

Deciphering the Influence of Unsteady Aerodynamics on Mechanosensation and Olfaction in Insect Flight

Chengyu Li

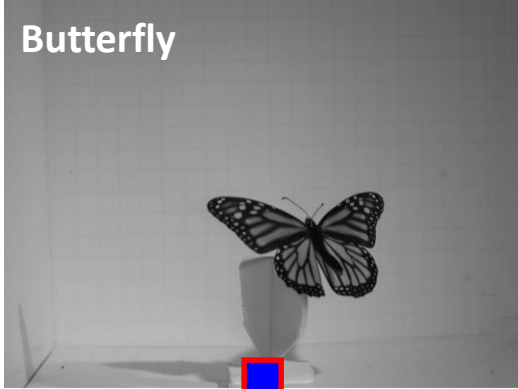
Associate Professor

Department of Mechanical & Aerospace Engineering
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Motivation: Biomimetics

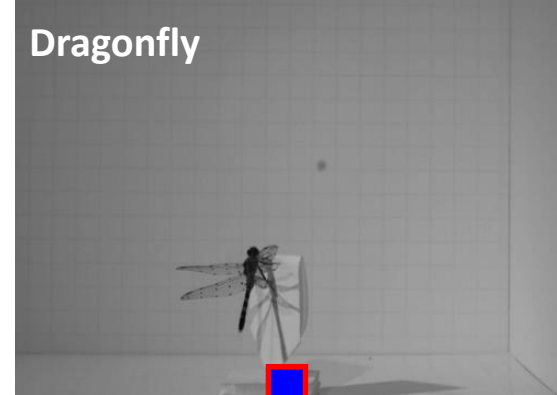
Butterfly



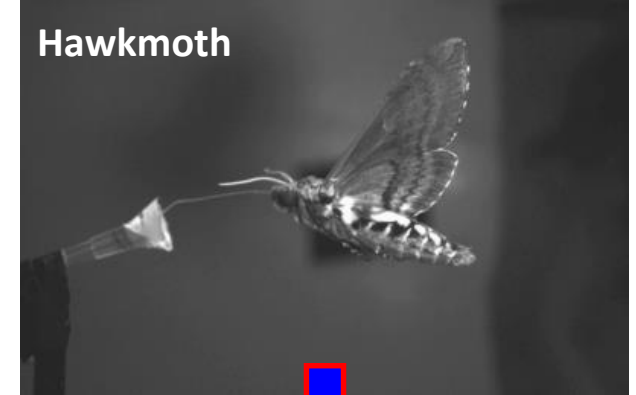
Bumblebee



Dragonfly



Hawkmoth



- Reveal fluid dynamic principles underlying biological locomotion
- Replicate the biological-level performance for man-made designs
- Discover solutions that go beyond the limits of biology

Clap-and-fling MAV



Robobee



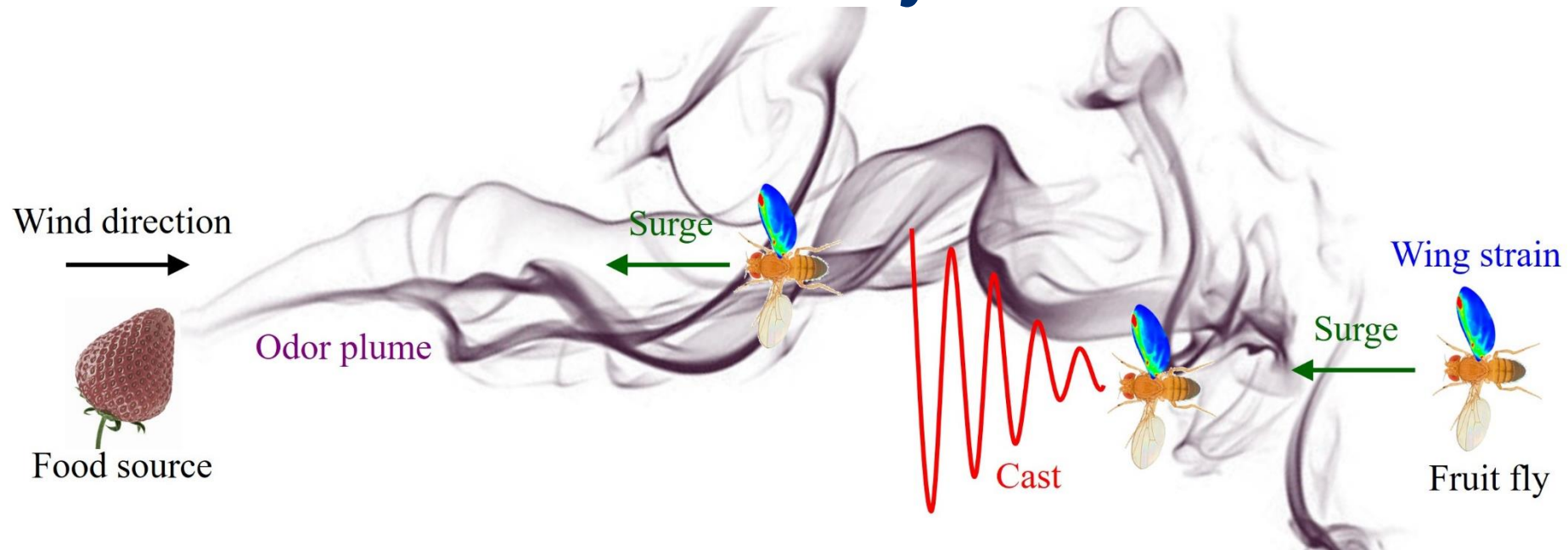
Soft fly



Smellicopter



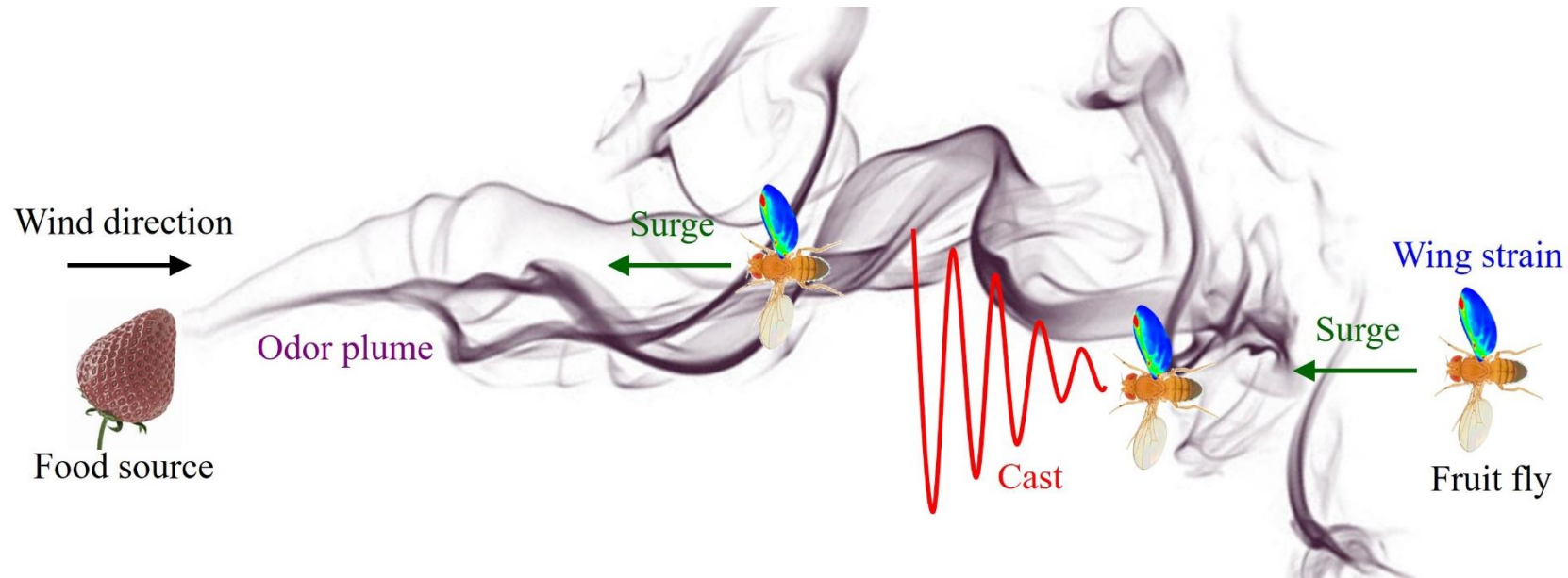
Research Objectives



- Specific Aim 1: Characterize the impact of unsteady aerodynamics on wing mechanosensation (Year 1-2)
- Specific Aim 2: Elucidate the influence of wing-induced flow on the spatiotemporal distribution of odor plume structures (Year 1-2)
- Specific Aim 3: Elucidate the mechanisms of odor-guided flapping flight by integrating mechanical and odorant stimulus (Year 2-3)

Outline

- Technical Challenges and Approaches
- Recent Progress (July 1st, 2024 - Present)
- Plan for Year 1 (July 1st, 2024- Jun 30th, 2025)

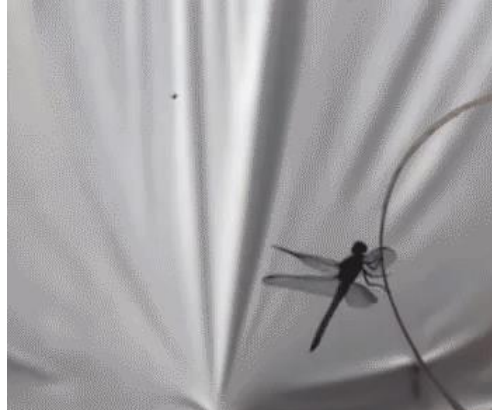


Challenges of Studying the Impact of Unsteady Aerodynamics

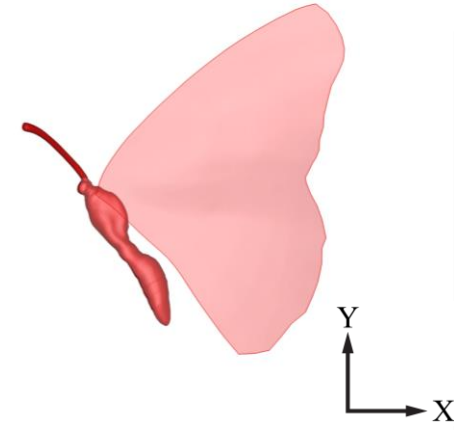
■ High Fidelity Modeling



Tiny size



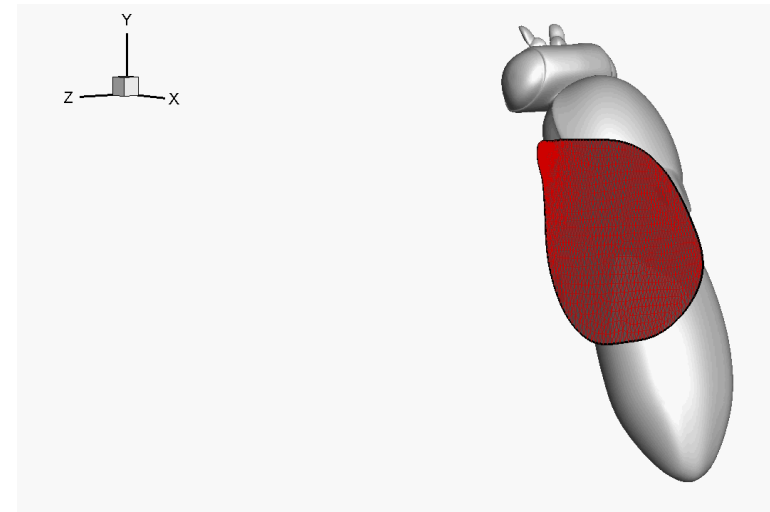
Fast and unpredictable



Complex kinematics and deformation

■ High Fidelity Numerical Simulation

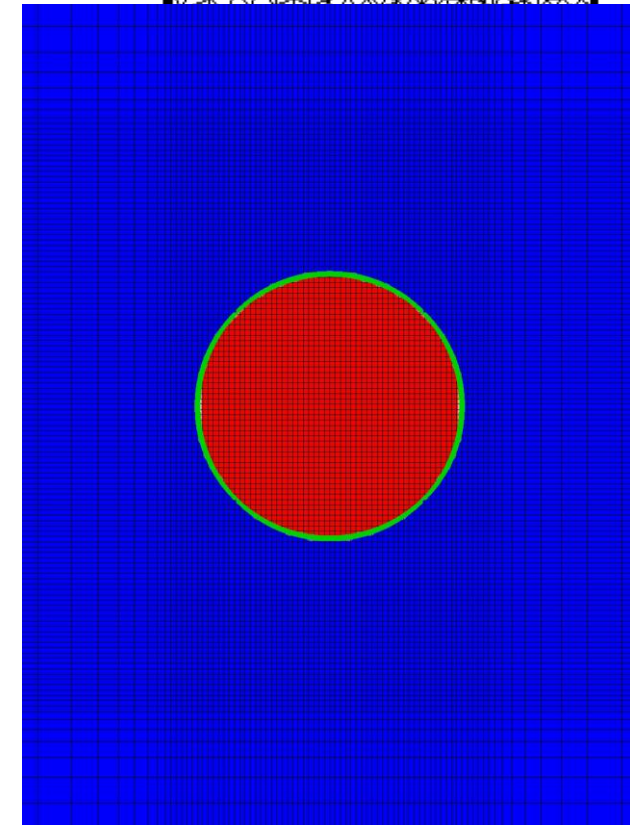
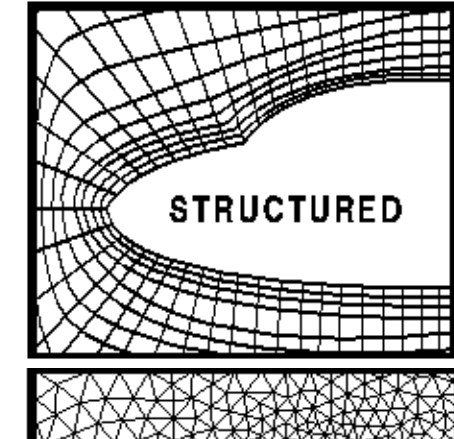
- Complex 3D geometries
- Moving boundaries
- Sharp edge
- Fluid-structure interactions
- Odorant transport in fluids



Challenges in CFD

■ Need to Tackle

- ☐ Complex 3D geometries
 - ☐ Moving boundaries
 - ☐ Fluid structure interaction
 - ☐ Resolution of vortex dynamics
 - ☐ Relatively low Reynolds number
 - ☐ Expensive 3D simulation
-
- ☐ Very challenging for conventional body fitted methods
 - ☐ Cartesian Grid Methods handle these problems in all its complexity



Numerical Methods

■ Unsteady, Incompressible Navier-Stokes Equations:

$$\frac{\partial u_i}{\partial x_i} = 0; \quad \frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re} \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

