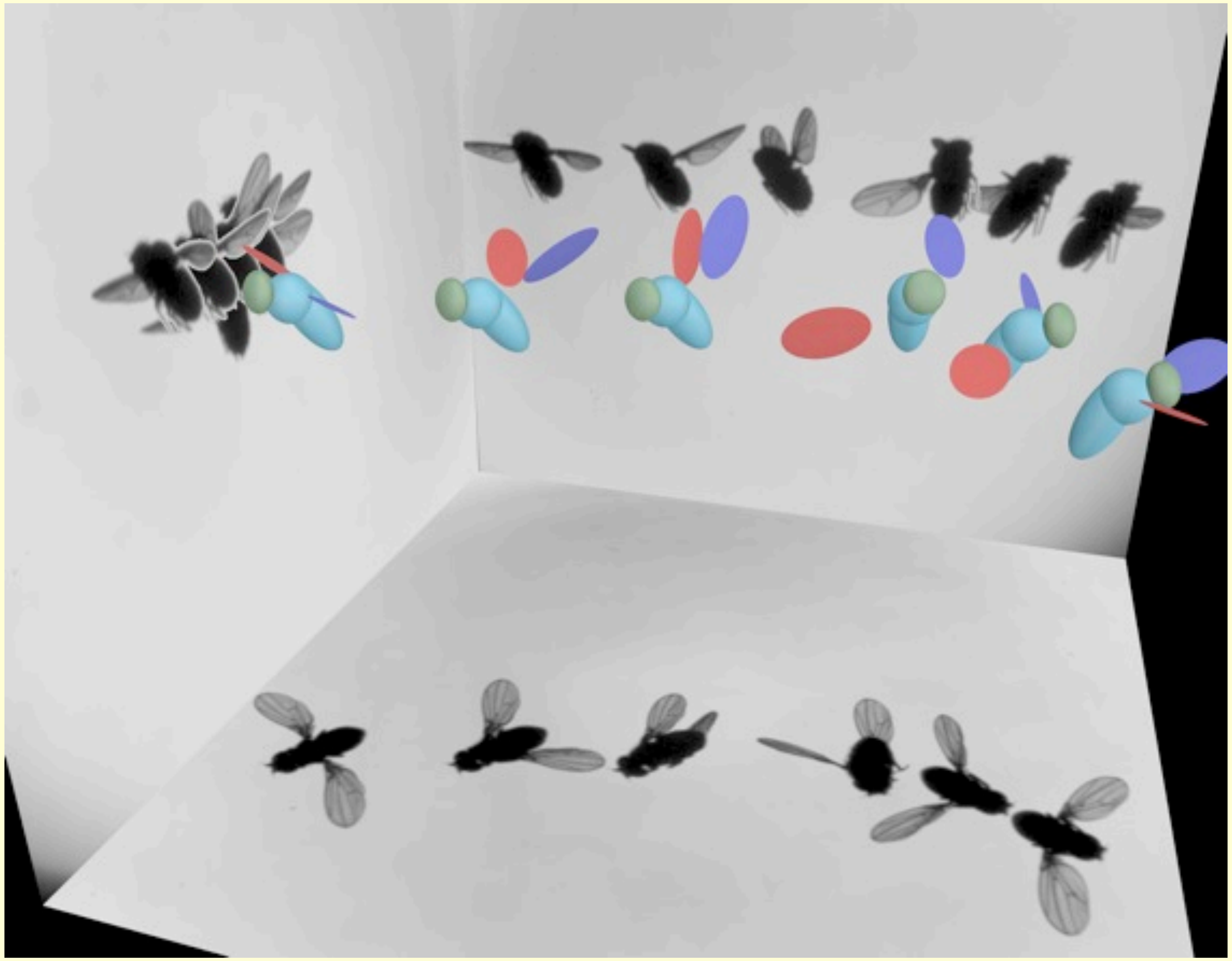
Insect Flight

movement and thoughts



Jane Wang
Cornell University

Students/Collaborators:

Aerodynamics of Dragonfly Flight/ Falling Paper

David Russell, Anders Andersen,Umberto Pesavento

Computational Fluid Dynamics:

Sheng Xu

Flight Dynamics of Fruit flies:

Leif Ristroph, Attila Bergou, Gordon Berman
Itai Cohen, John Guckenheimer

Stability Analysis of Insects in Free Flight:

Song Chang

Papers:

http://dragonfly.tam.cornell.edu

Support:

NSF, AFOSR, ONR, Packard Foundation

Quantitative Study of Organismal Behavior

from flight dynamics to neural dynamics

neural science

visual stimulus

visual neurons

motor neurons

muscle actuation

wing motion

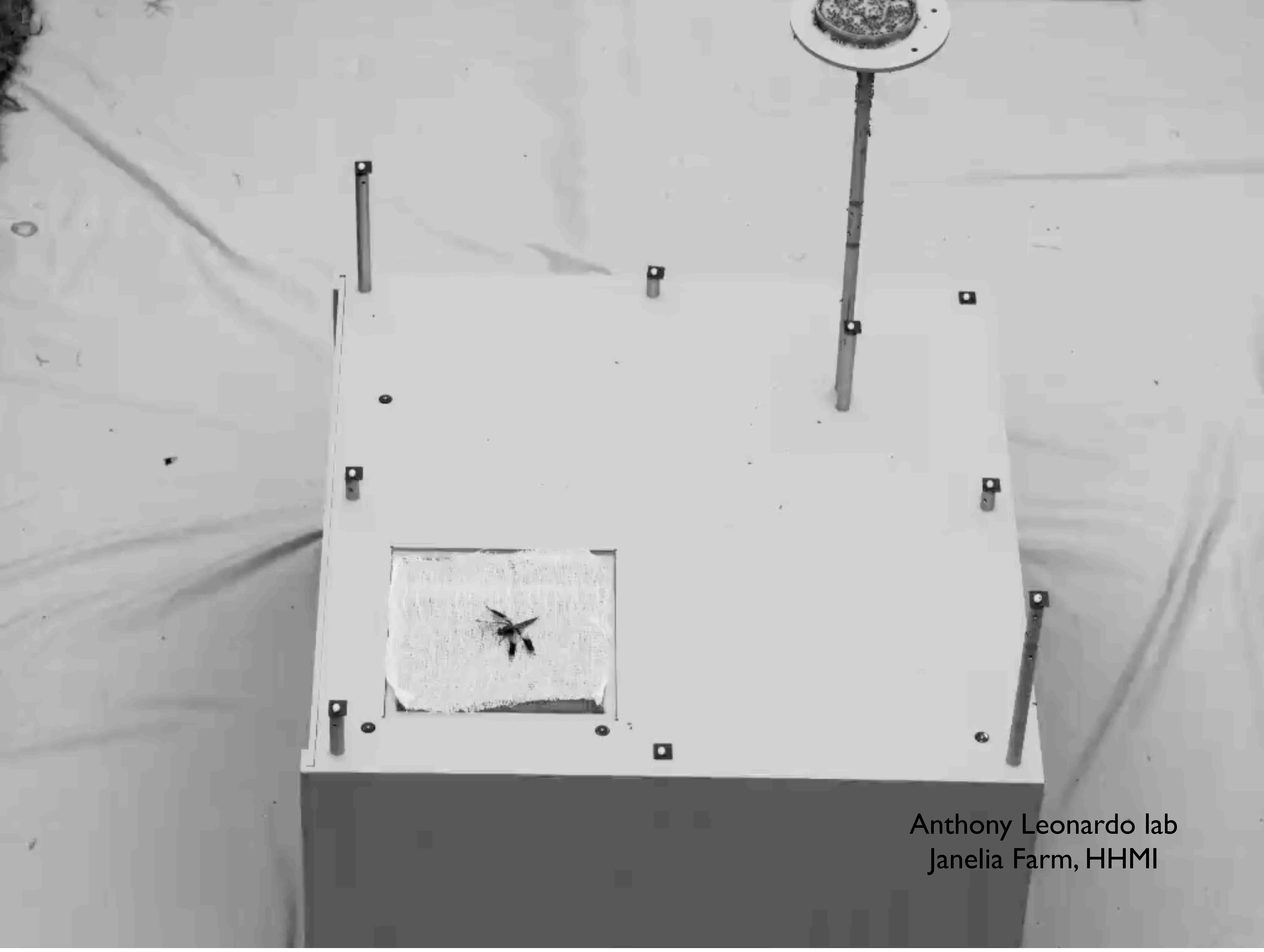
body motion

physics of flight

aerodynamics

3D flight dynamics

Why Do Organisms Move the Way They Do?


