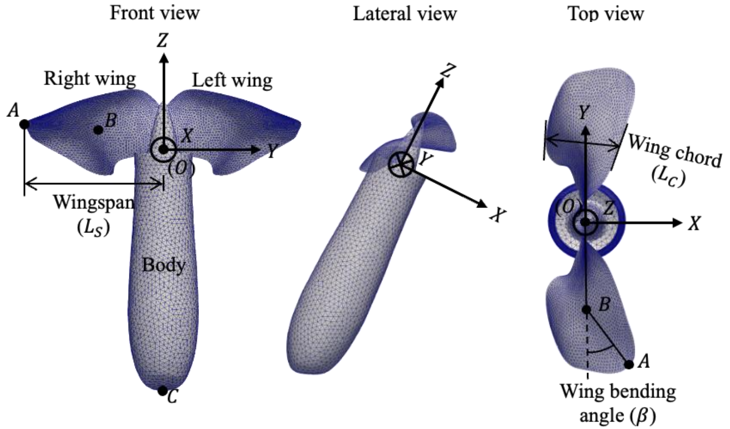
← Velocity at solid point

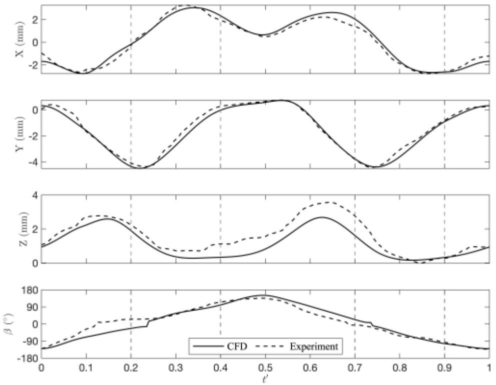
Solid Solver
Newton–Euler Equations
- Lagrangian grid
- Treat as rigid body
- Prescribed wing motion



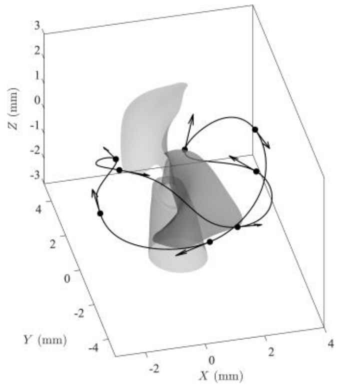
Lagrangian-Eulerian Coupling (IBM Kernel)

Validation: Wing Kinematics





Coordinate of wing tip (point A),
wing bending angle β vs time

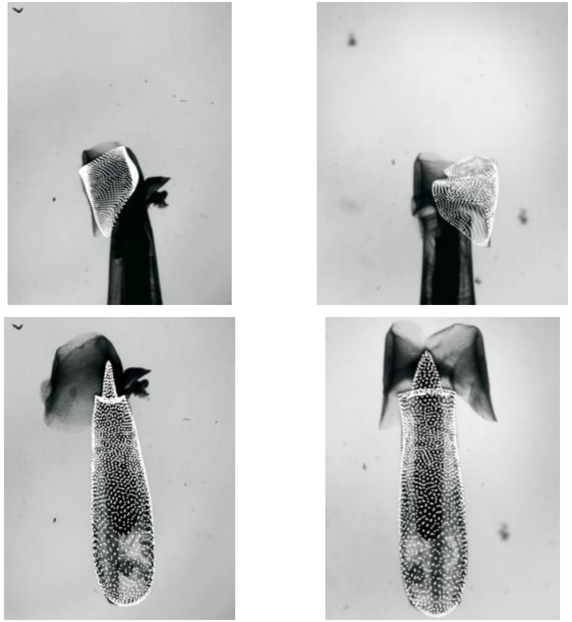


Trajectory of wing tip (point A)

Comparison between the numerical input and experimental video

Wing kinematics

Body



Lateral view

Back view

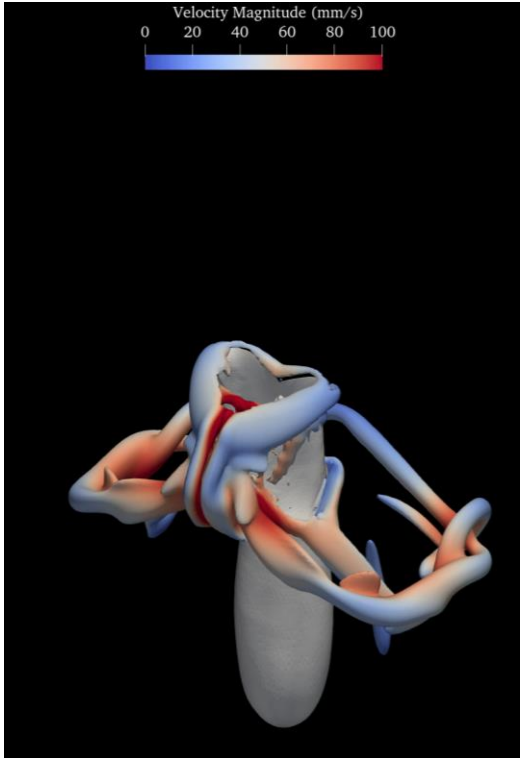
Motion captured software: DLT dv7

Numerical processing:

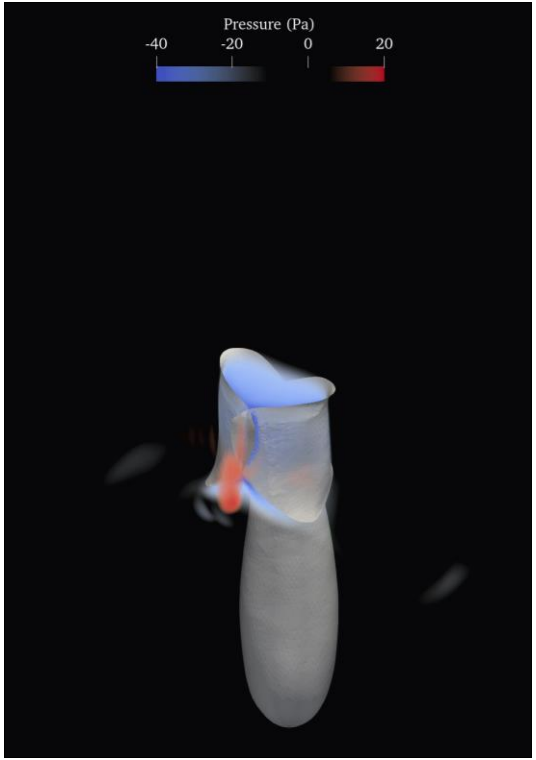
Thin Plate Spline (TPS), Non-Rigid ICP

The left wing kinematics is from the mirroring of the right wing.

Result: Swimming Animation



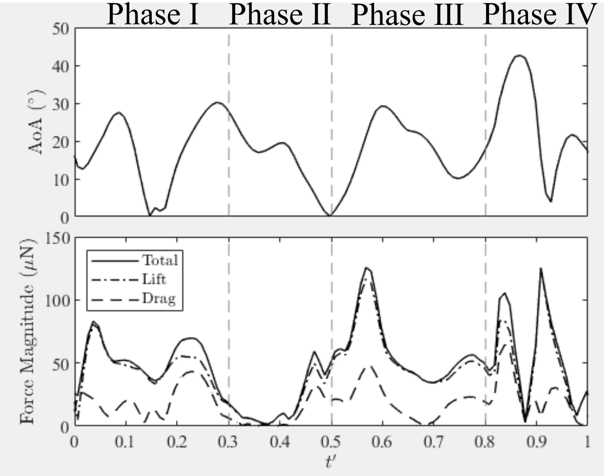
Vortex Visualization by Q-criterion, color represents the velocity magnitude



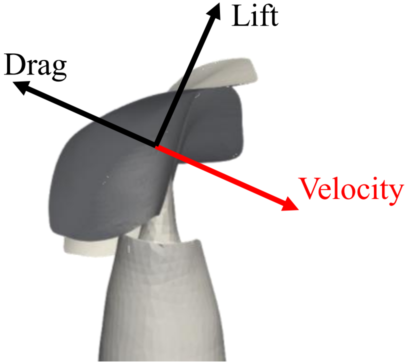
Pressure field

- Leading-edge (LEV) and trailing-edge (TEV) vortices persist throughout the flapping cycle.
- LEVs generate low-pressure regions along the front edge of the wing, enhancing and sustaining lift while stroking.
- Wing–wing interaction induces alternating low- and high-pressure zones between the wings.
- This pressure modulation promotes LEV formation in the next stroke.

Result: Wing Force Decomposition (Lift and Drag)



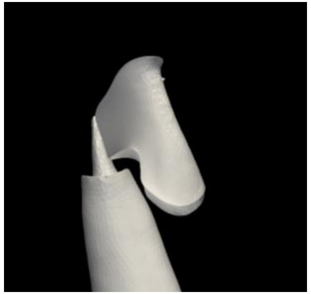
Angle of Attack and Force Magnitude



Lift consistently contributes more than drag, indicating a lift-based propulsion strategy.