■ Fractional Step Method (2nd order central scheme):

1st sub-step: Modified momentum equation, solve for u^*

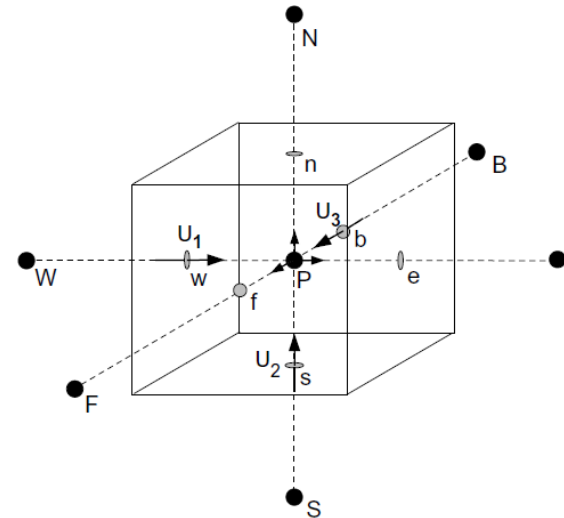
$$\frac{u_i^* - u_i^n}{\Delta t} = \frac{1}{2} \left[3 \frac{\delta(U_j^n u_i^n)}{\delta x_j} - \frac{\delta(U_j^{n-1} u_i^{n-1})}{\delta x_j} \right] = -\frac{1}{\rho} \frac{\delta p^n}{\delta x_i} + \frac{1}{2} \nu \left[\frac{\delta}{\delta x_j} \left(\frac{\delta u_i^*}{\delta x_j} \right) + \frac{\delta}{\delta x_j} \left(\frac{\delta u_i^n}{\delta x_j} \right) \right]$$

2nd sub-step: Pressure correction, solve for p'

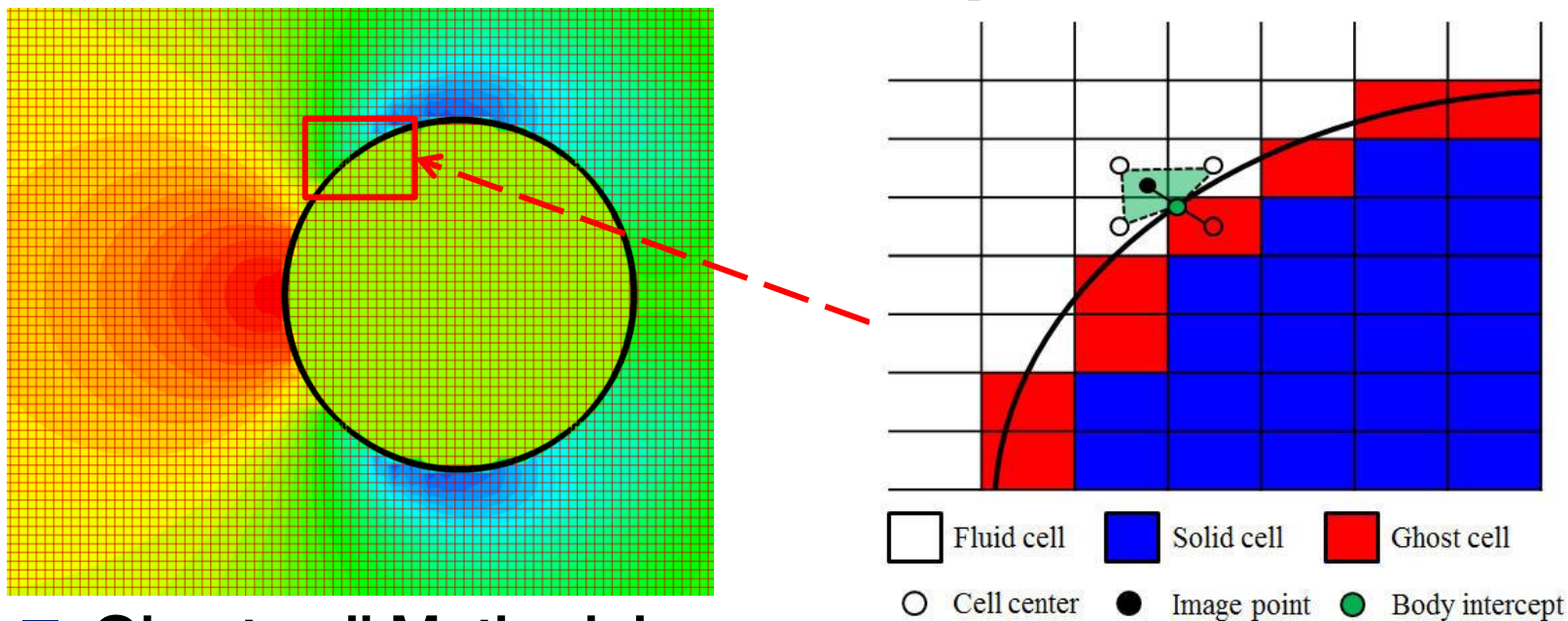
$$\frac{u_i^* - u_i^n}{\Delta t} = \frac{1}{\rho} \frac{\delta p'}{\delta x_i} \quad \frac{1}{\rho} \frac{\delta}{\delta x_i} \left(\frac{\delta p'}{\delta x_i} \right) = \frac{1}{\Delta t} \frac{\delta U_i^*}{\delta x_i}$$

3rd sub-step: Update pressure and velocity

$$\begin{cases} p^{n+1} = p^n + p' \\ u_i^{n+1} = u_i^* - \Delta t \frac{1}{\rho} \left(\frac{\delta p'}{\delta x_i} \right) \end{cases}$$



Direct B.C. Imposition



■ Ghost-cell Methodology:

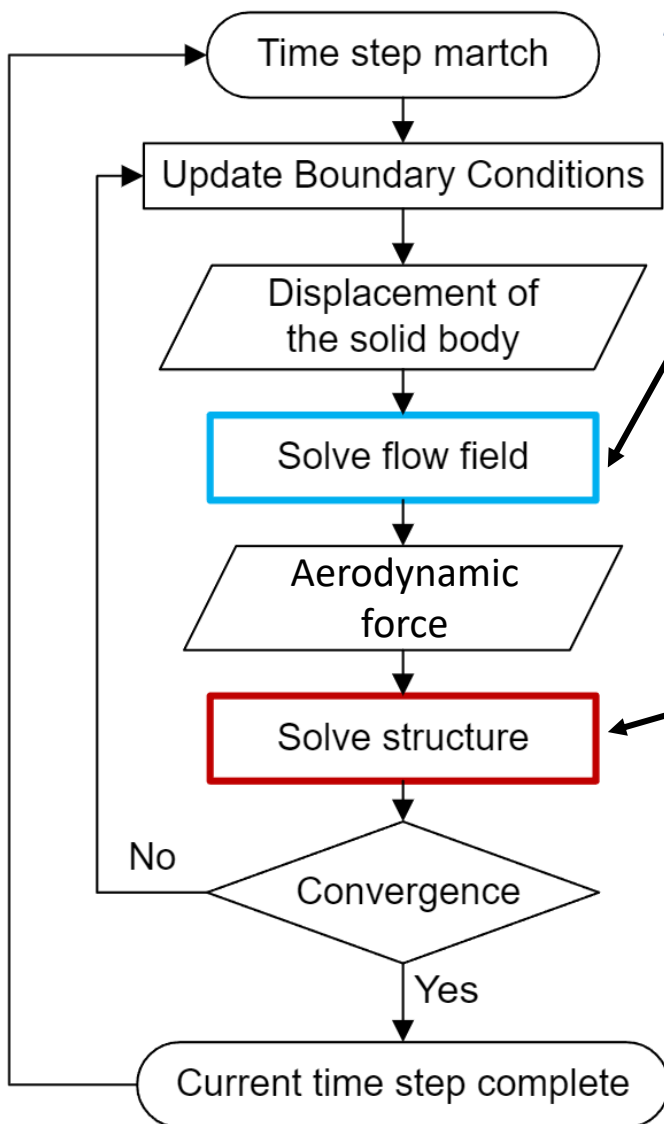
Ghost cells are defined as cells in the solid that have at least one neighbor in the fluid

■ Ghost-cell Formulation (2nd order accuracy):

$$\phi(x, y, z) = C_1xyz + C_2xy + C_3yz + C_4xz + C_5x + C_6y + C_7z + C_8$$

$$\{C\} = [V]^{-1} \{\phi\} \qquad \phi_{IP} = \sum_{i=1}^8 \alpha_i \phi_i + O(\Delta^2)$$

Fluid-Structure Interaction



Flow Solver

- Sharp-interface Immersed Boundary Method (IBM):

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re} \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

$$\frac{\partial u_i}{\partial x_i} = 0;$$

Structure Dynamics Solver

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{D}\dot{\mathbf{X}} + \mathbf{f}_{internal}(\mathbf{X}) = \mathbf{f}_{external}(t)$$

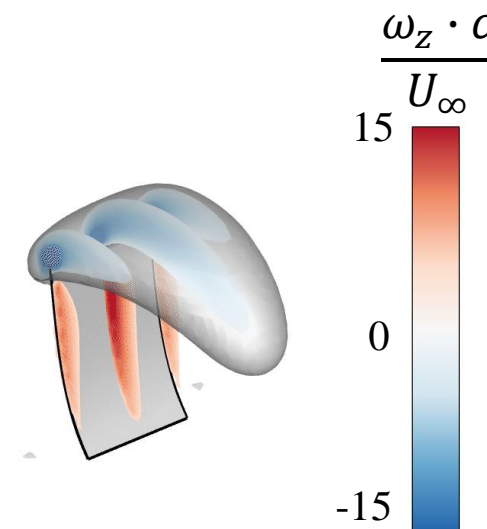
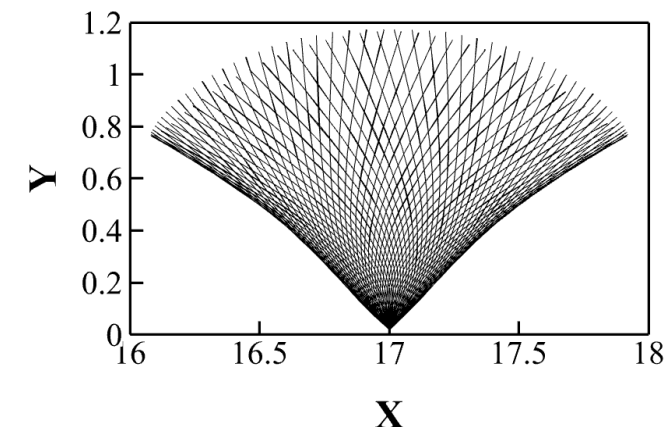
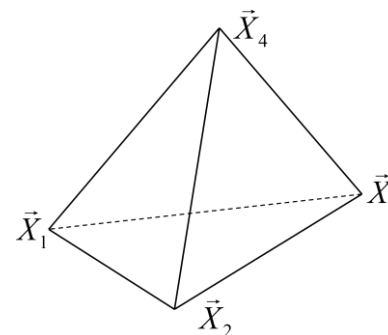
Mass Matrix

Damping Matrix

Internal force

External force

(Aerodynamic force)