Anthony Leonardo lab
Janelia Farm, HHMI

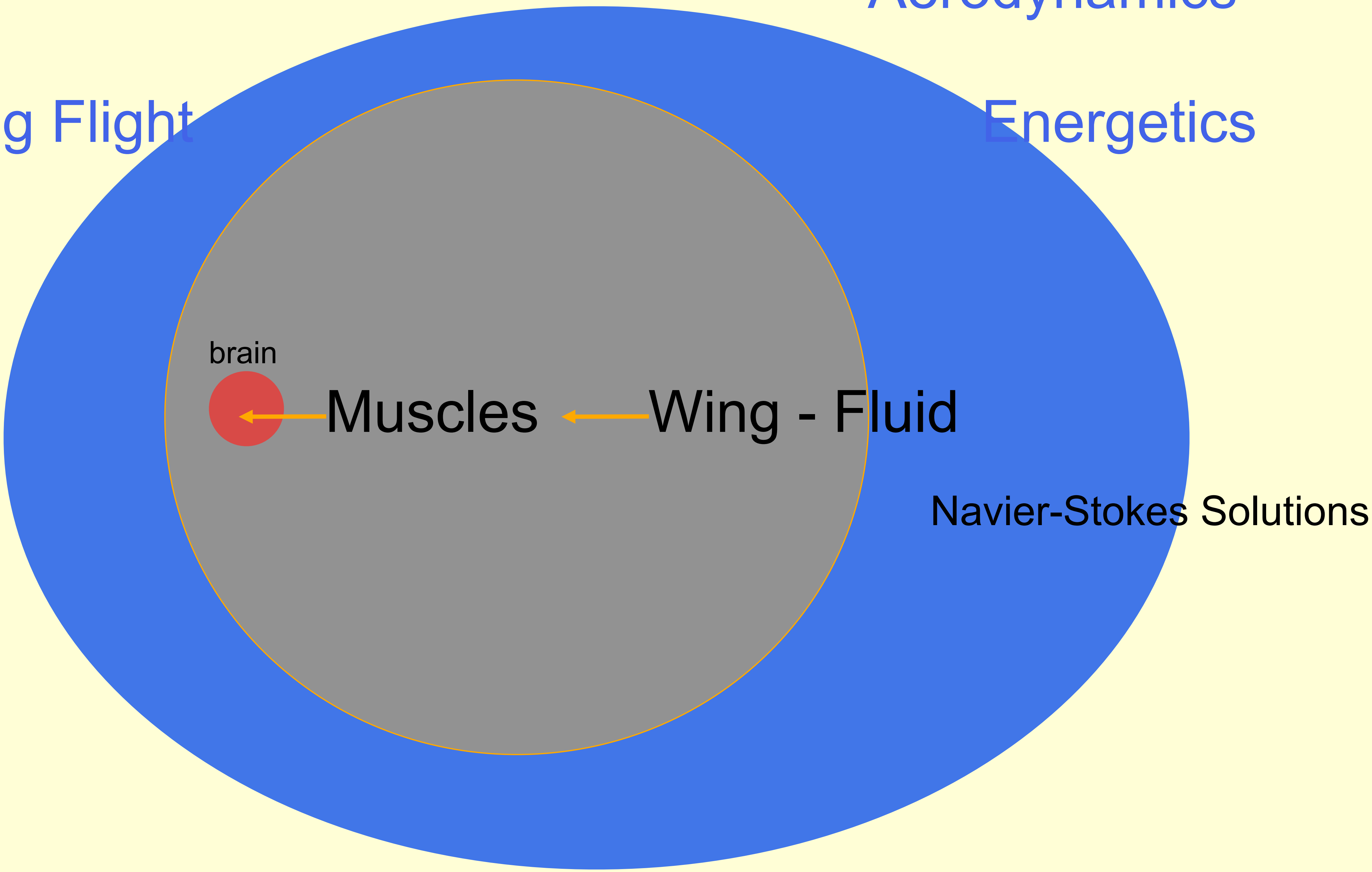
Dissecting Insect Flight

Dynamics

Aerodynamics

Maneuvering Flight

Energetics



Taking It Apart

I. Kinematics

II. Aerodynamics and Computational Methods

III. Energetics and Optimization

IV. Dynamics and Control

V. Stability and Control

Le vol d'un pélican vu de profil.

MAREY ET LE VOL DES OISEAUX

Les premières études scientifiques des mouvements des êtres vivants sont l'œuvre d'Étienne-Jules Marey. Le rôle de Marey dans les recherches concernant le vol des oiseaux a été considérable.

Entre 1860 et 1880, il a essayé nombre d'appareils de mesure, la plupart basés sur son « tambour » pneumatique transmettant les mouvements à un style inscripteur. Les expériences de Marey ont porté également à cette époque sur la synthèse des mouvements des ailes. En 1882, reprenant une idée de Pénaud, Marey fut le premier à réussir, grâce à l'appareil chronophotographique à plaque fixe avec disque obturateur, des images successives d'oiseaux en vol, rapprochées jusqu'à cinquante par seconde ou espacées et dissociées grâce à un miroir tournant. Combinant trois appareils, en 1883, Marey obtint simultanément sur fond noir trois vues : de profil, de dessus et de trois quarts.

Marey créait en 1882 le fusil photographique à plaque circulaire mobile, puis, en 1888, il remplaçait la plaque fixe du chronophotographe par une bande de papier sensible située au foyer et se déplaçant de façon intermittente régulière avec arrêts aux passages des trous du disque obturateur. En 1889 et 1890, Marey perfectionnait cet appareil par l'introduction de bandes sensibles en celluloïd, puis transparentes, et, en 1892, il projetait sur un écran les séries d'images obtenues.

Les travaux chronophotographiques de Marey forment la base de l'invention de la cinématographie.

A la fin de sa carrière, Marey étudia au moyen de fumées les remous produits par différents corps ou placés dans un courant d'air.

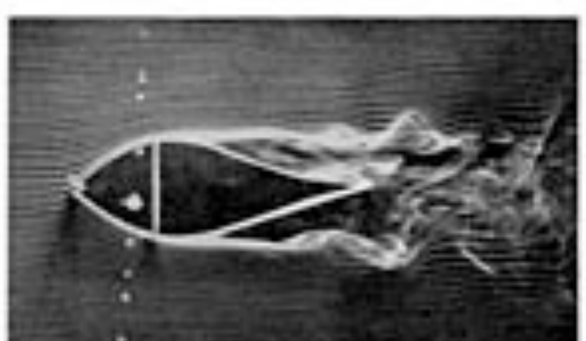
Étienne-Jules Marey, membre de l'Institut (1830-1904).

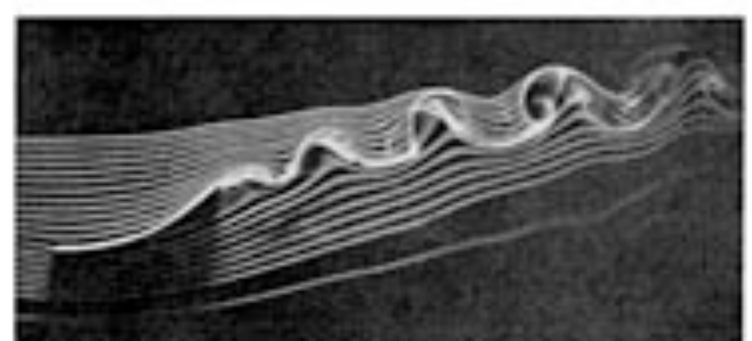
Chronophotographie avec images dissociées par l'emploi d'un miroir tournant (vers 1890).

Vol d'un canard (1882).

Phases du coup d'aile d'un goéland.

Envol d'un goéland.





Déformations des filets d'un courant d'air, marqués par de la fumée d'amadou, au contact d'un corps fuselé et d'une surface courbe (1900-1901).

E. J. Marey
1830-1904

Monday, September 30, 2013

difference, that an insect allowed to take flight after a string is tied to its leg can remain in the air without difficulty, while a bird similarly treated will fall to the ground as soon as the string is stretched. The apparatus of Professor Marey, as improved by him, is sufficient to determine, with the greatest precision, the number of beats of the wing per minute, as well as the particular curve of flight; and, among other observations, he informs us that, while the sparrow makes thirteen movements of the wing in a second, and the wild duck nine, the buzzard (*Buteo vulgaris*) beats its wings only three times in the same interval. As a general rule, he finds that the time occupied in depressing the wing is always decidedly longer than that of elevation, excepting in birds of a small wing area, in which case the two periods are almost equal. At starting the bird appears to make fewer strokes, but with a greater amplitude of stretch than subsequently. The rapidity of the stroke, on the other hand, appears to diminish anew when the bird has obtained a high degree of velocity.

The comparison of the two modes of flight may be summed up by saying, that in the bird the extremity of the wing describes a simple helix, while in the insect a series of lemniscates is traced. The difference in the two curves will be appreciable by an examination of the diagrams.

FLIGHT OF A BIRD.

FLIGHT OF AN INSECT.

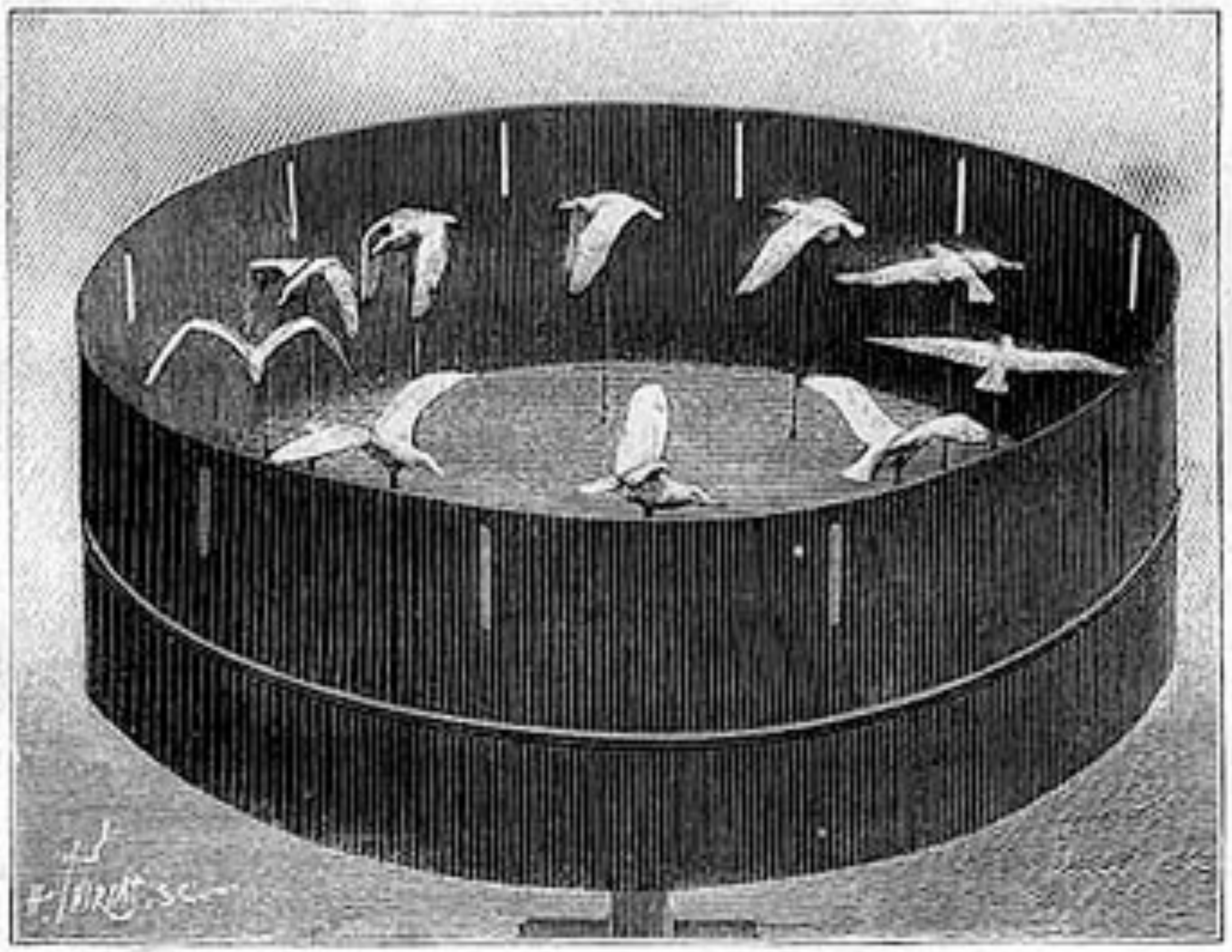
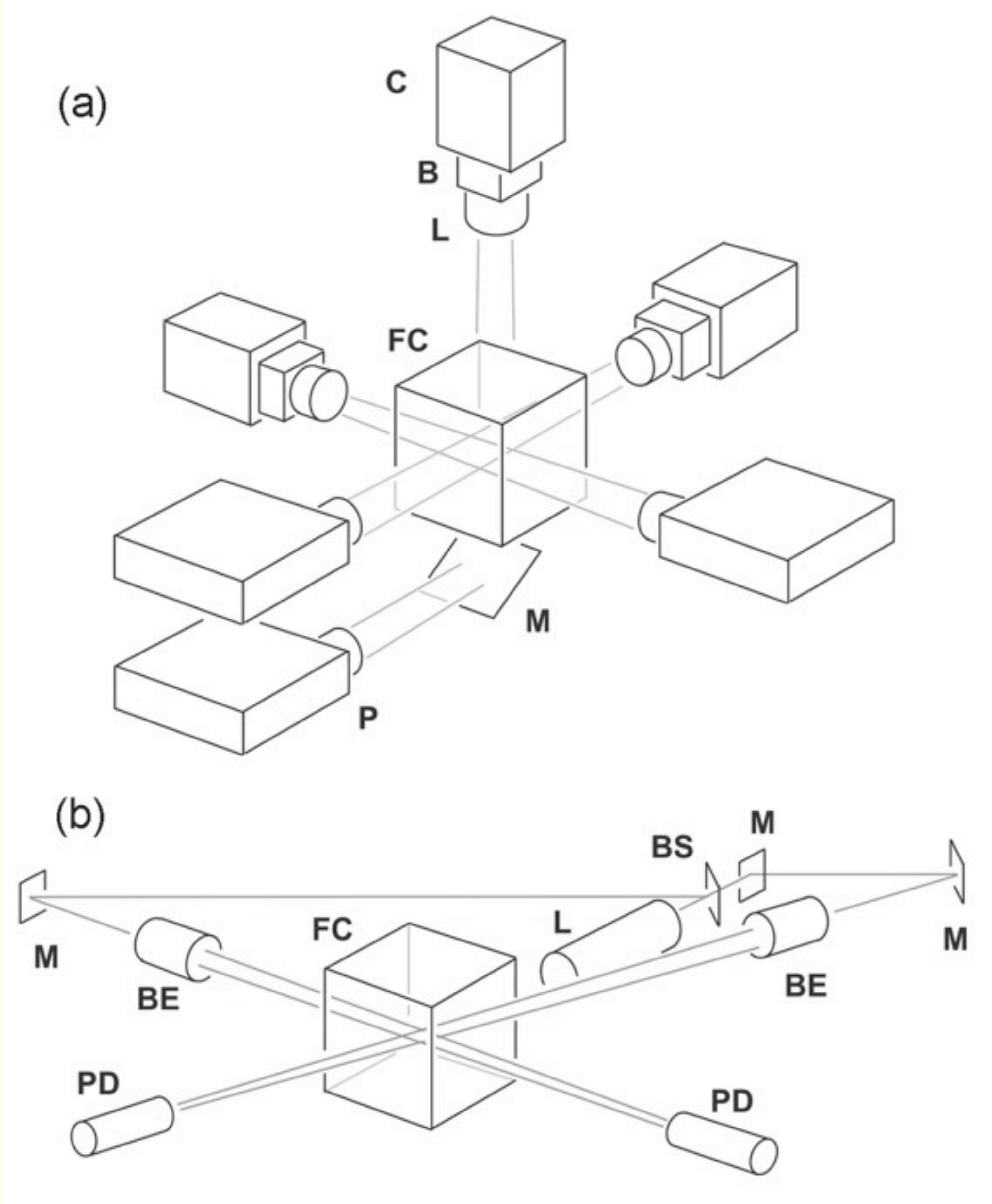