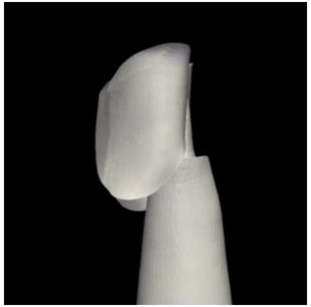
Phase I: Stroke from back to front

Phase II: Interaction in front of body

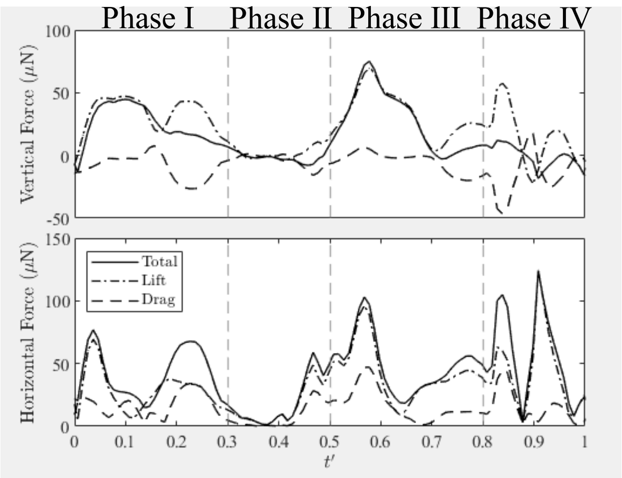


Phase III: Stroke back

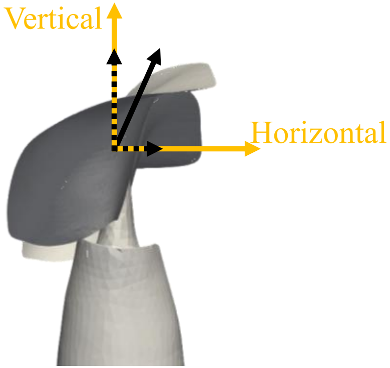
Phase IV: Meet at back of body



Result: Wing Force Decomposition (Vertical and Horizontal)

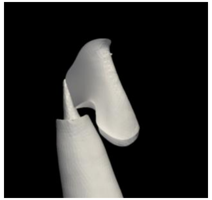


Vertical and Horizontal Force



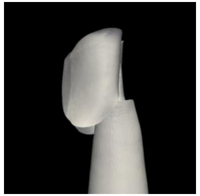
Phase I

Phase II



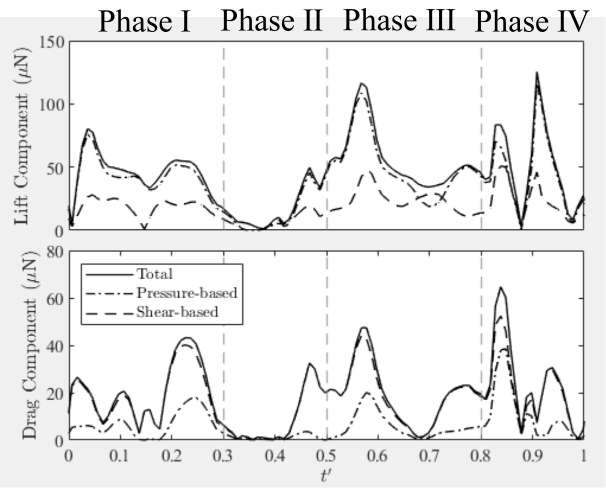
Phase III

Phase IV



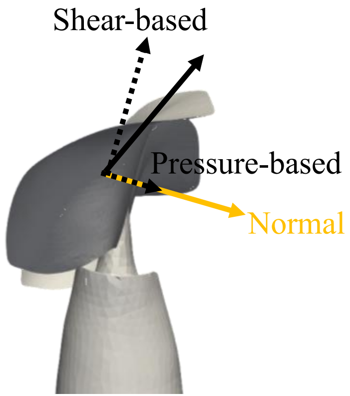
Vertical force comes mainly from lift which is the main source to pull the animal upward.

Result: Wing Force Decomposition (Pressure- and Shear-Based)



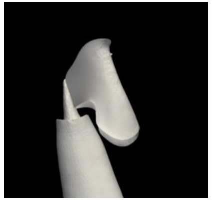
Pressure- and Drag-Based Component

Lift is mainly pressure-driven, while drag is dominated by shear stress on the wing surface.