Solver Validation

Reduced stiffness $K = 0.1 \sim 50$

$$K = EI / (\rho U^2 \bar{c}^3)$$

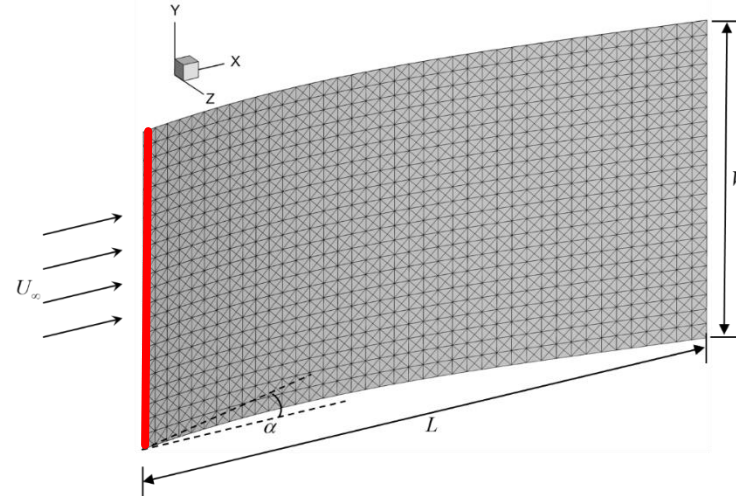
Aspect ratio $W/L = 0.54$

Mass ratio $M = 0.1$

$$M = \rho_s h / \rho_f L$$

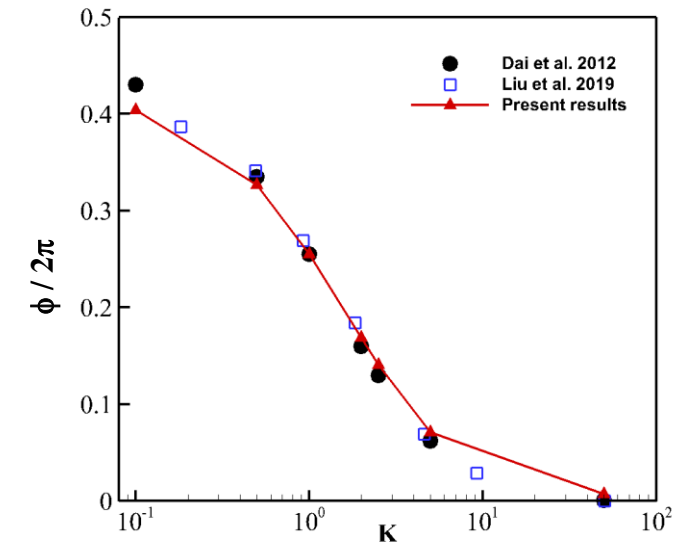
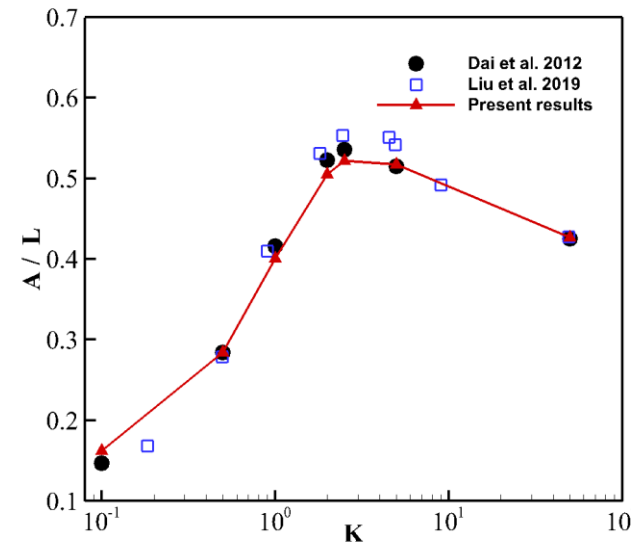
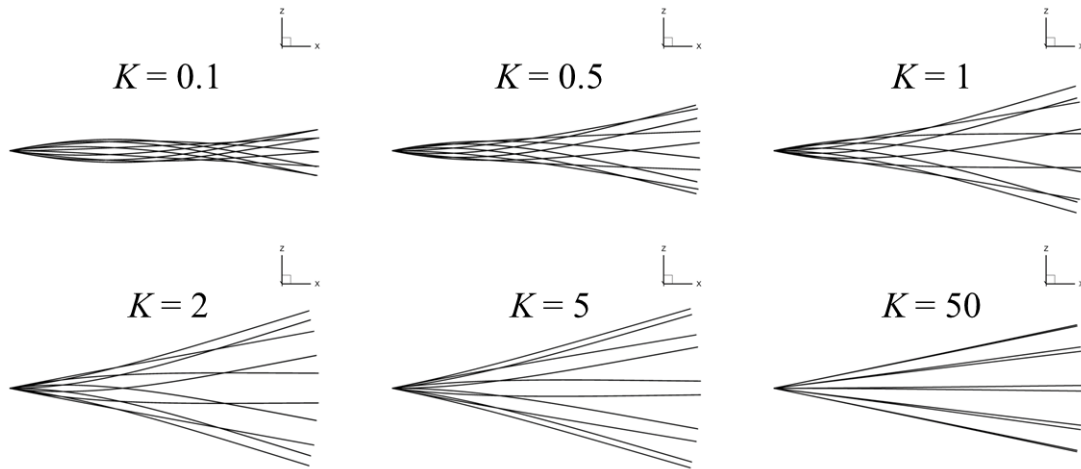
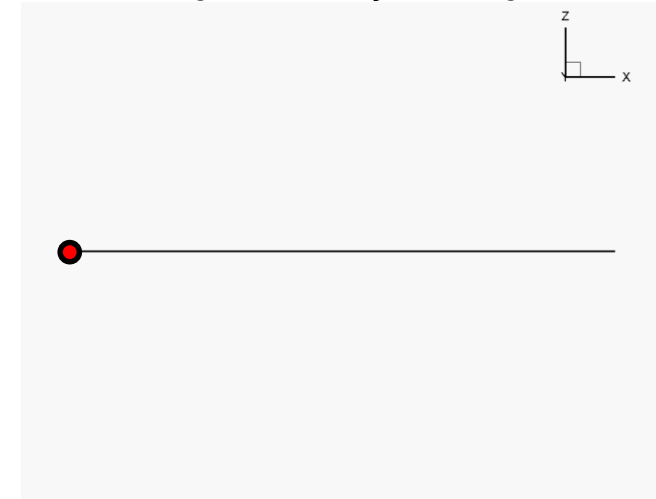
Reynolds number $Re = 640$

$$Re = UL / \nu$$

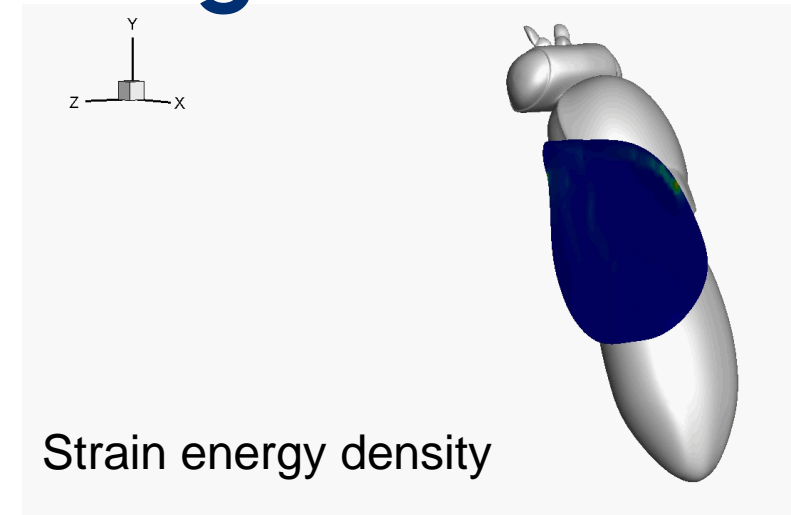
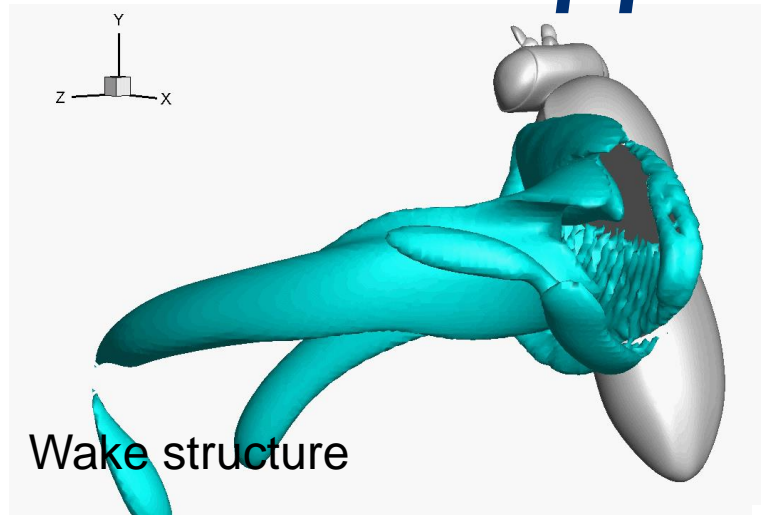
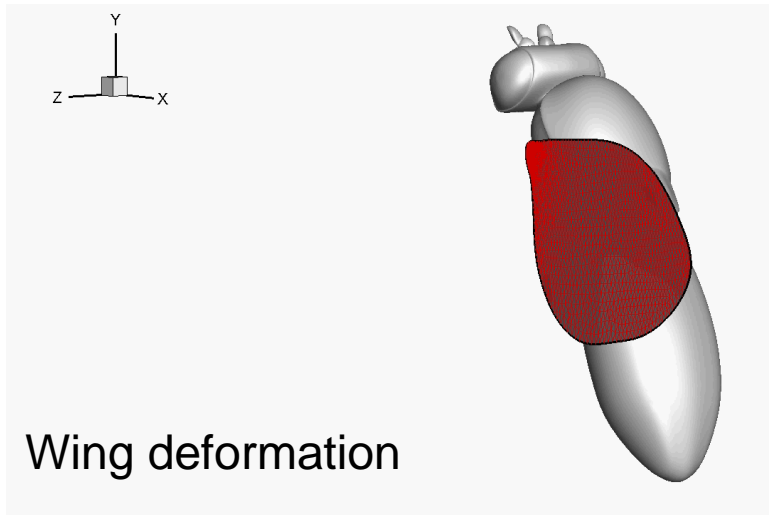


Root rotational angle:

$$\alpha = \alpha_0 \sin(2\pi f t), \alpha_0 = 12^\circ$$

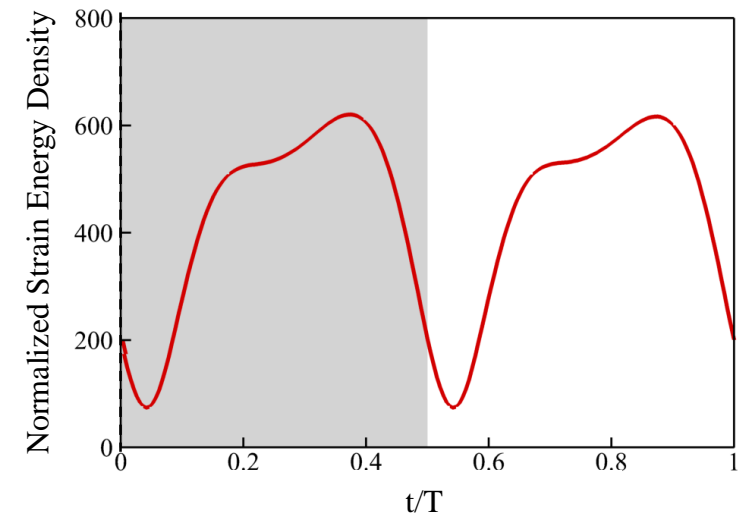
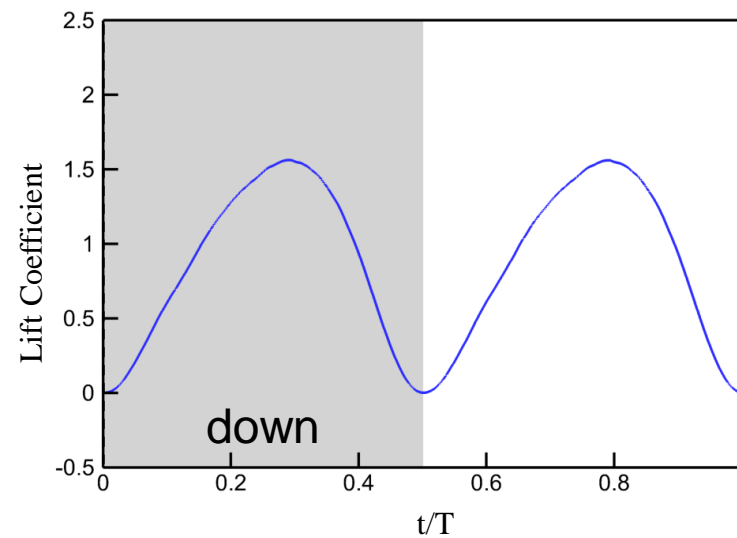
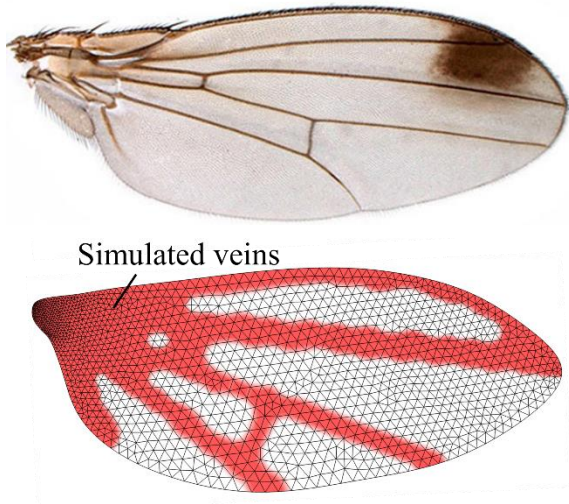


FSI Simulation of Flapping Wings



Reduced stiffness $K = 3.94$

$$K = EI / (\rho U^2 \bar{c}^3)$$



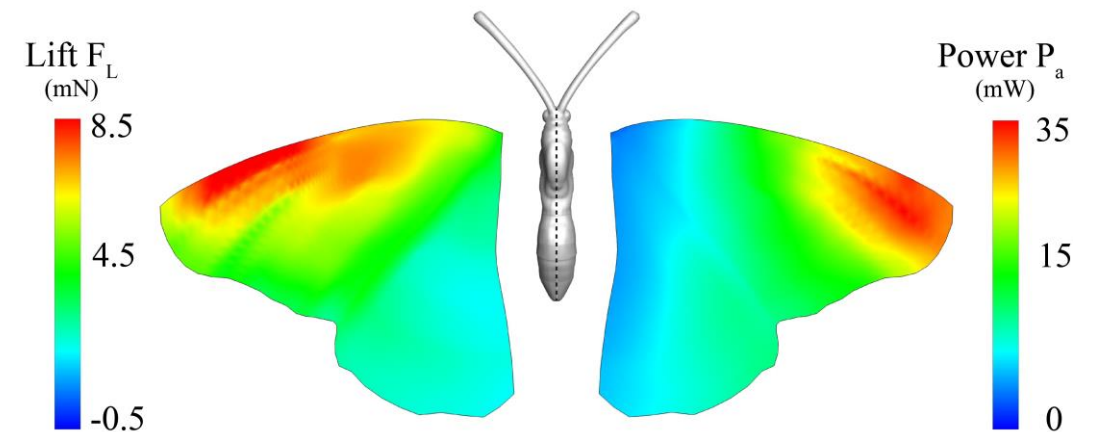
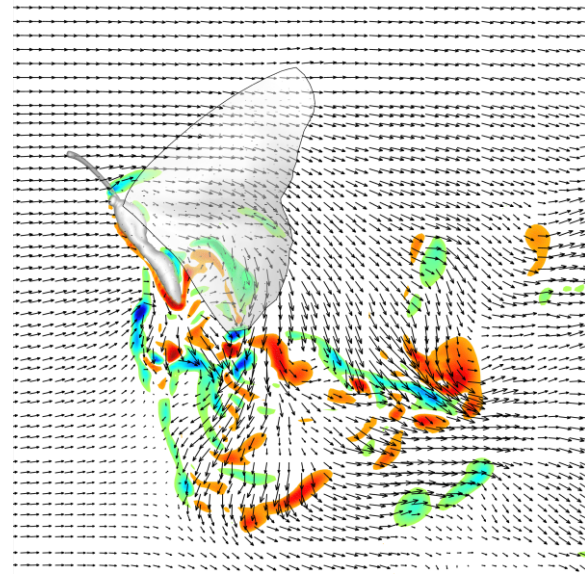
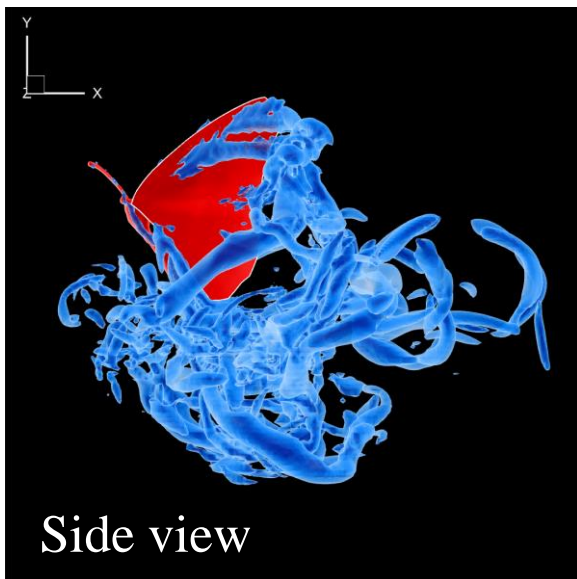
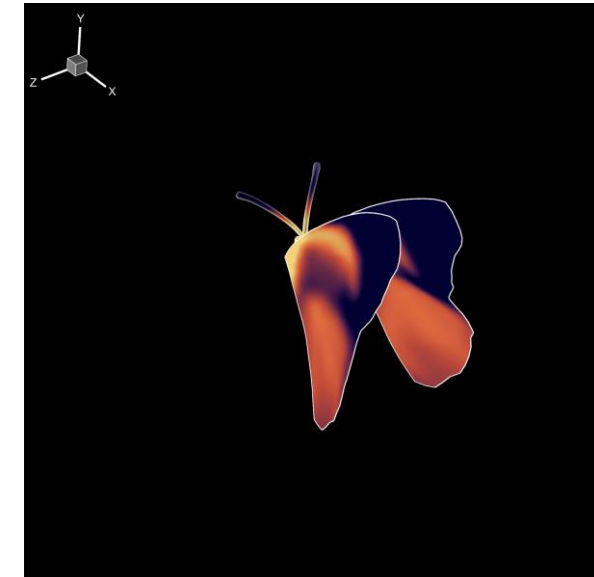
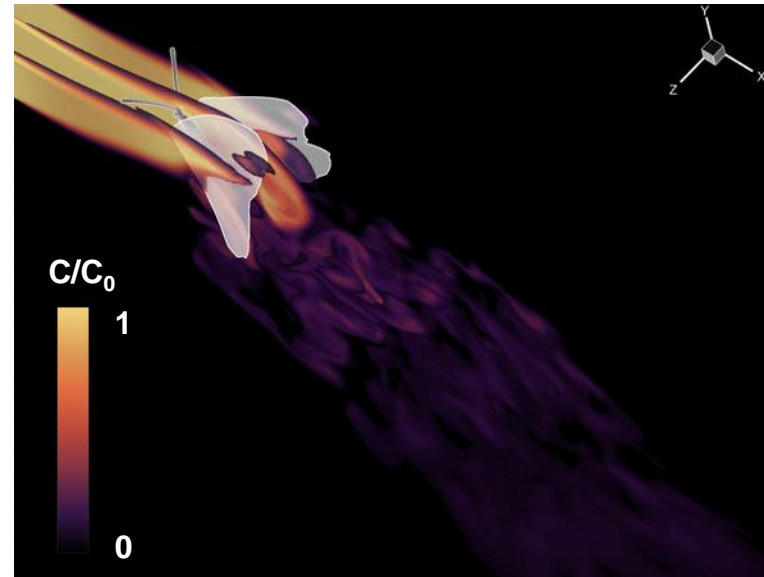
Odorant Transport in Fluid