Fig. 9. — Zootrope dans lequel sont disposées 10 images en relief d'un goéland dans les attitudes successives du vol.

Harper Magazine
1870

Other previous work:
Weis-Fogh and Jensen (1956)
Ellington (1984)
Fry, Sane, Dickinson (2003)

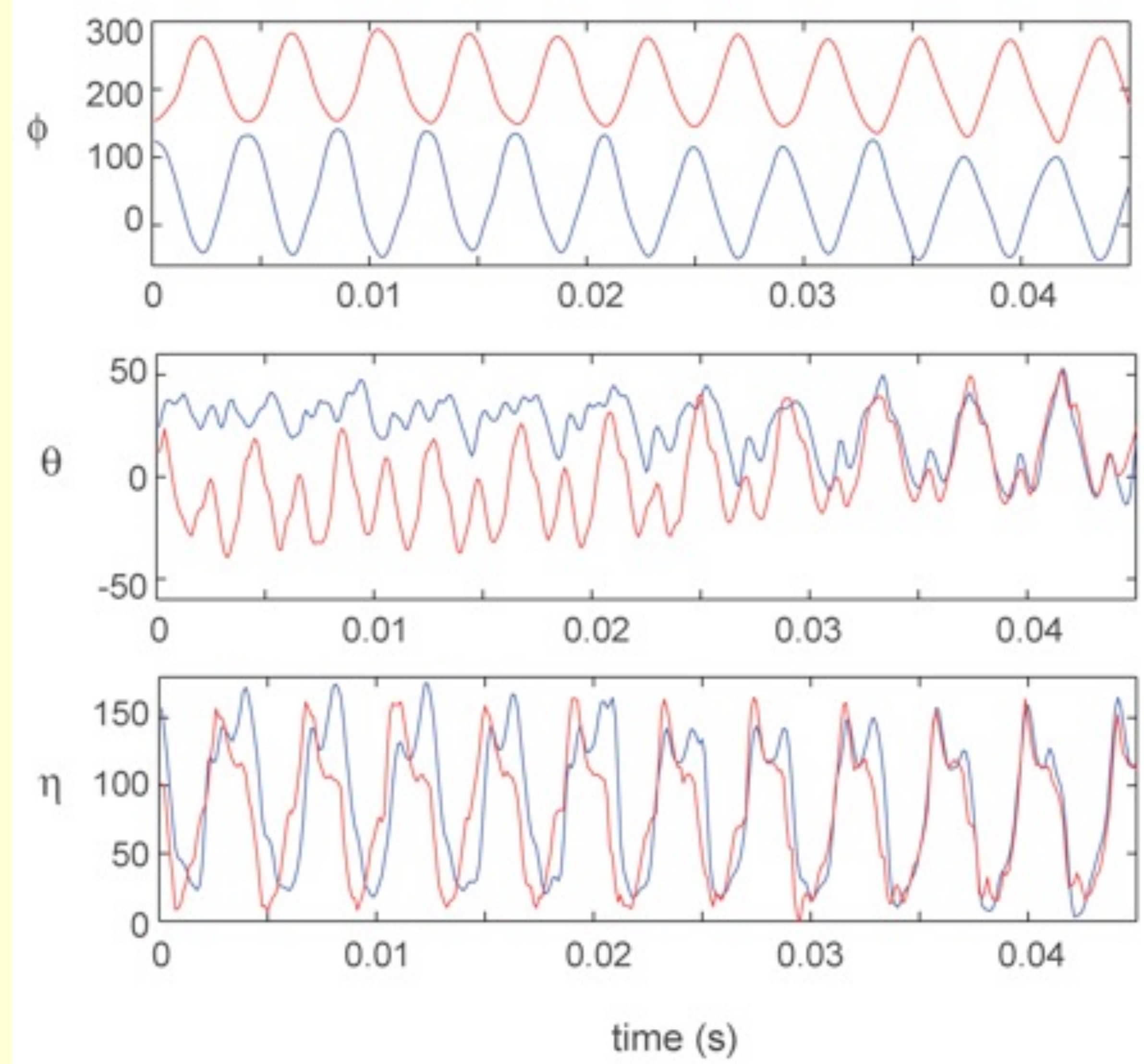


Leif Ristroph and Itai Cohen

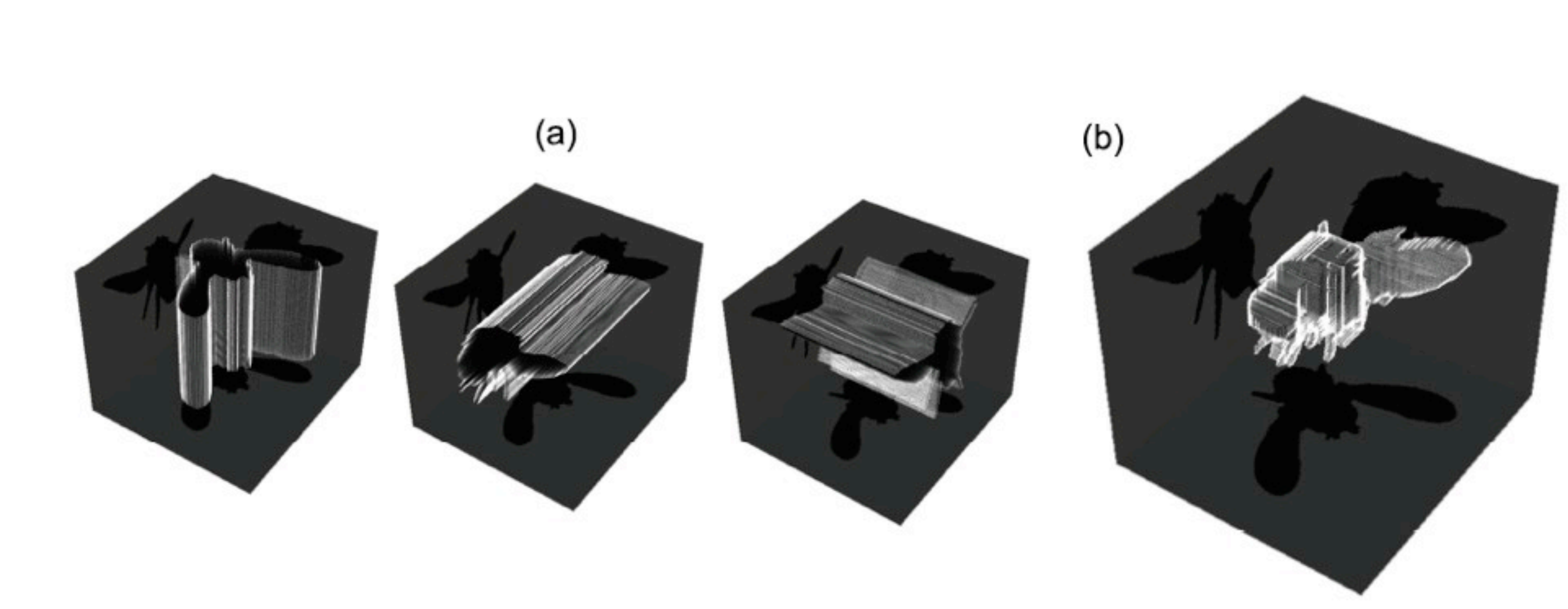
Subtle change of wing kinematics

Lots of data

--> high accuracy & statistics
in tracking



Automatic Tracking of Wing and Body Motions (without using markers)