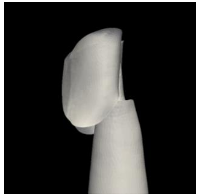
Phase I

Phase II

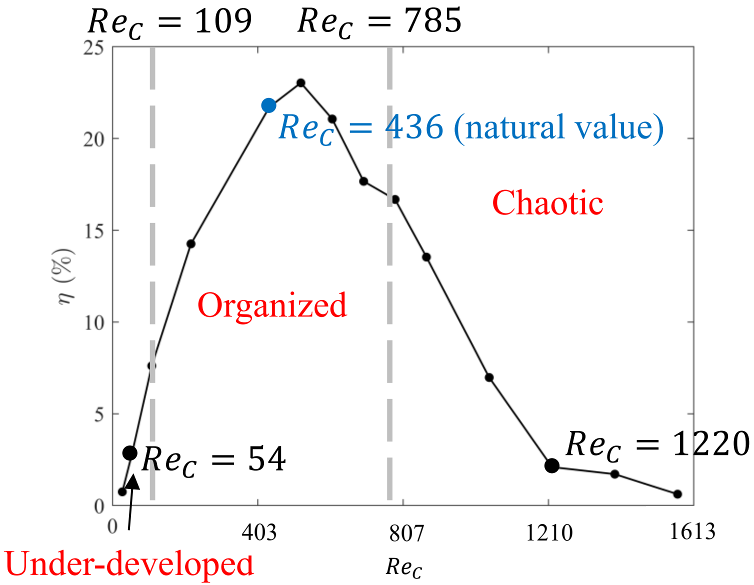


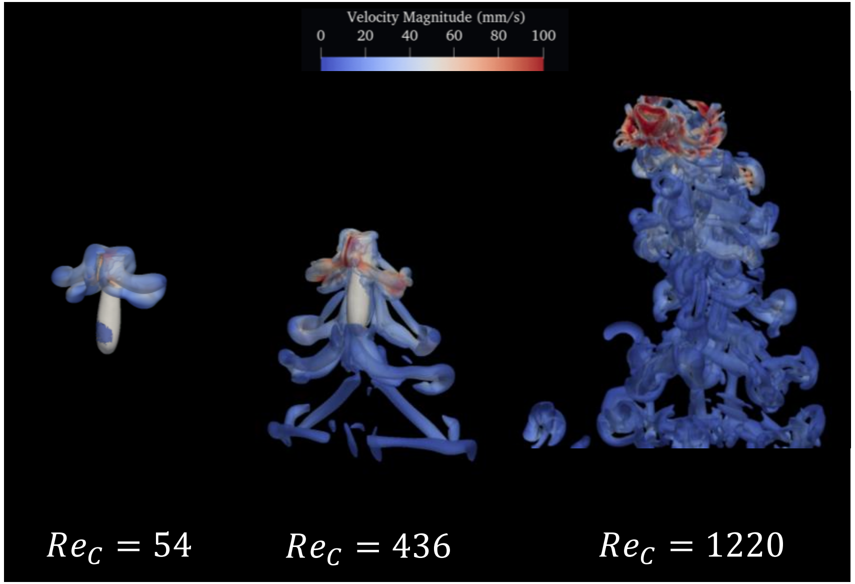
Phase III

Phase IV



Result: Efficiency and Wake Vortex Structure





Chordwise Reynolds number:

$$Re_c = \frac{2\phi f L_S L_C}{\nu}$$

ϕ: Stroke amplitude
L_S: Length of wing span
L_C: Length of wing chord

Efficiency:

$$\eta = \frac{TU + P_{gravity}}{P_{in}}$$

T: Net thrust
U: Swimming speed
P_{in}: Input power

- Low Re (< 109): **Viscous effects dominate**, vortices are damped or merge too early, reducing wake effectiveness.
- Mid Re: **Structured and coherent vortex shedding** enhances momentum transfer and propulsion performance.
- High Re (> 785): **Chaotic vortex shedding**, many small vortices dissipate rapidly, causing energy loss.

Efficient swimming relies on **well-timed, organized wakes**.

Conclusion:

- **Geometry Reconstruction:** Wing kinematics and body shape were accurately reconstructed from experimental videos.
- **Stable Lift Mechanism (LEV):** Stable LEVs persist throughout the stroke and sustain lift via low-pressure generation.
- **Pressure Modulation by Wing-Wing Interaction:** Wing–wing interaction modulates pressure and supports LEV formation in the next stroke.
- **Lift-Dominated Propulsion:** Swimming is lift-dominated, with vertical force mainly from lift, horizontal force aided by drag.
- **Lift and Drag Components:** Lift is pressure-driven; drag is shear-based.
- **Most Efficient Reynolds Number:** Peak swimming efficiency occurs at Re = 400 – 500, where vortex shedding is coherent.
- **Wake Structure Matters:** Both viscous dominated and chaotic flow regimes reduce efficiency due to poor wake structure.

Future work:

- Investigate the underlying mechanism of lift enhancement due to wing–wing interaction.

Reference:

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[4] Menzer, A., Gong, Y., Fish, F. E., & Dong, H. (2022). Bio-inspired propulsion: Towards understanding the role of pectoral fin kinematics in manta-like swimming. Biomimetics, 7(2), 45.

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Thank you!

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