$$\left\{ \begin{array}{l} \frac{\partial u_i}{\partial x_i} = 0 \\ \frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{1}{Re} \frac{\partial}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} \right) \\ \frac{\partial C}{\partial t} + U_i \frac{\partial C}{\partial x_i} = D \frac{\partial^2 C}{\partial x_i^2} \end{array} \right.$$

Continuity

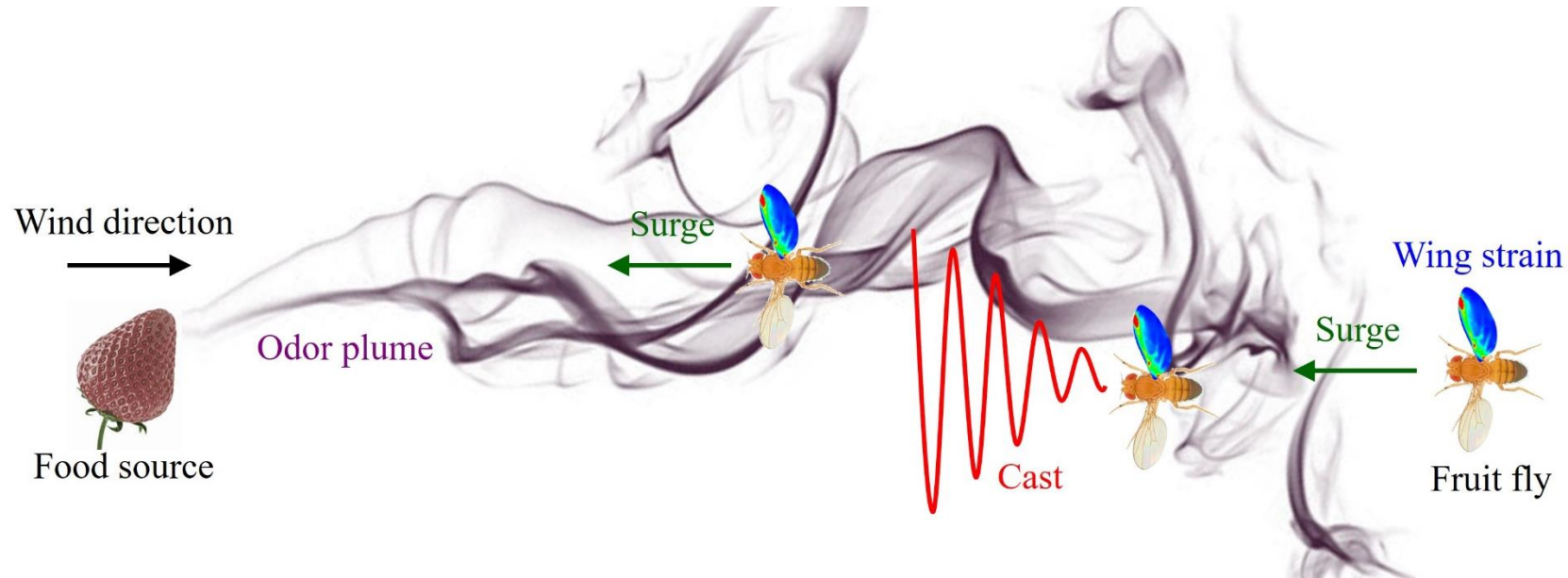
Momentum

Advection-diffusion



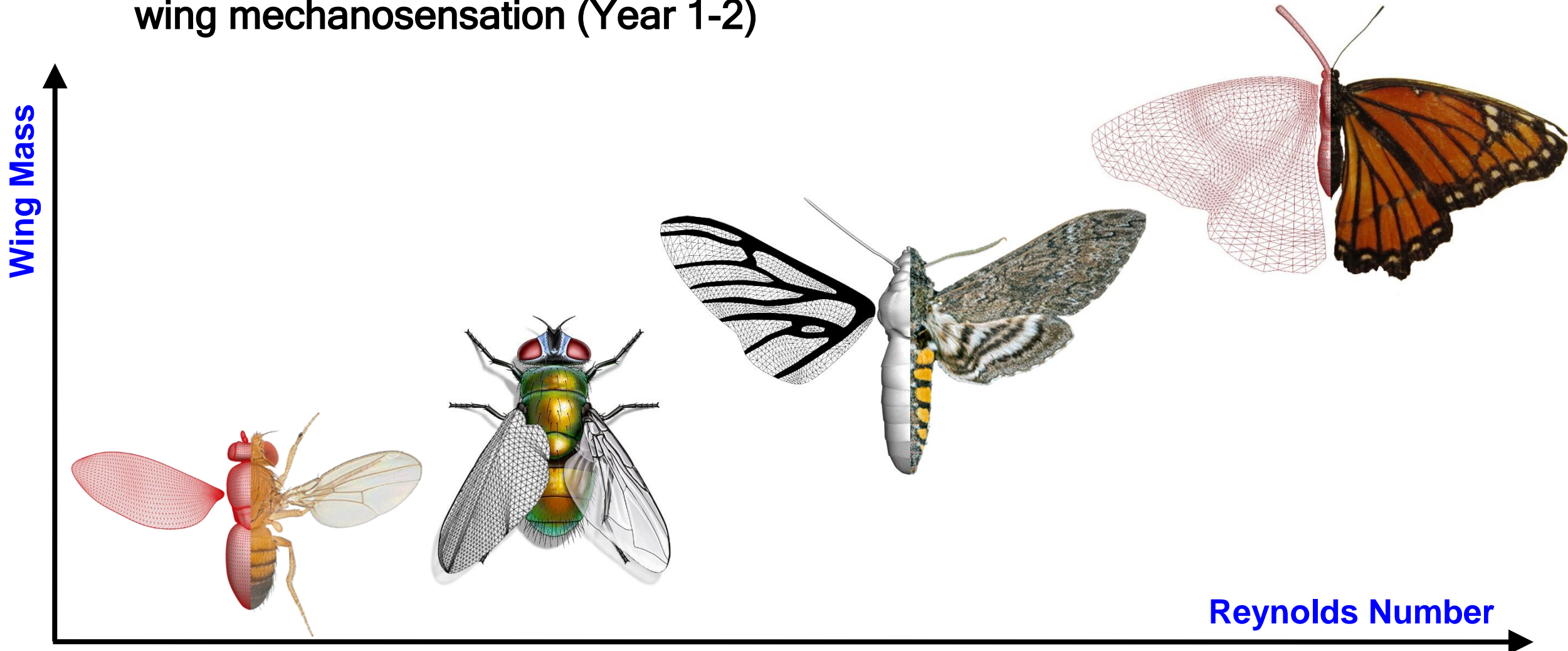
Outline

- Technical Challenges and Approaches
- Recent Progress (July 1st, 2024 - Present)
- Plan for Year 1 (July 1st, 2024- Jun 30th, 2025)



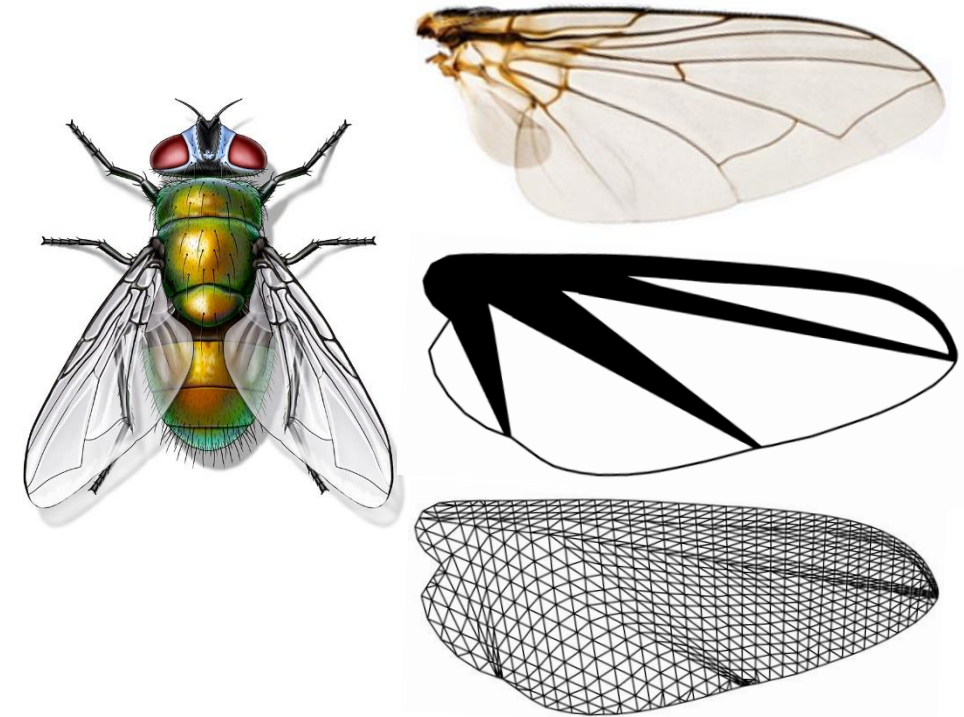
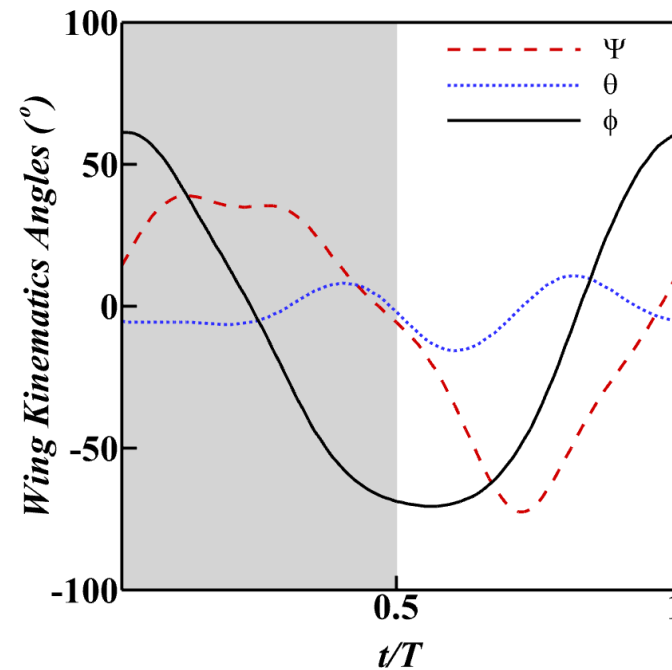
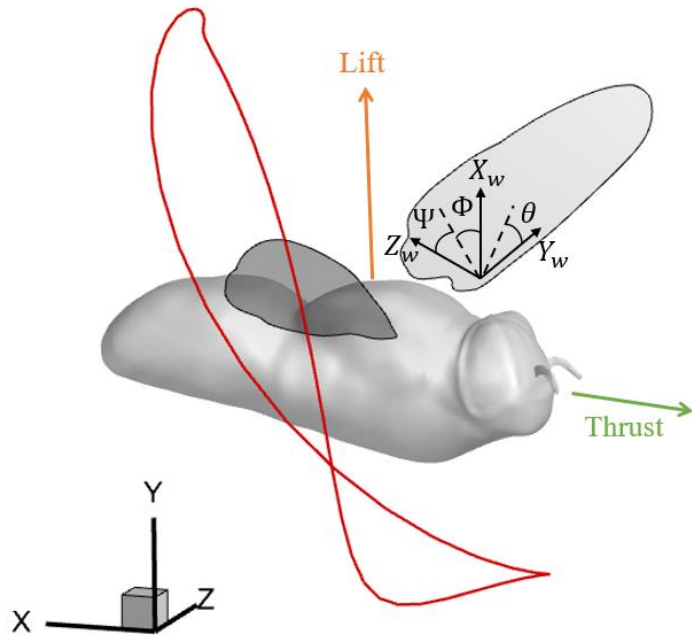
Recent Progress

- Specific Aim 1: Characterize the impact of unsteady aerodynamics on wing mechanosensation (Year 1-2)