Ristroph, Berman, Bergou, Wang, Cohen, J. Exp. Biol.(2009)

Automatic Tracking of Wing and Body Motions

1. Visual hull (maximal volume encompassing the fly)

2. Clustering Algorithm (separate body and wings)

3. Centroid (position)

4. Principal axes (orientation)

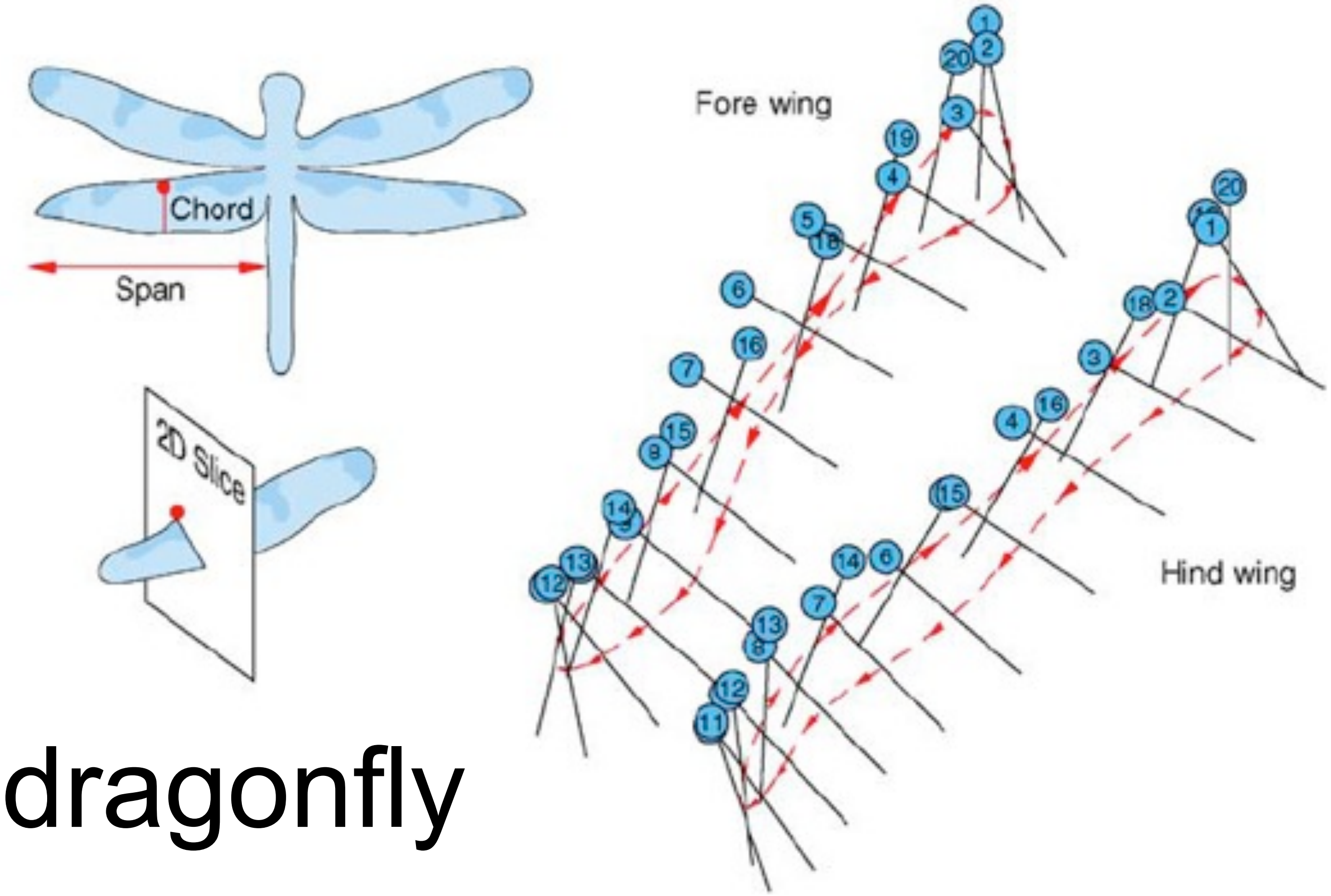
+ camera calibration and etc.…

hours

reduced to

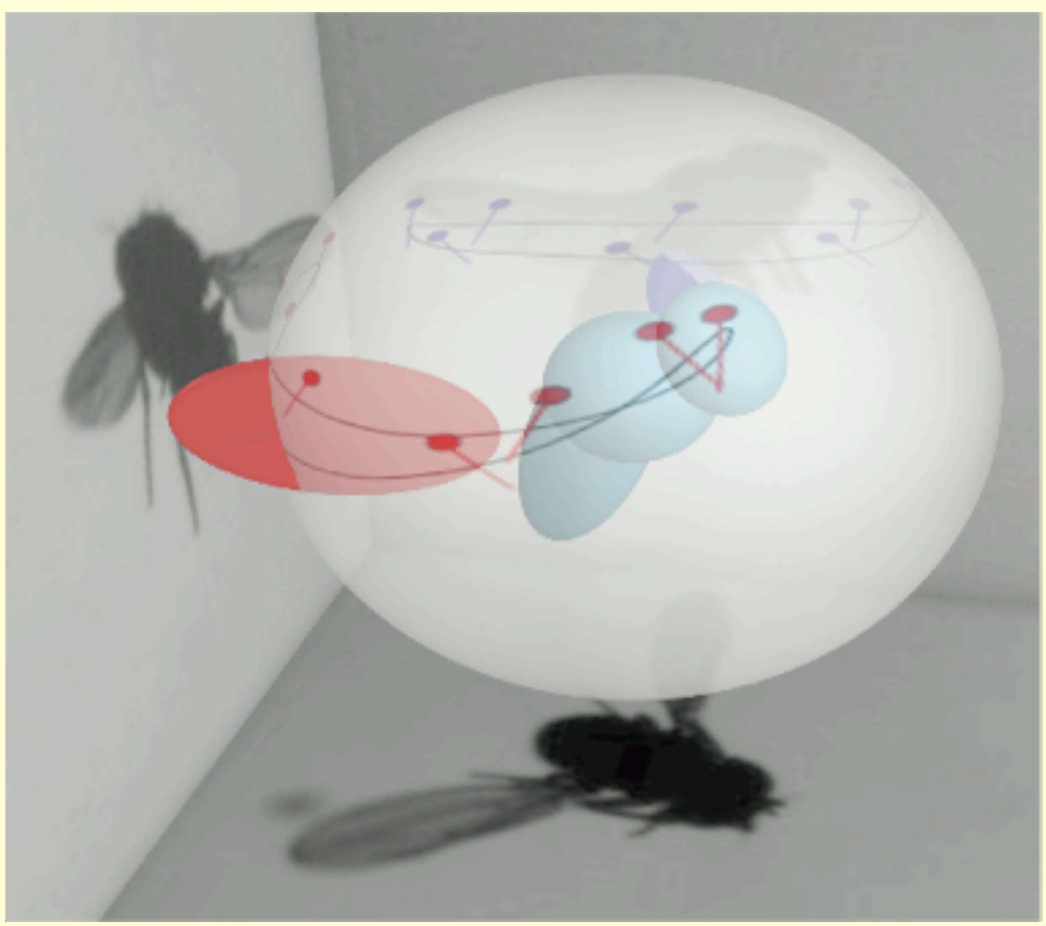
minutes

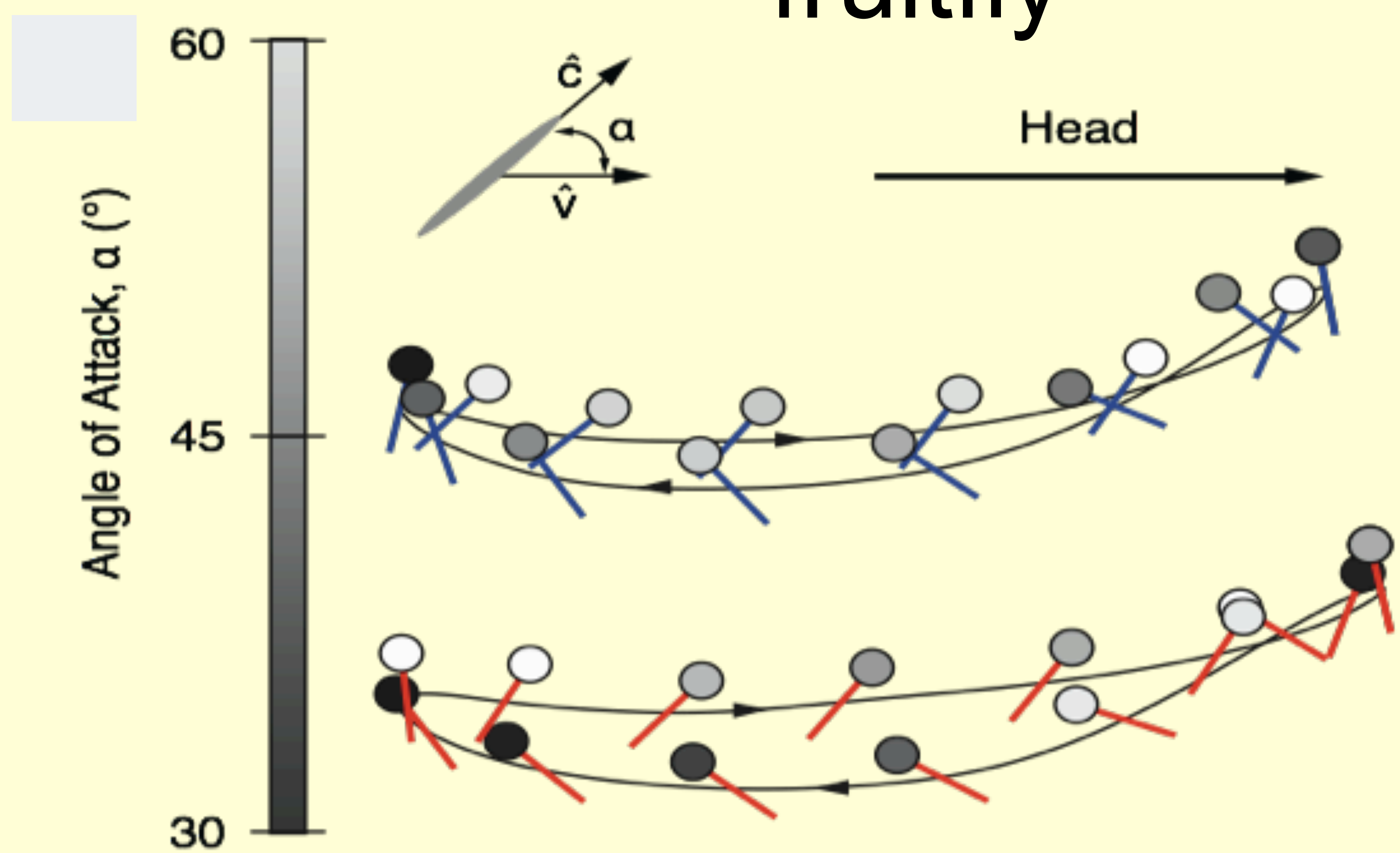
Why the Observed Motions?



dragonfly

fruitfly





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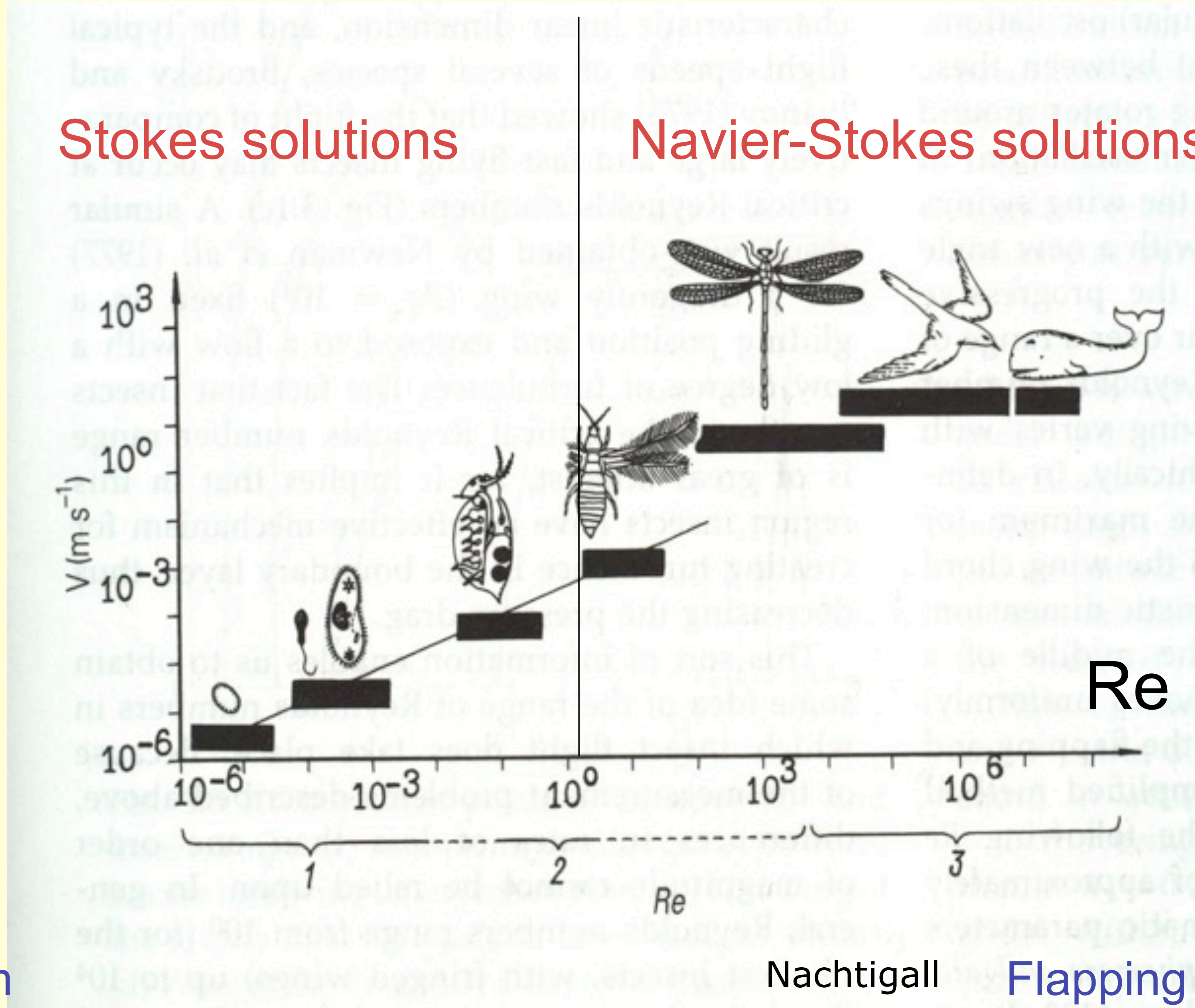
Life in Fluids



Nachtigall

Scallop theorem
Flagellar/Cillia swimming
Rotating helix/Helical wave/undulatory motion

Flapping flight/swimming
Gliding
Airplanes

G.I.Taylor, 1951, 1952 Swimming Micro-organisms
Purcell,1977 Life at Low Reynolds numbers
Lauga and Powers 2009

Lighthill, 1975
Childress, 1981
Ellington 1984, Dickinson1999
Wang 2005

Governing Equations

Navier-Stokes equations for incompressible flows:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \tfrac{1}{\mathrm{Re}} \nabla^2 \mathbf{u}$$