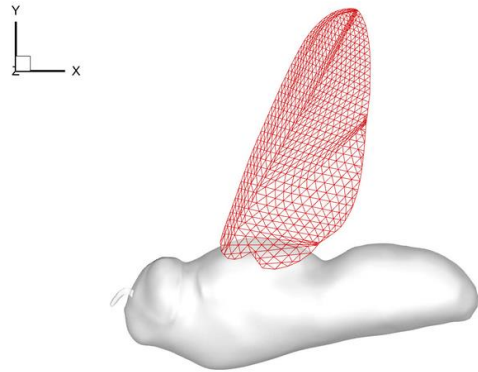


Wing Kinematics of Blue Bottle Fly

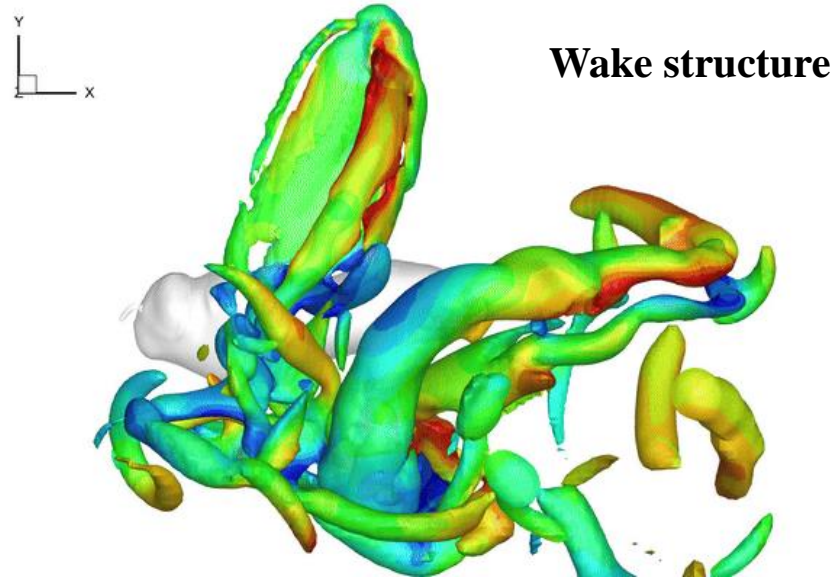
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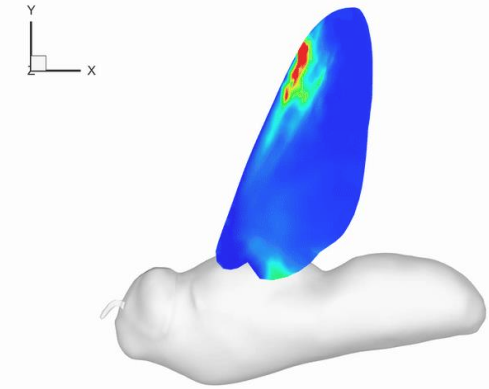
Fluid-Structure Interaction of a Blue Bottle Fly Wing



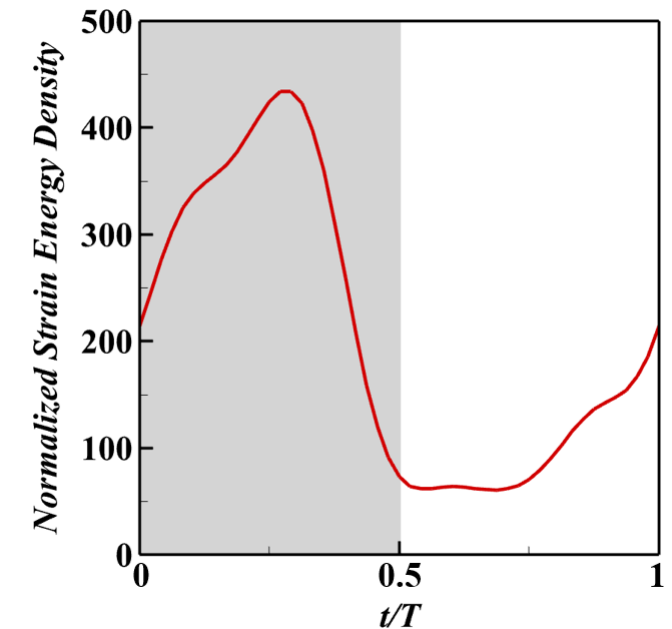
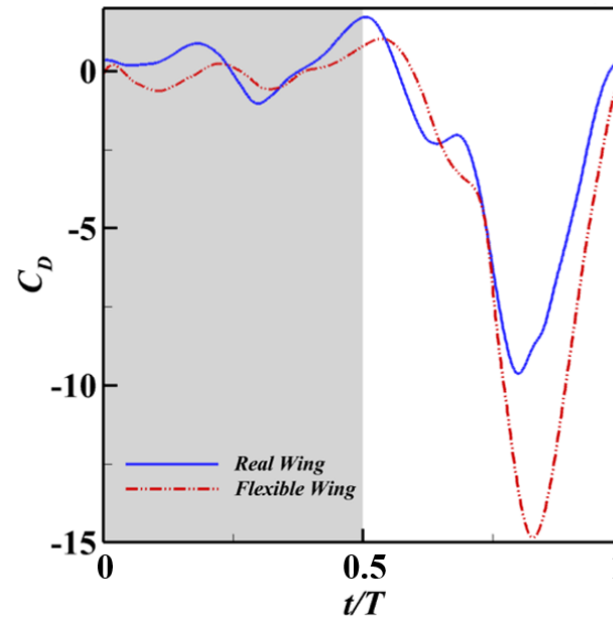
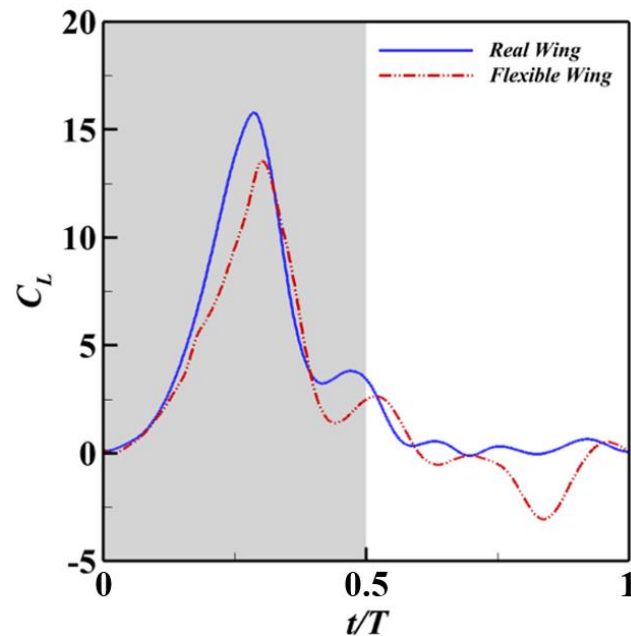
Wing deformation



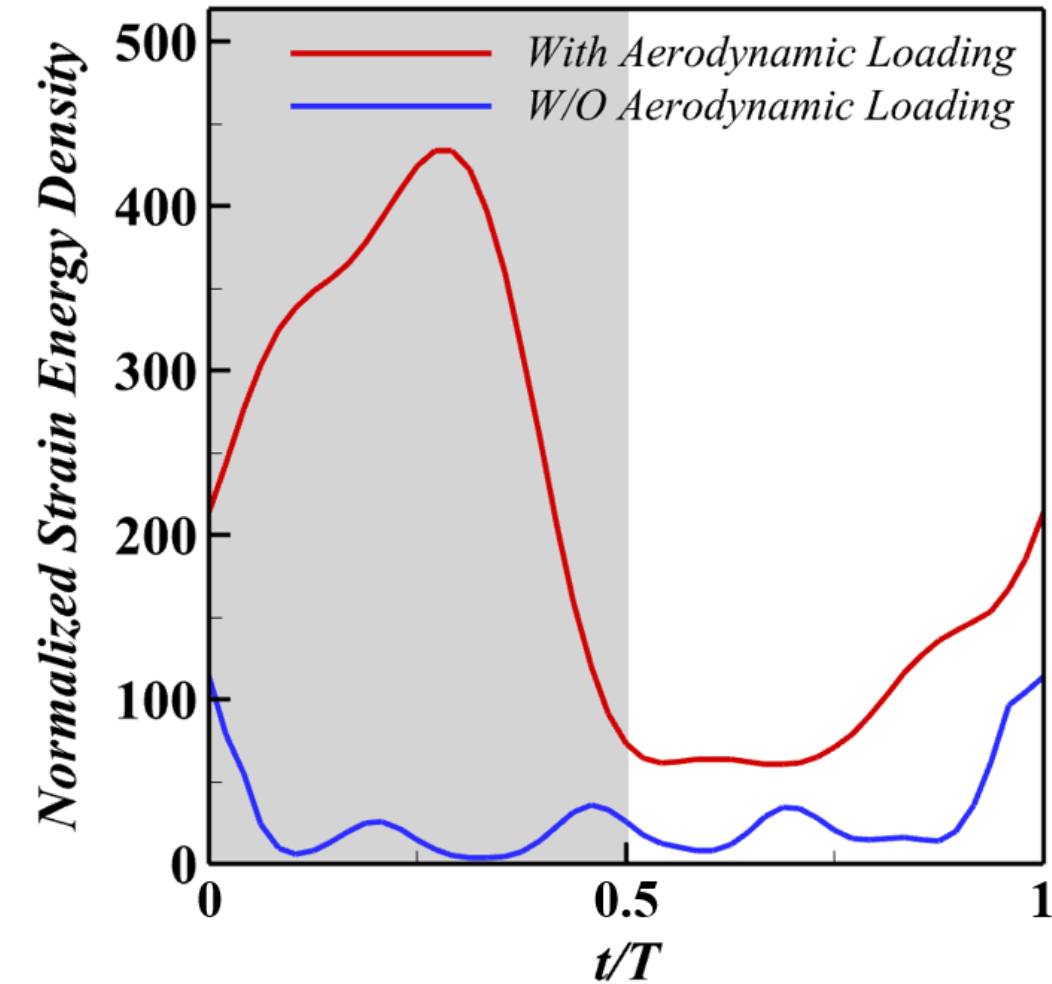
Wake structure



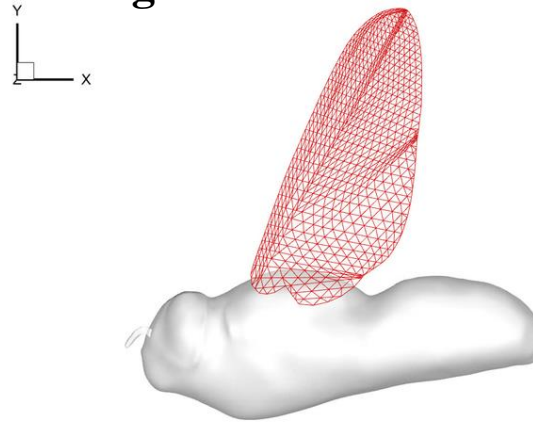
Strain energy density



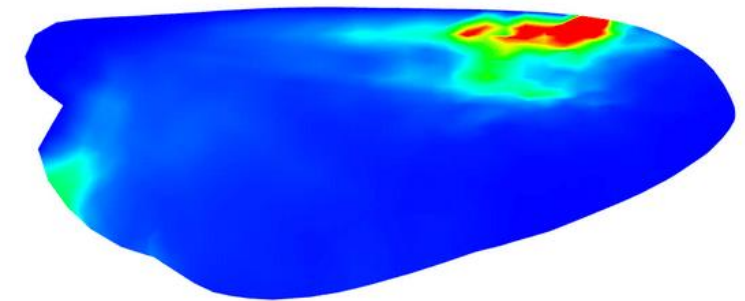
Effects of Aerodynamic Loading (Blue Bottle Fly)



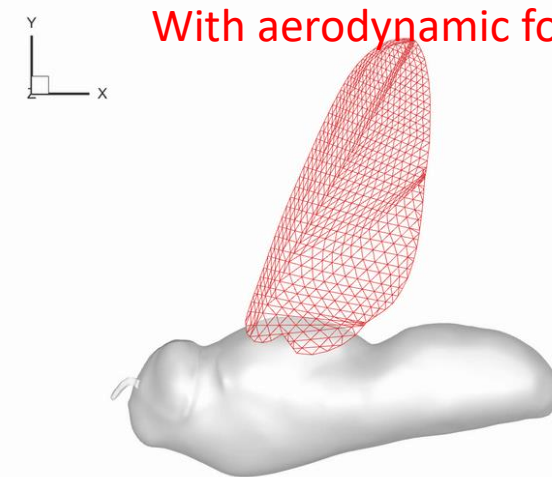
Wing deformation



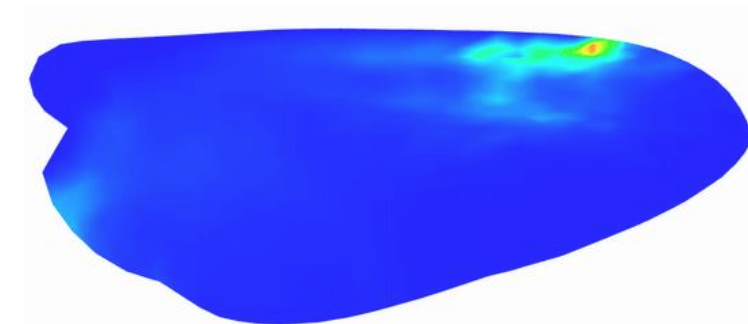
Strain energy density



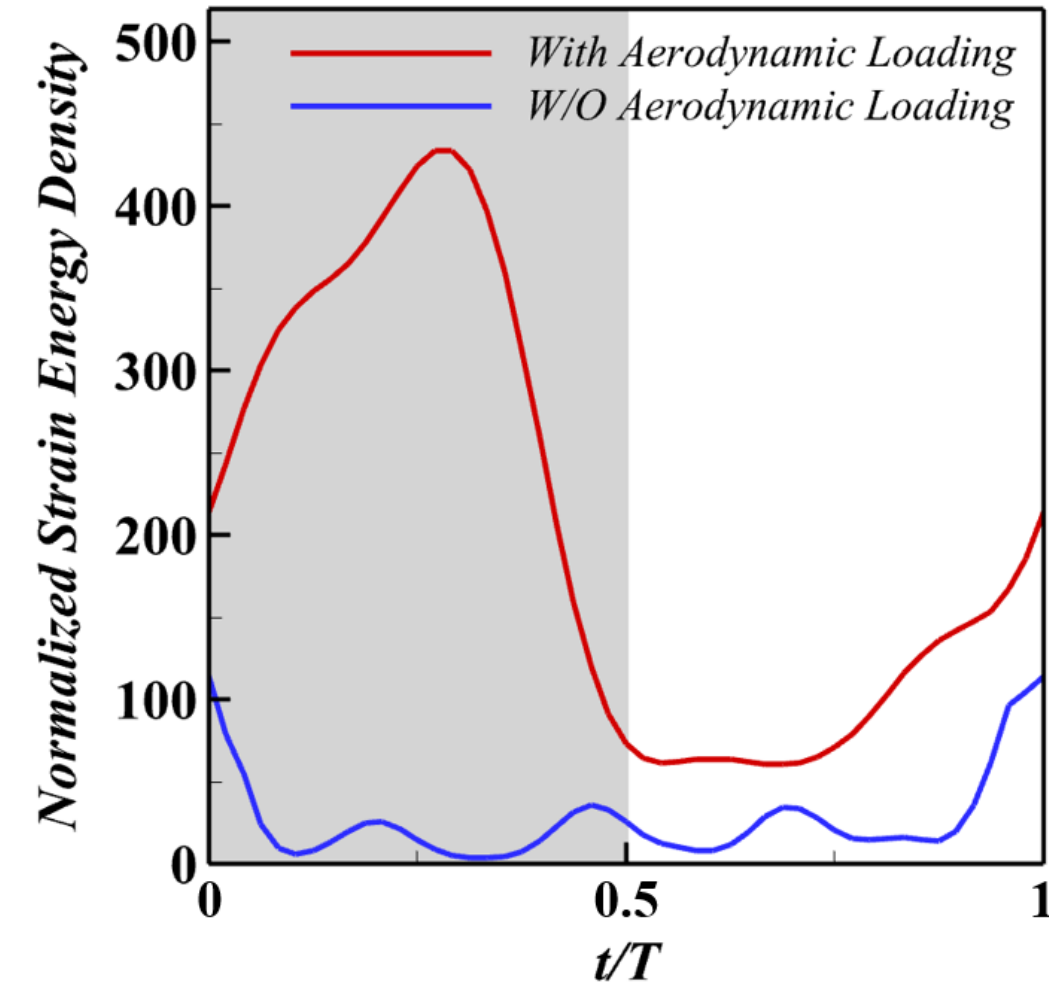
With aerodynamic force



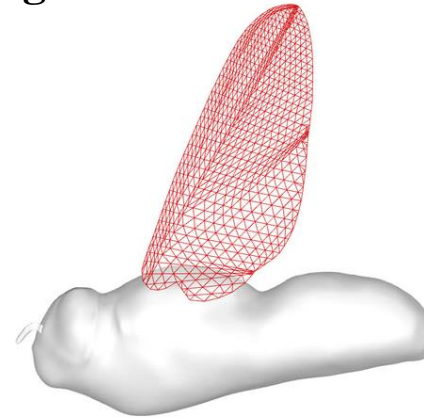
W/O aerodynamic force



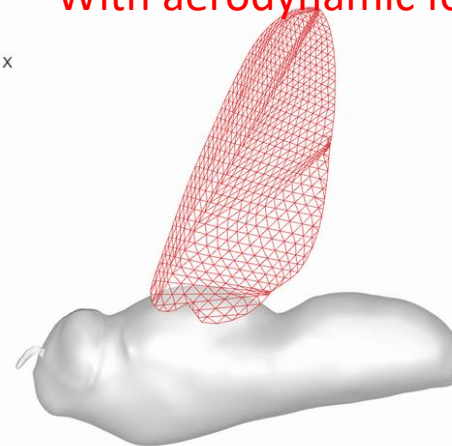
Effects of Aerodynamic Loading (Blue Bottle Fly)