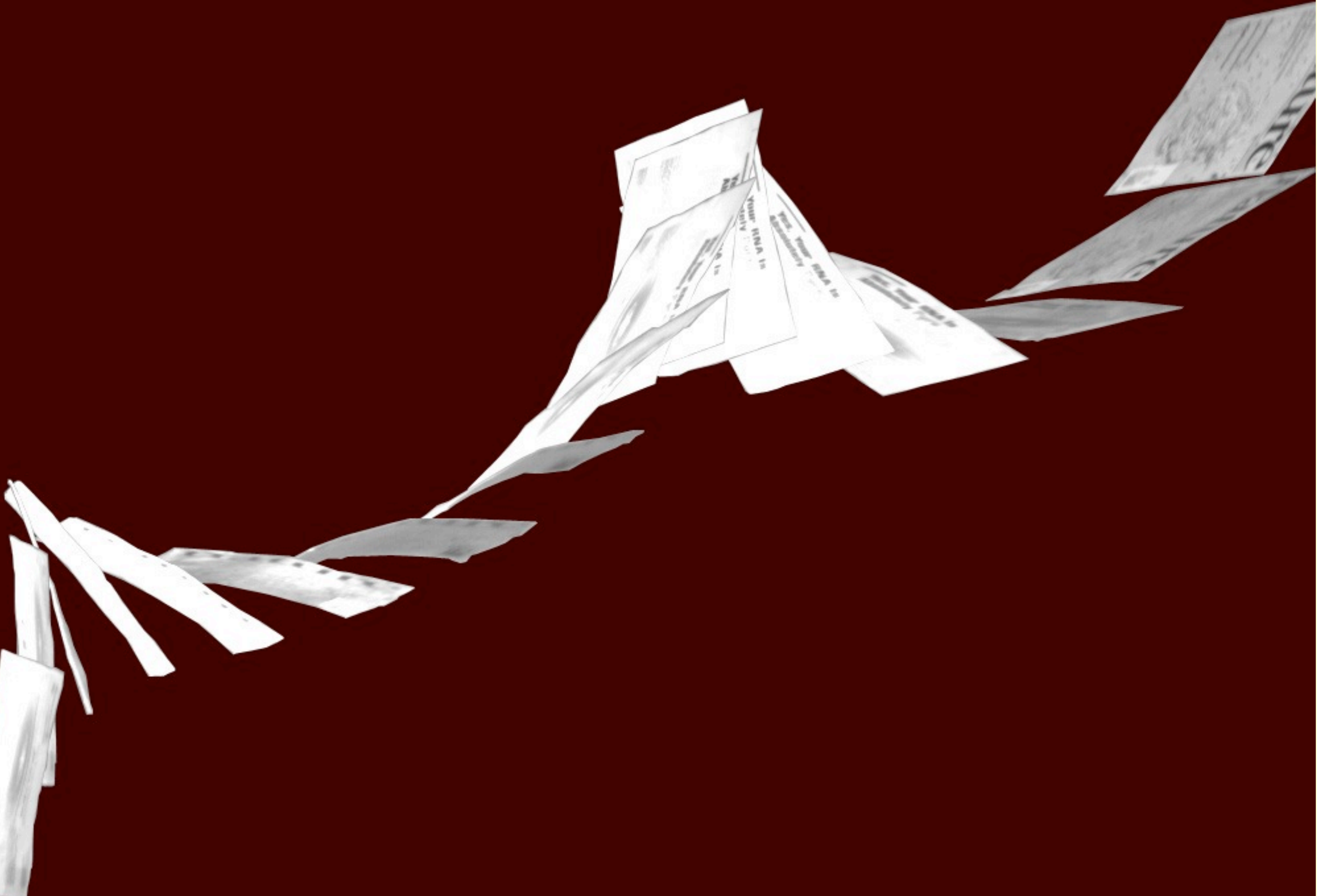
$$\nabla \bullet \mathbf{u} = 0$$

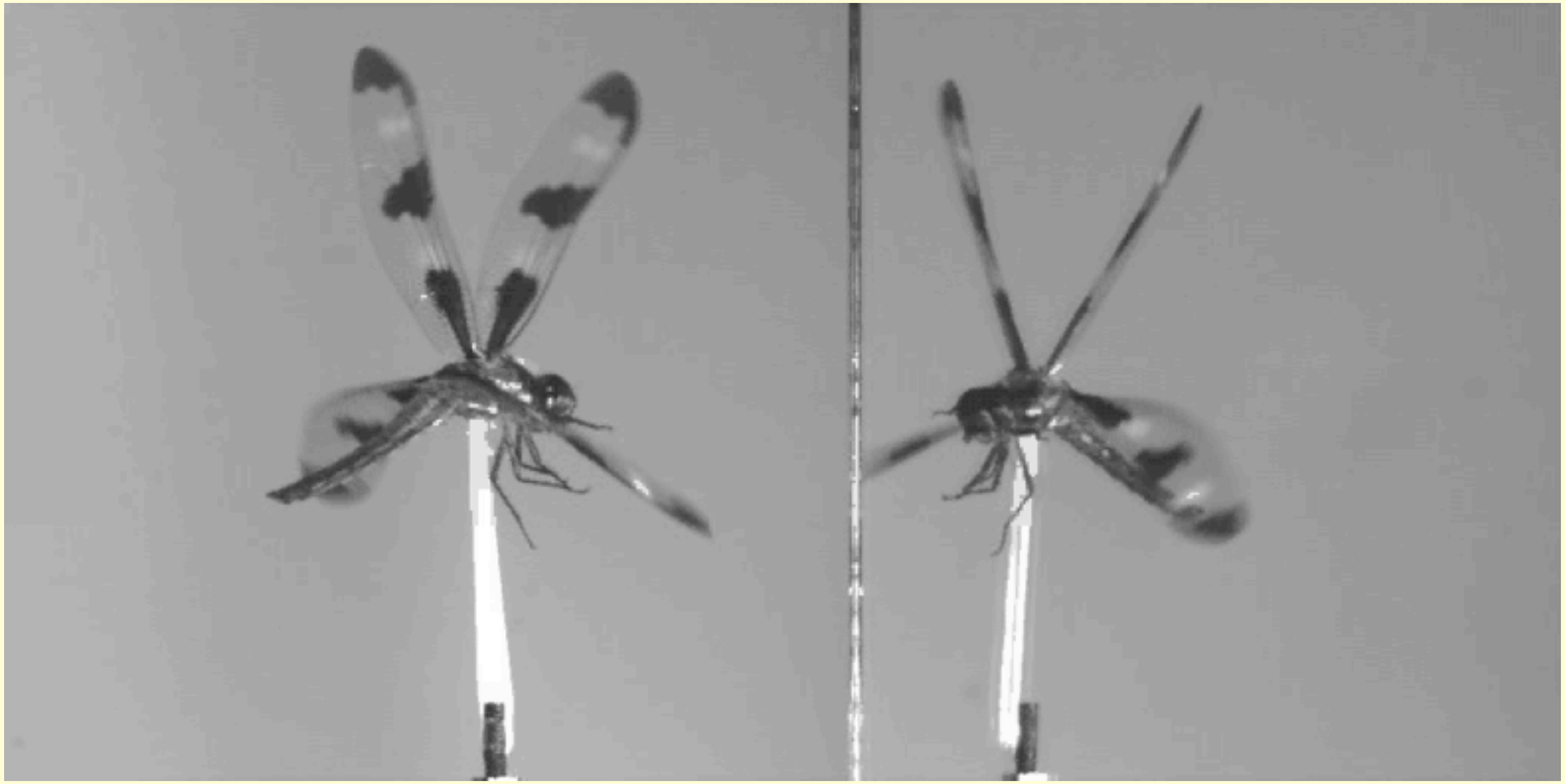
Boundary condition (no-slip) (wing kinematics):

$$\mathbf{u}_b = \mathbf{v}_b$$

Dynamics of the wing coupled to the fluid:

$$m \frac{d\mathbf{v}_b}{dt} = \mathbf{F}_{fluid} + F_{ext}$$

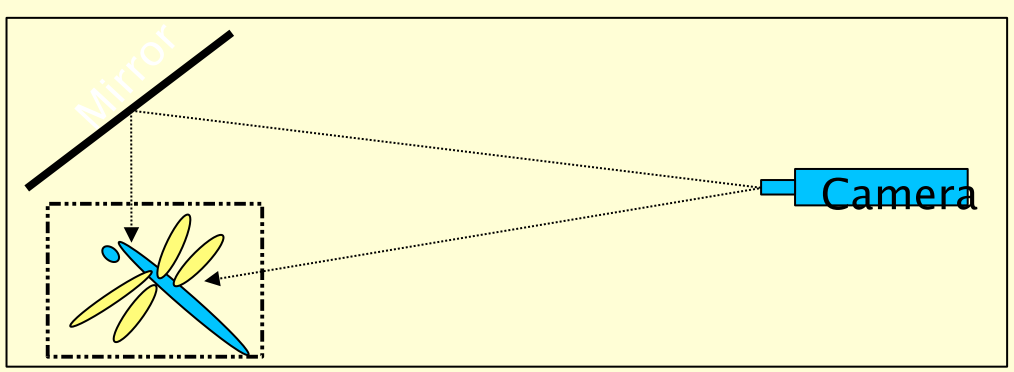


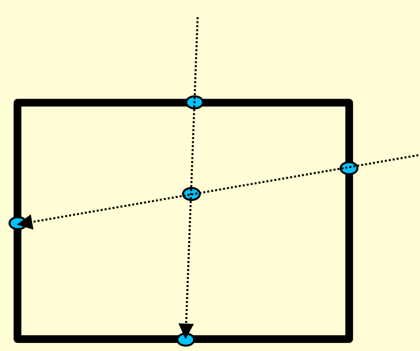


marker based tracking

1600fps,1024x1024

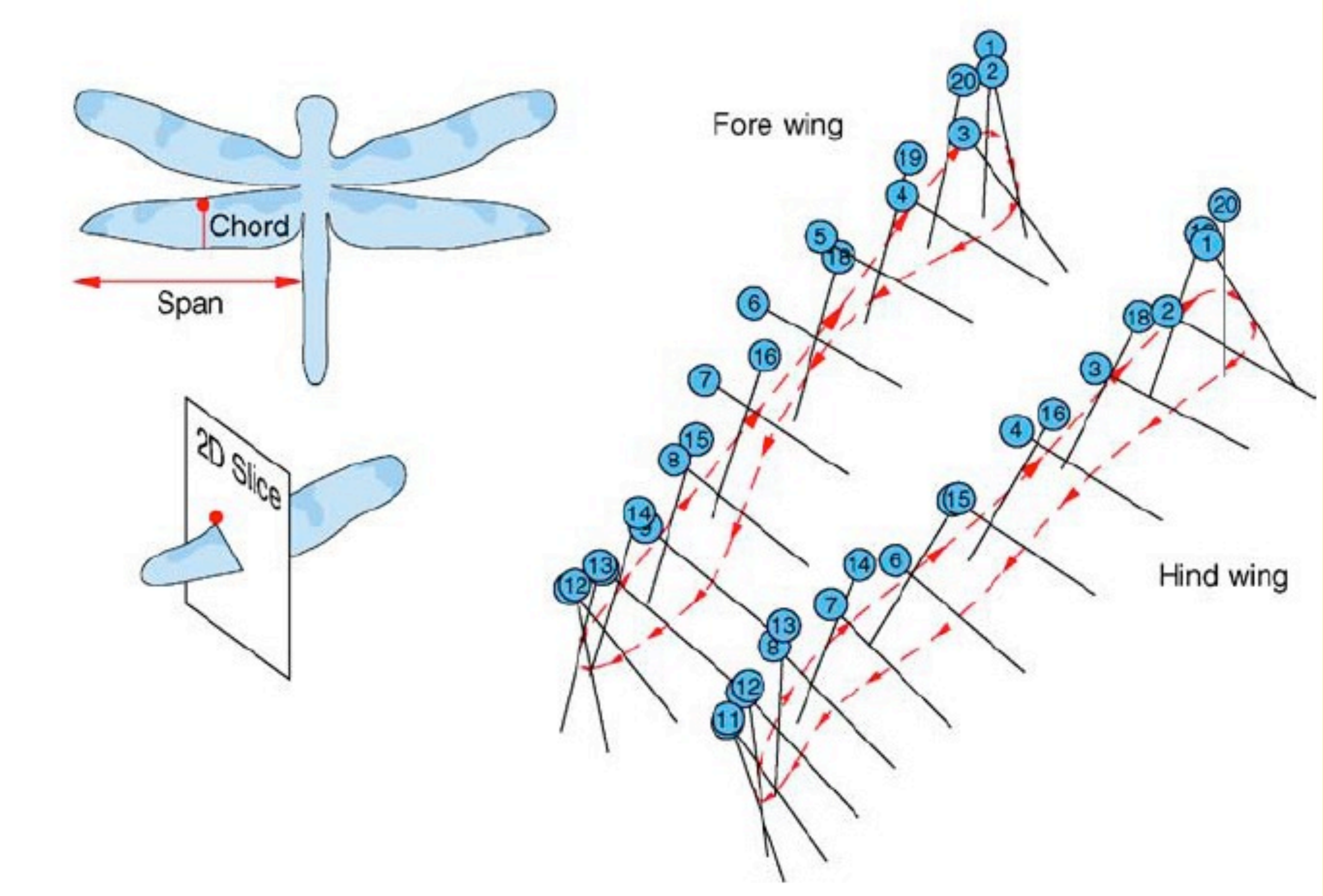
mirror





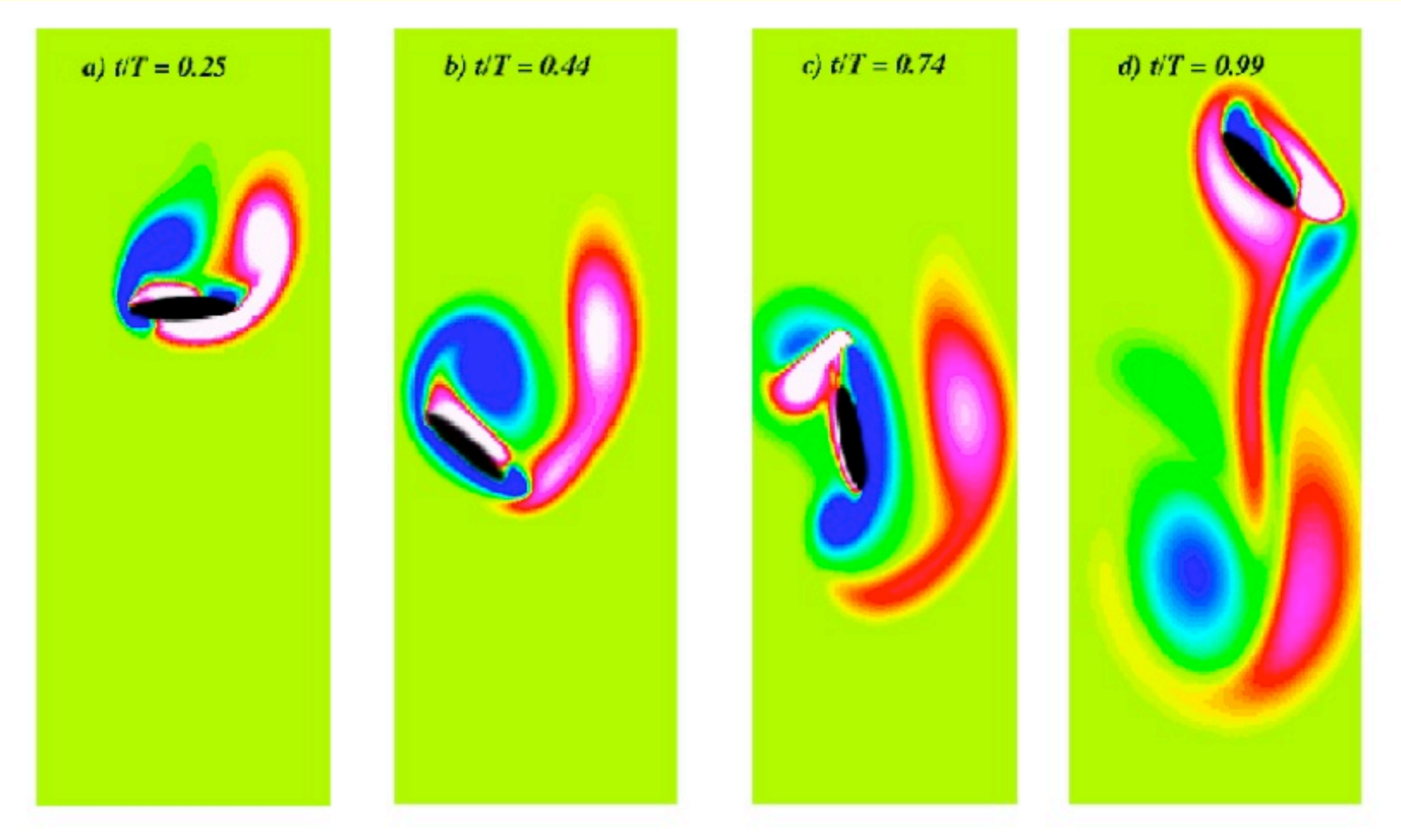
L ~ 1cm
Freq ~ 40Hz
Re =UL/ν ~ 3000

Wing Kinematics



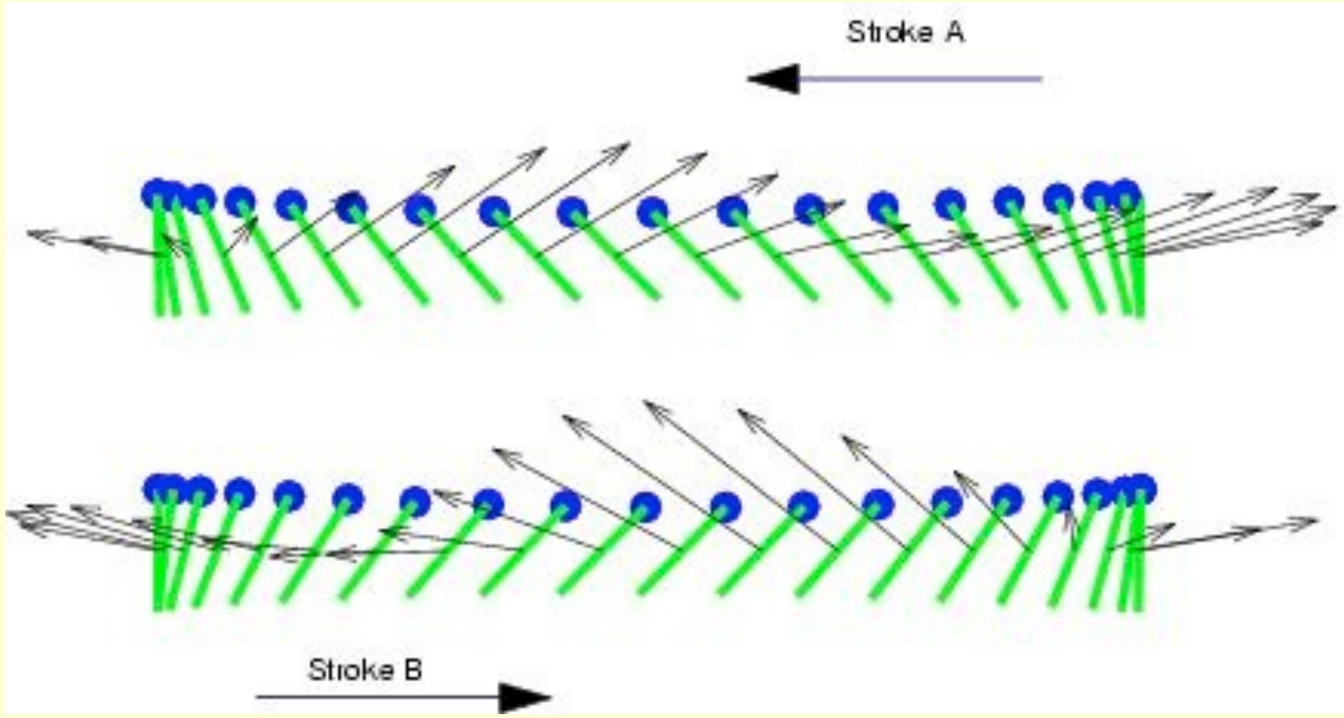
How does an insect flap its wings

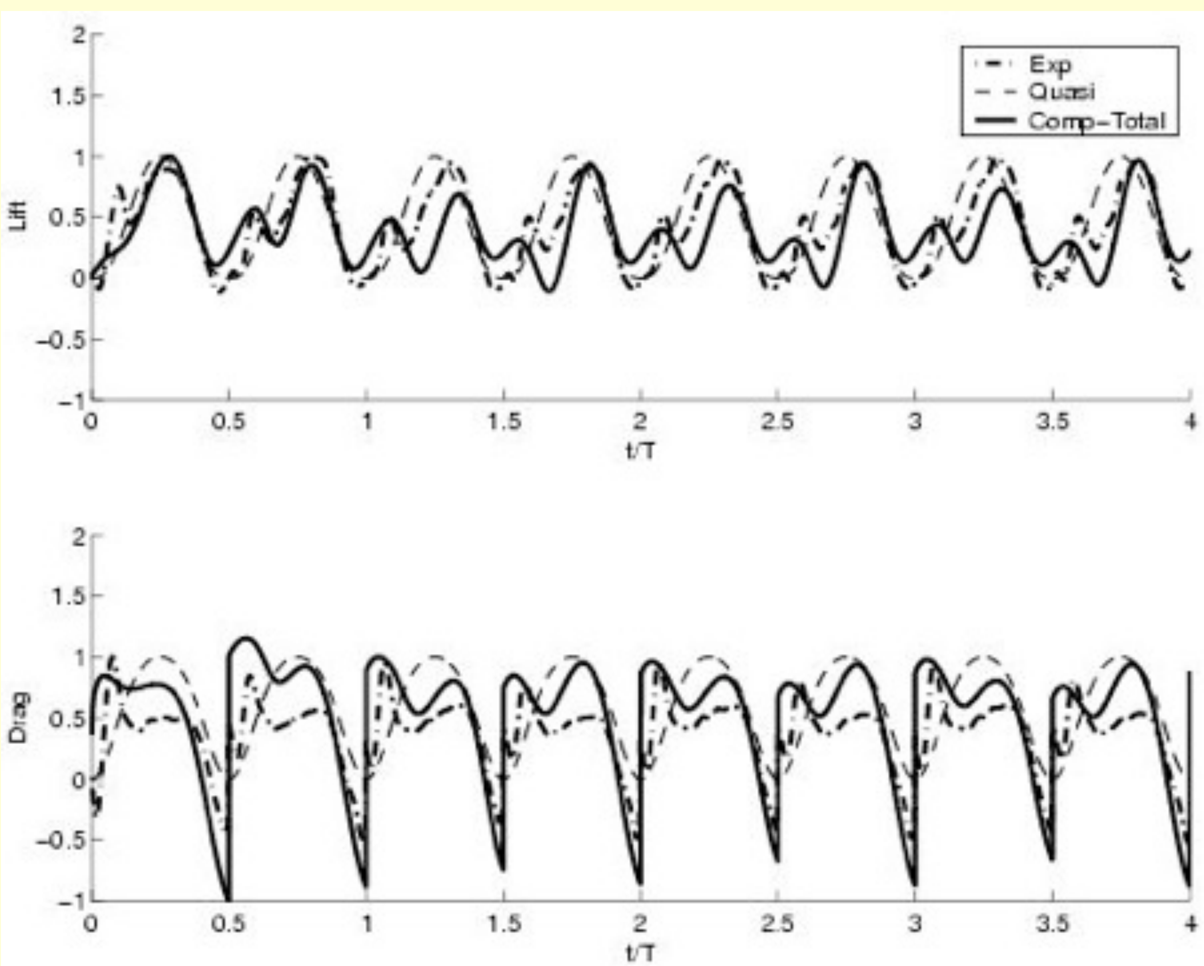
to generate enough forces to hover?