Wing deformation



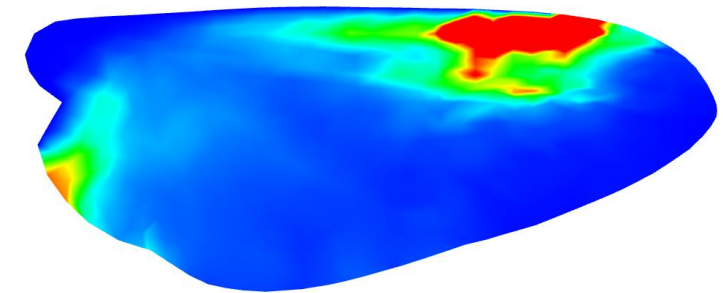
With aerodynamic force



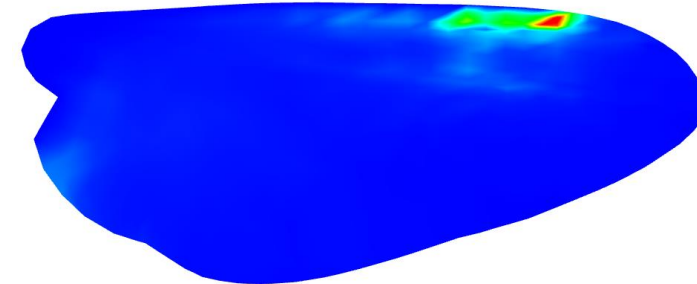
W/O aerodynamic force

Strain energy density

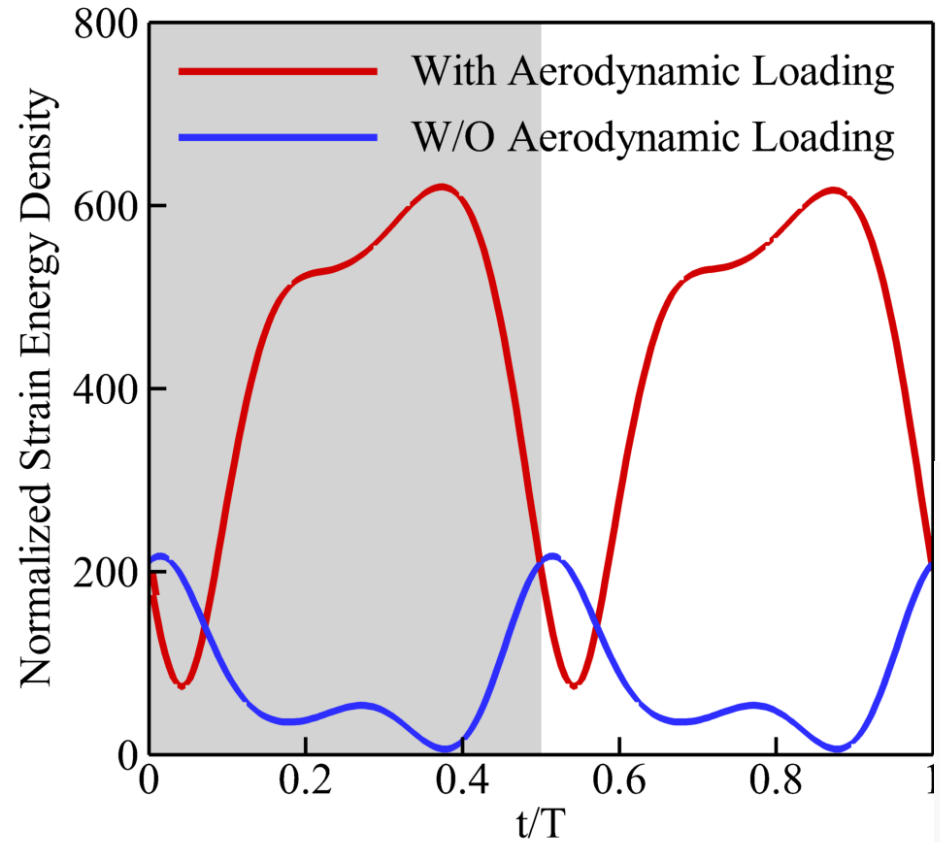
With aerodynamic force



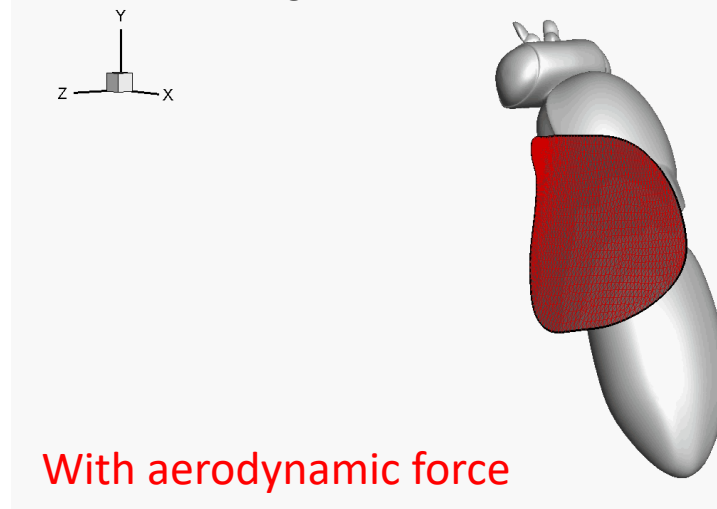
W/O aerodynamic force



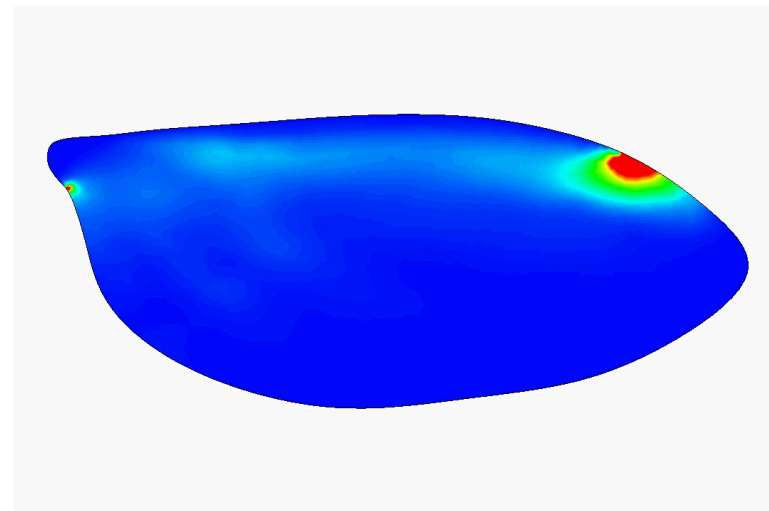
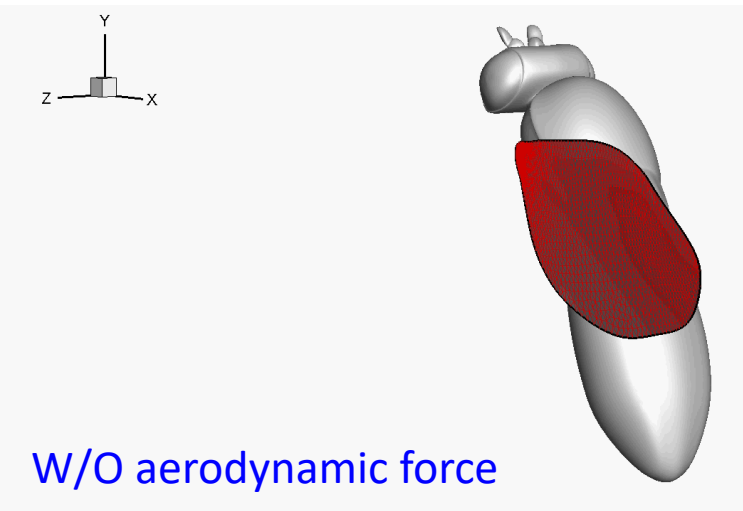
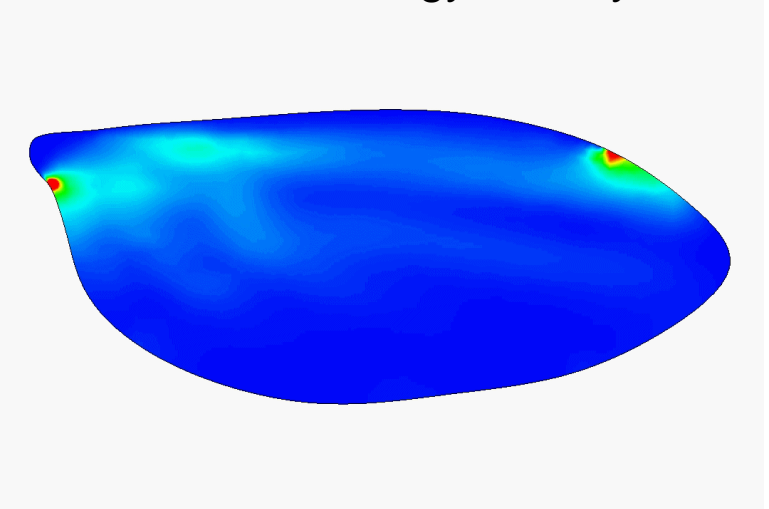
Effects of Aerodynamic Loading (Fruit Fly)



Wing deformation

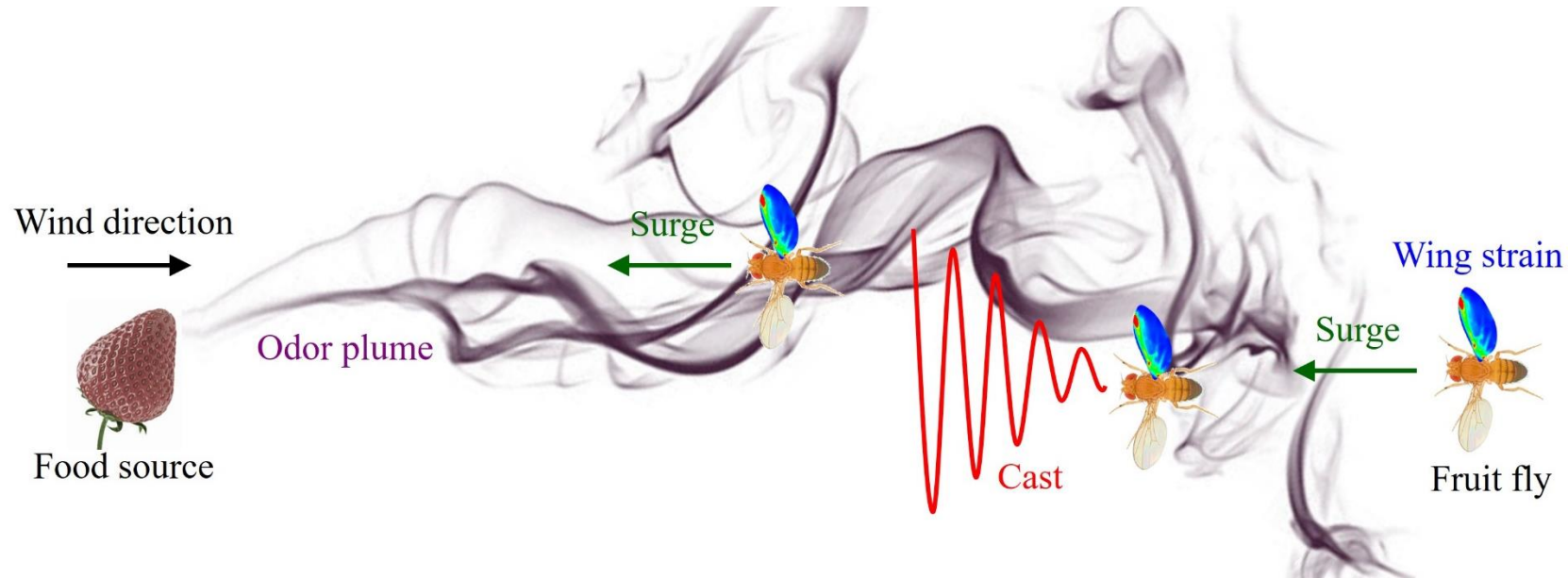


Strain energy density

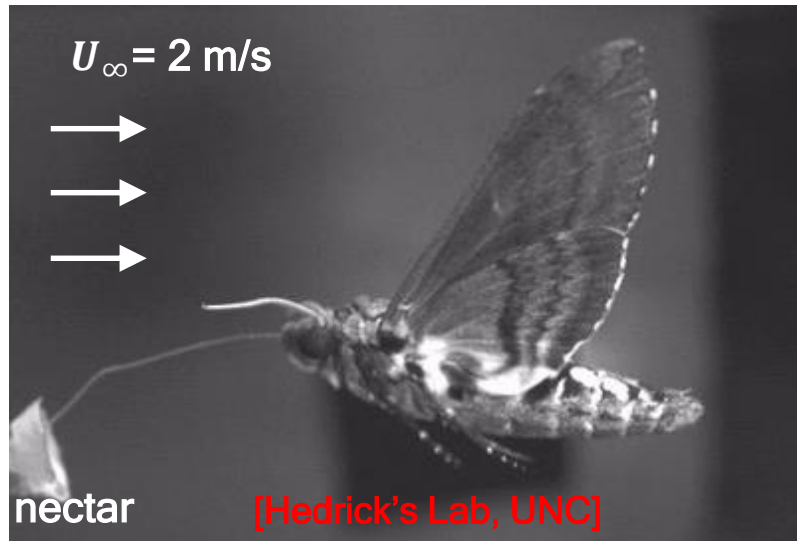


Outline

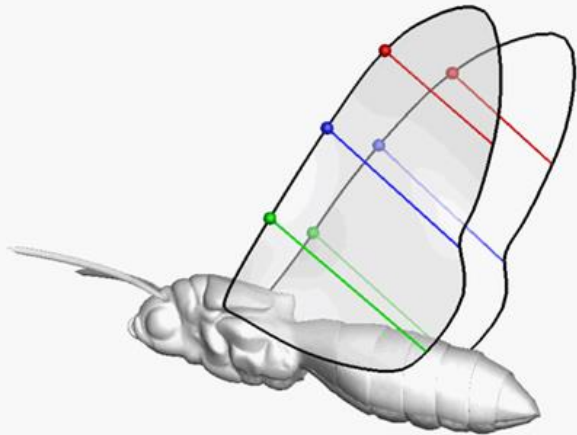
- Technical Challenges and Approaches
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- **Plan for Year 1 (July 1st, 2024- Jun 30th, 2025)**



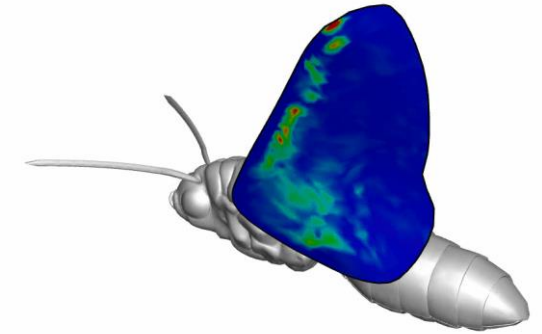
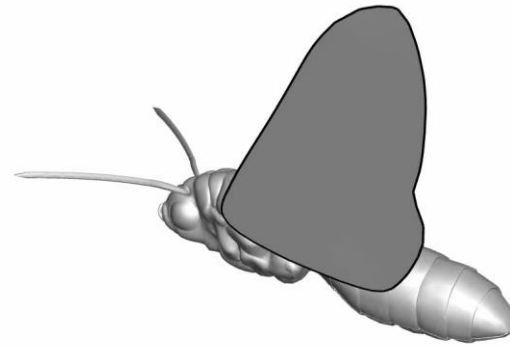
Effects of Aerodynamic Loading (Hawkmoth)



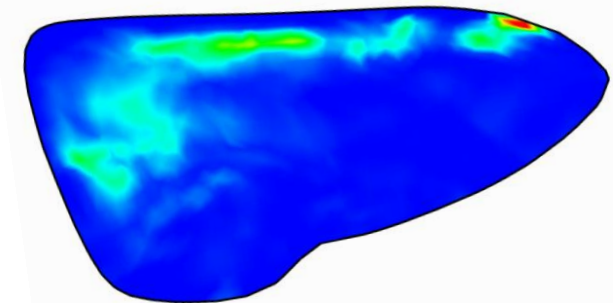
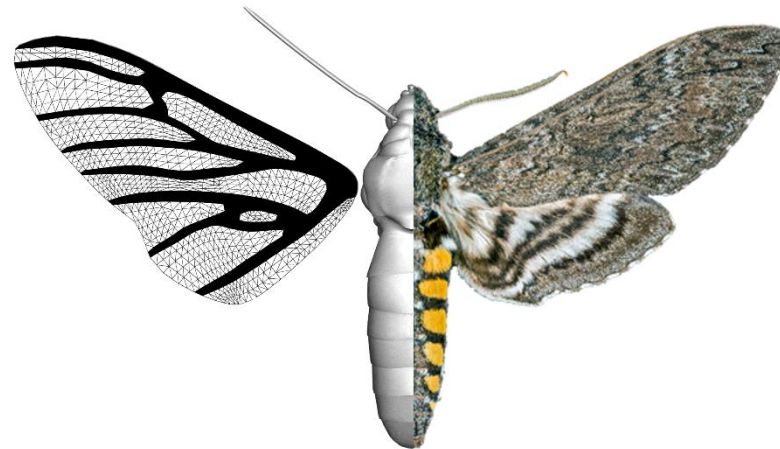
3D Reconstruction



$f = 25.6 \text{ Hz}$

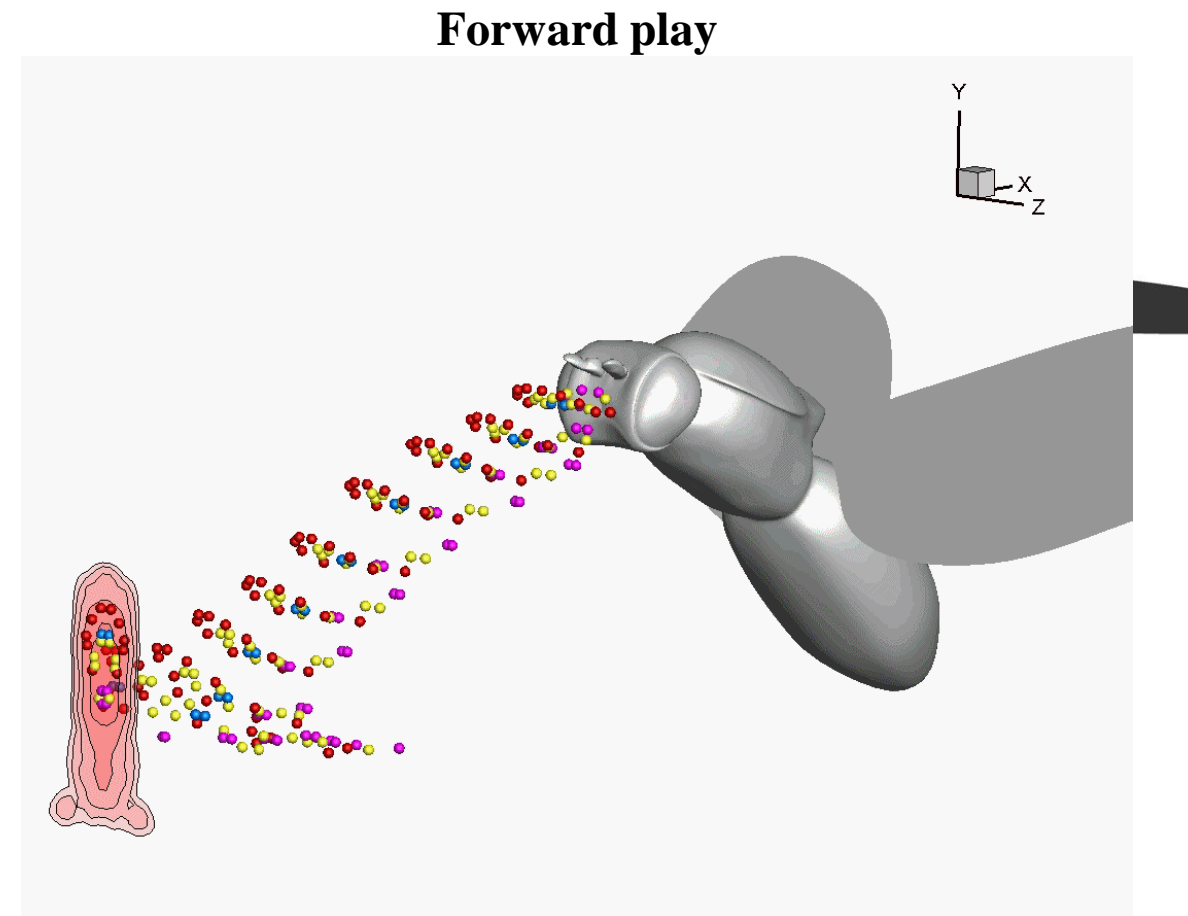
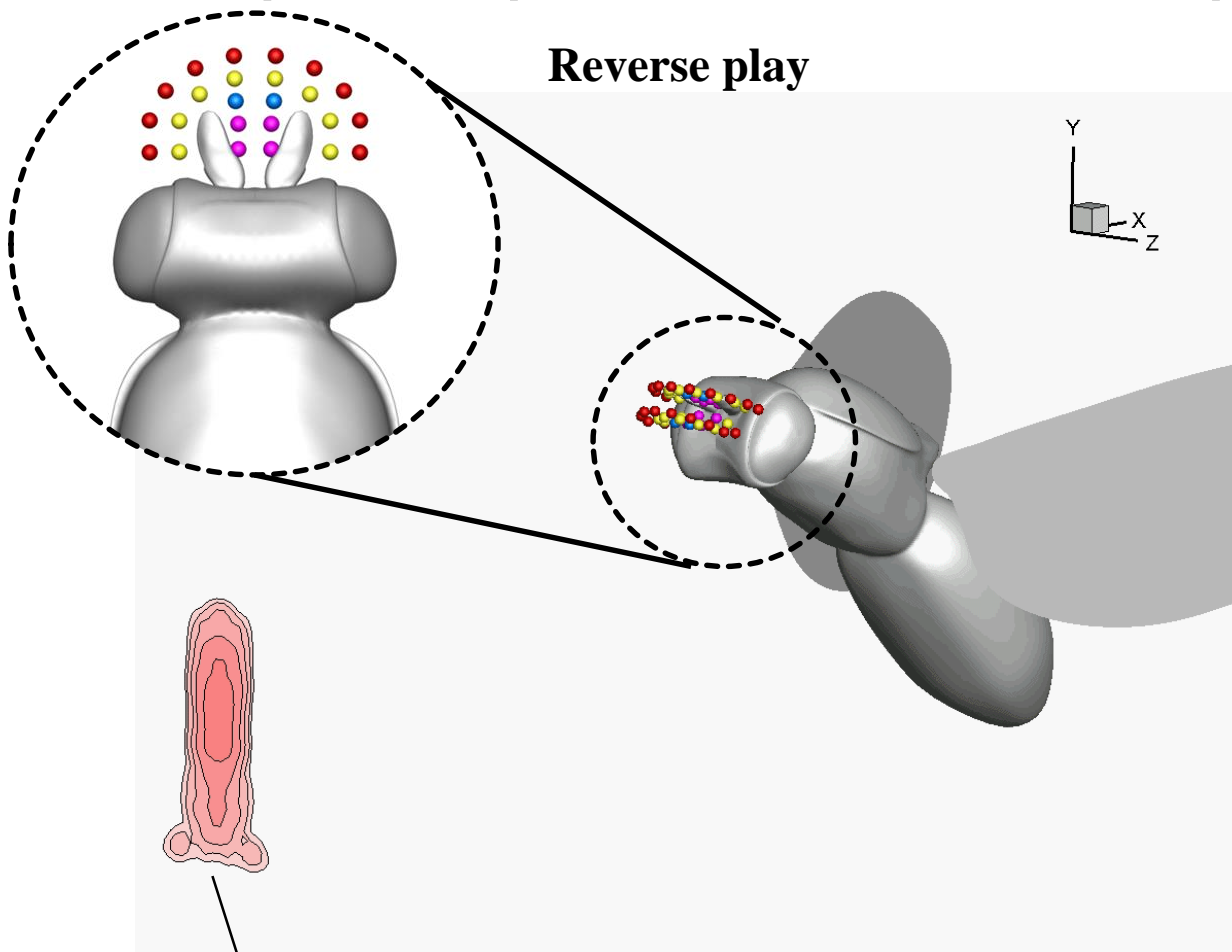


Fluid-Structure Interaction

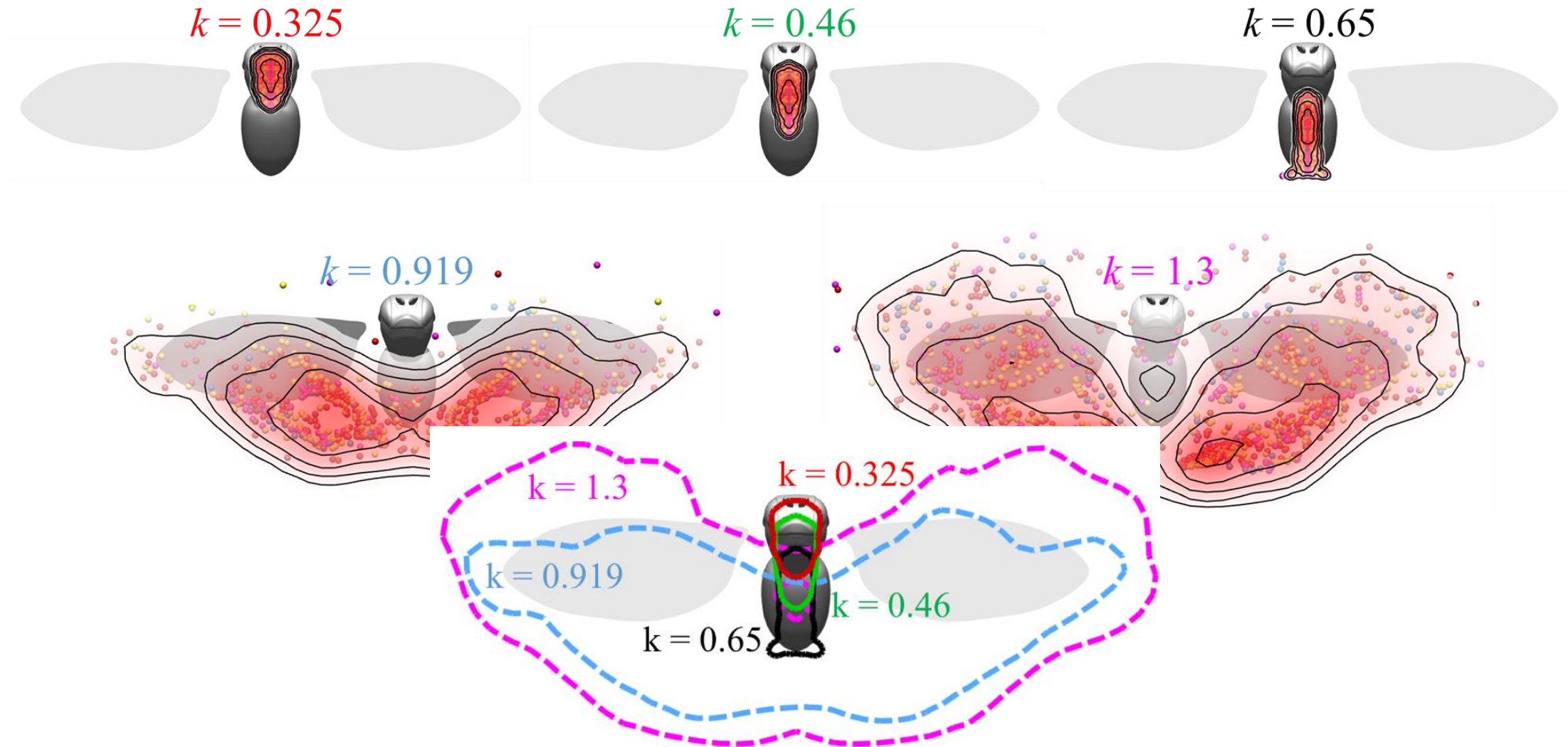


Plan for Year 1

- Specific Aim 2: Elucidate the influence of wing-induced flow on the spatiotemporal distribution of odor plume structures (Year 1-2)



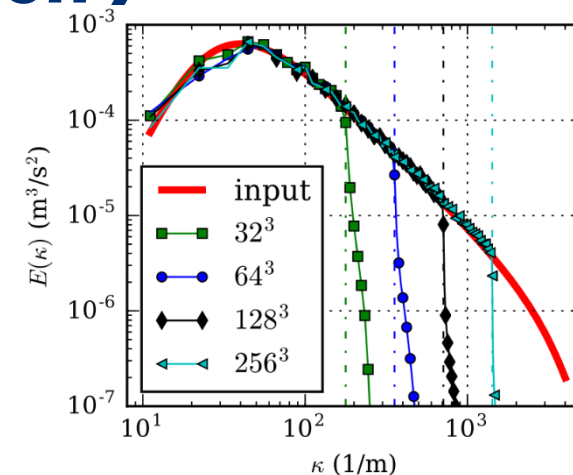
Odor Sampling Range



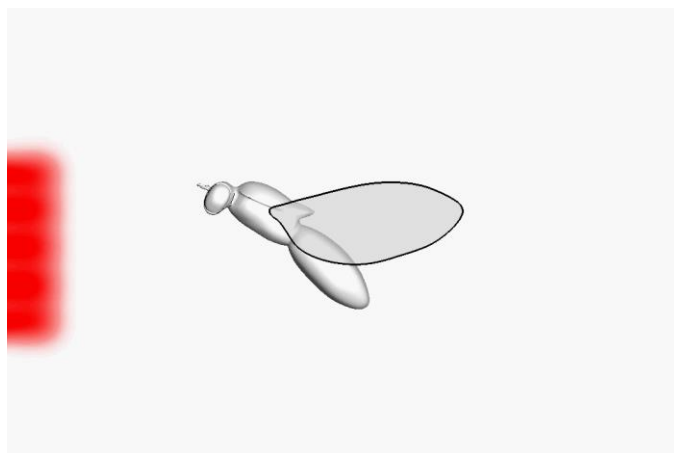
Effects of Turbulence Intensity

The von Kármán–Pao spectrum:
$$E(\kappa) = \alpha \frac{u'^2}{\kappa_e} \frac{(\kappa / \kappa_e)^4}{(1 + \kappa / \kappa_e)^{17/6}} \exp \left[-2 \left(\frac{\kappa}{\kappa_\eta} \right)^2 \right]$$

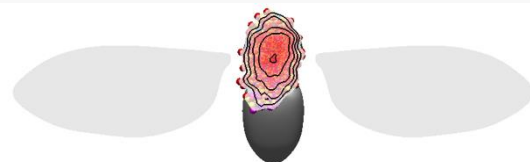
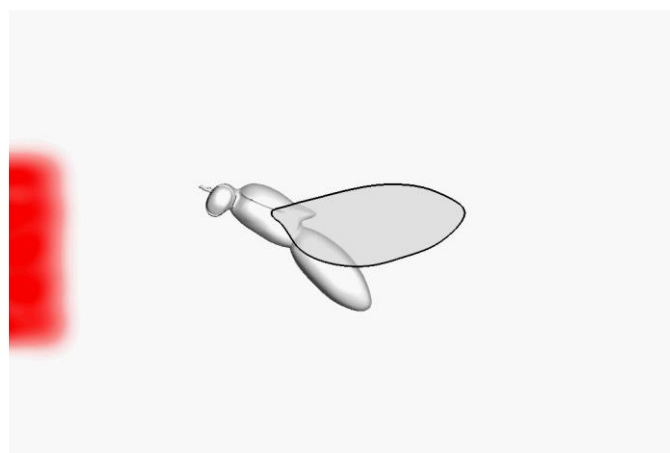
Synthetic velocity components:
$$\mathbf{u} = 2 \sum_{m=1}^M q_m \cos(\boldsymbol{\kappa}_m \mathbf{x} - \psi_m) \boldsymbol{\sigma}_m$$



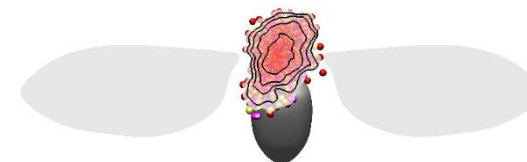
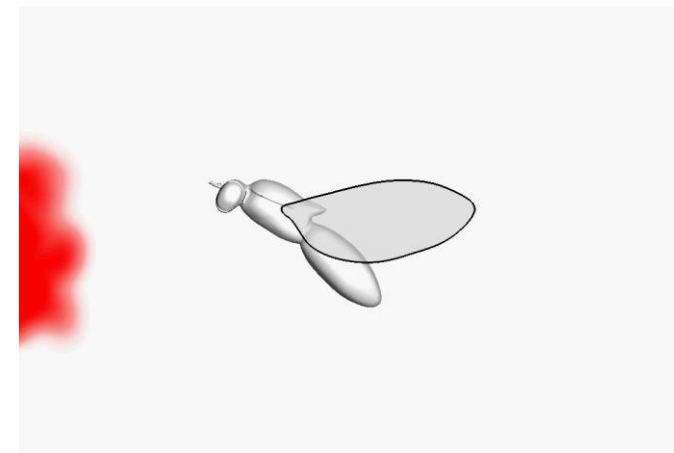
$k = 0.325$



$Tu = 0$

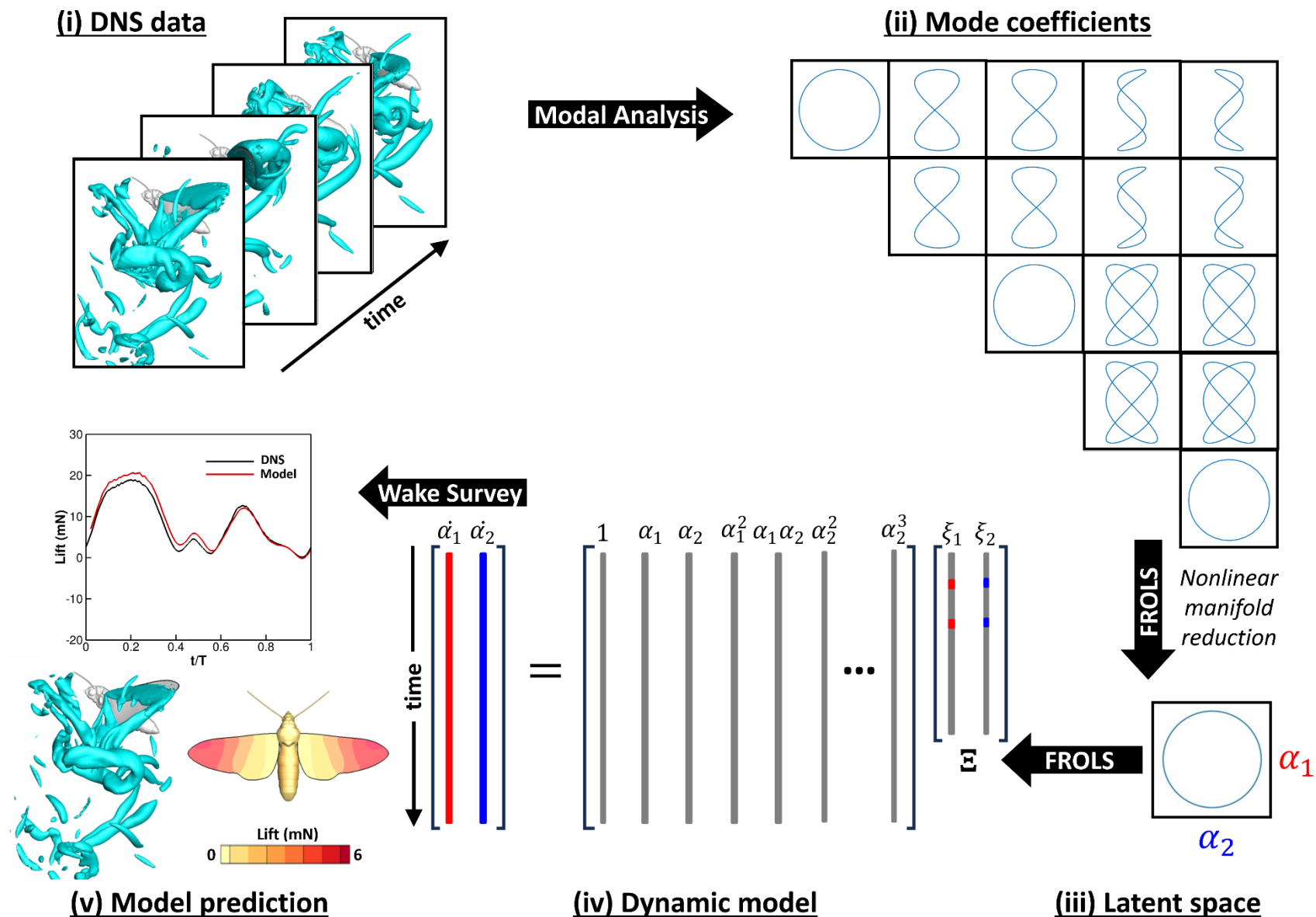


$Tu = 0.3$



$Tu = 0.9$

Extract Interpretable and Generalizable Models



Accomplishments

■ Journal Publications

- Lou, Lei, Dong, and Li, Wing-antenna interaction reduces odor fatigue in butterfly odor-tracking flight, *Journal of Fluid Mechanics*, in press, 2024
- Lionetti, Lei, Hedrick, and Li, Benefits of low-speed flight in odor-tracking navigation for hawkmoths, *Physical of Fluids*, under review, 2024

■ Conference Proceedings

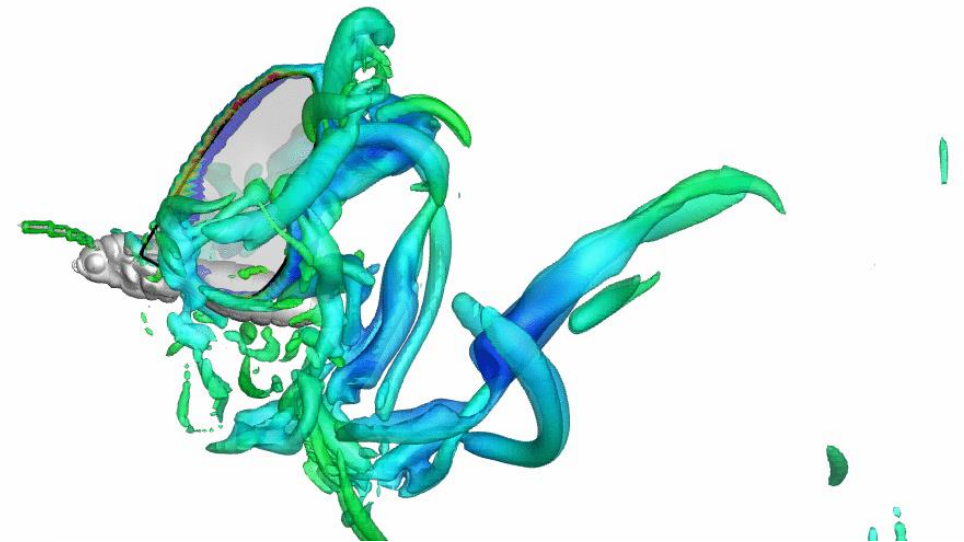
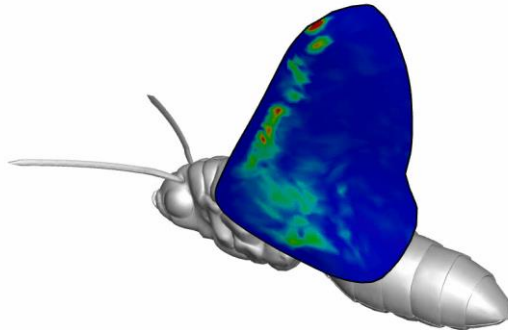
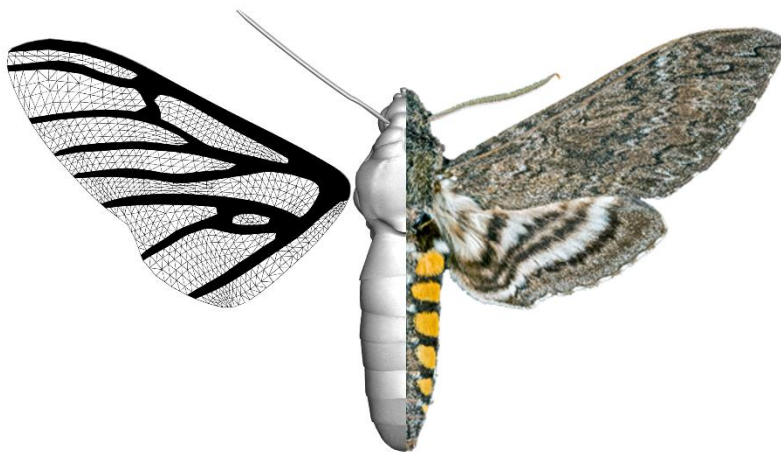
- Lionetti, Hedrick, and Li, Sparse reduced-order modeling of a hovering hawkmoth's wake, ASME FEDSM, 2024

■ Conference Abstracts

- Lionetti and Li, Data-driven reduced-order modeling of a flying hawkmoth's wake, APS DFD, 2024
- Haider, Lionetti, Lou, and Li, Effects of wing damage on aerodynamic performance and structural integrity in flapping wings, APS DFD, 2024

Summary

- We have conducted 3D fluid-structure interaction simulations of insect wings by solving both Navier-Stokes equations for the flow and nonlinear structural equations for the wing.
- We will characterize the impact of wing-induced unsteady flow on mechanical stimuli across a range of scales (i.e., ~ 2 mm for fruit flies and ~ 10 cm for hawkmoth) and wingbeat frequencies (i.e., ~ 20 Hz for hawkmoth and ~ 200 Hz for fruit flies).



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■ Lab Members:



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Thank You for Your Attention!

Questions?