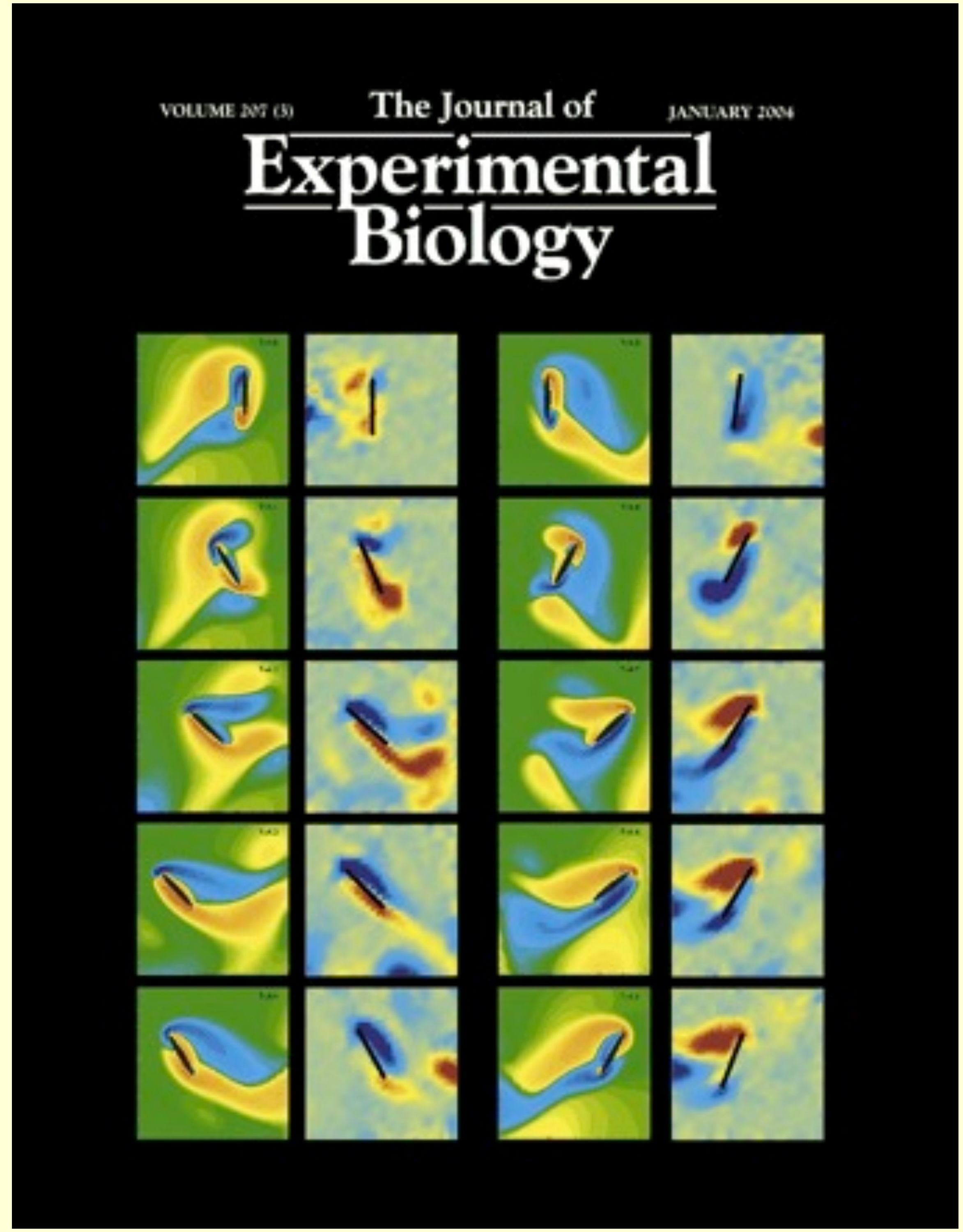


Wang, Phys. Rev. Lett. 2000

Comparing Against Experiments

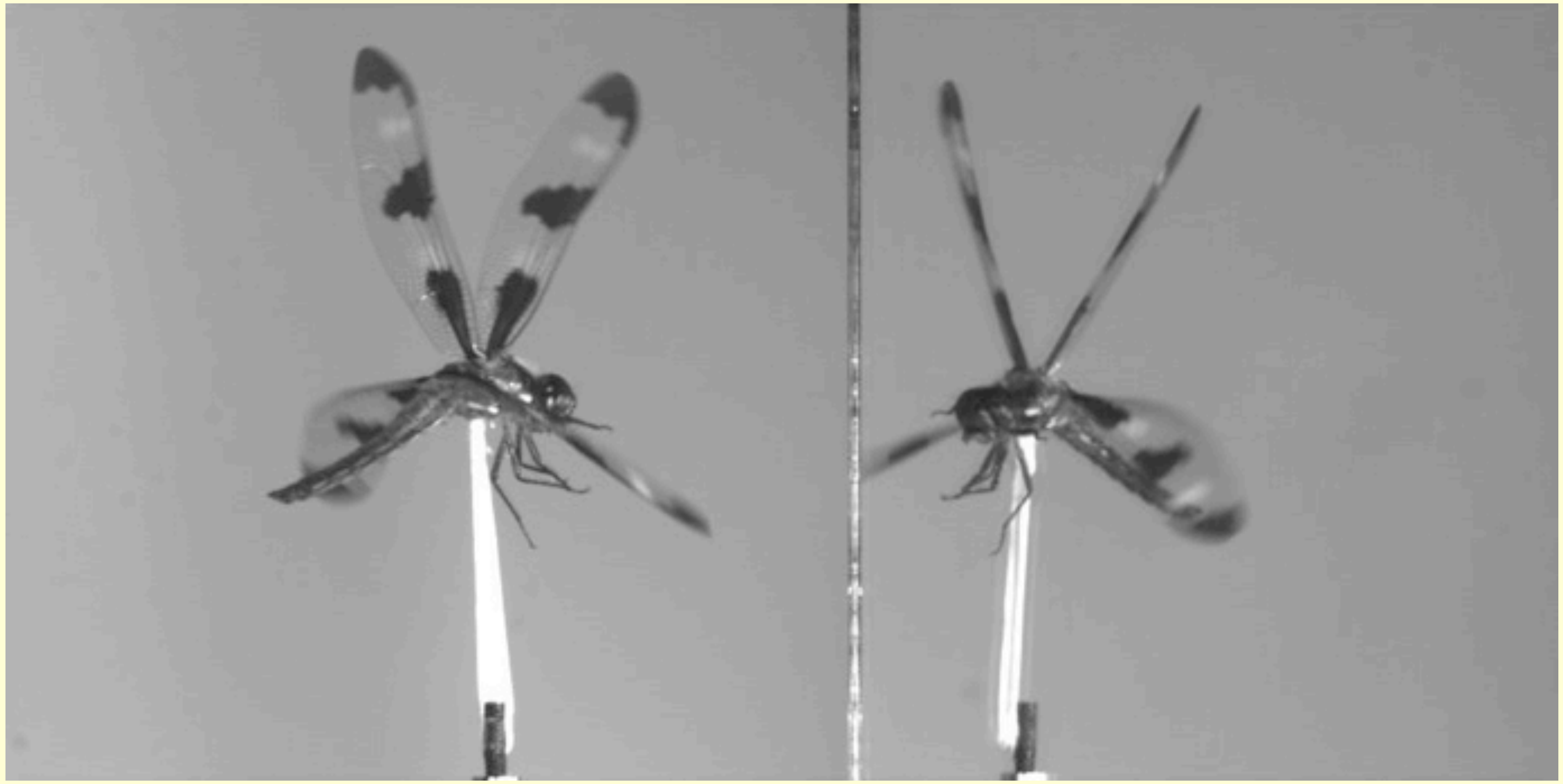


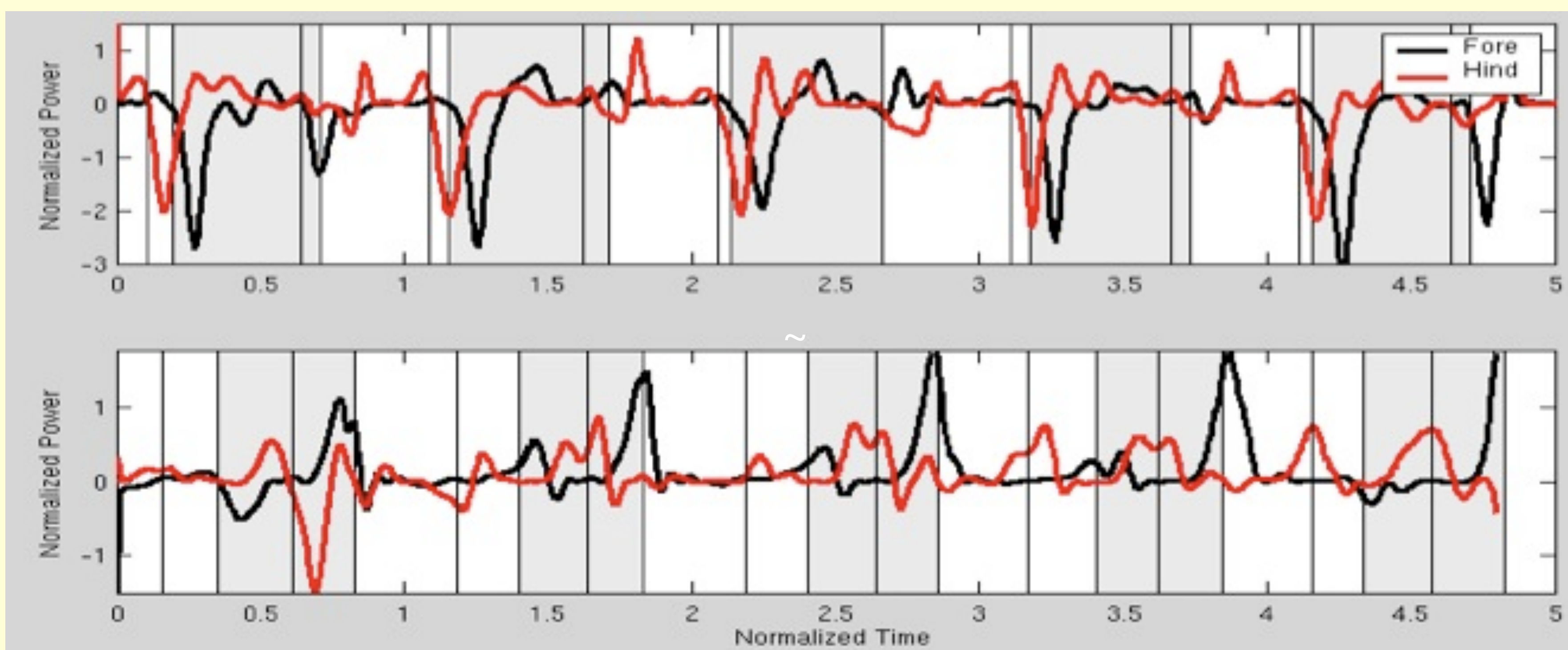




Wang, Birch, and Dickinson, JEB (2004)

Passive Wing Pitching





Bergou, Xu, Wang, J. Fluid Mech., 2007

Computing the Navier-Stokes Equation

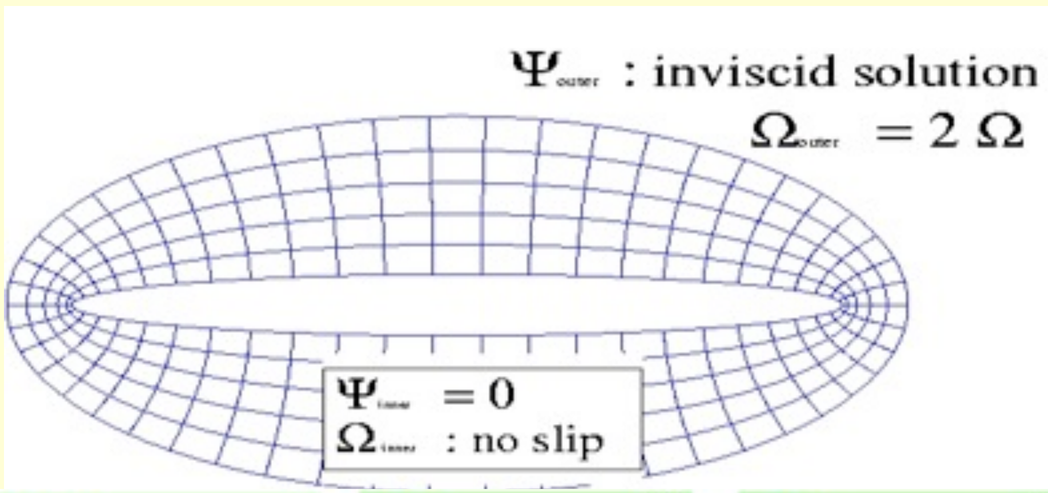
Which Method for Which Problem

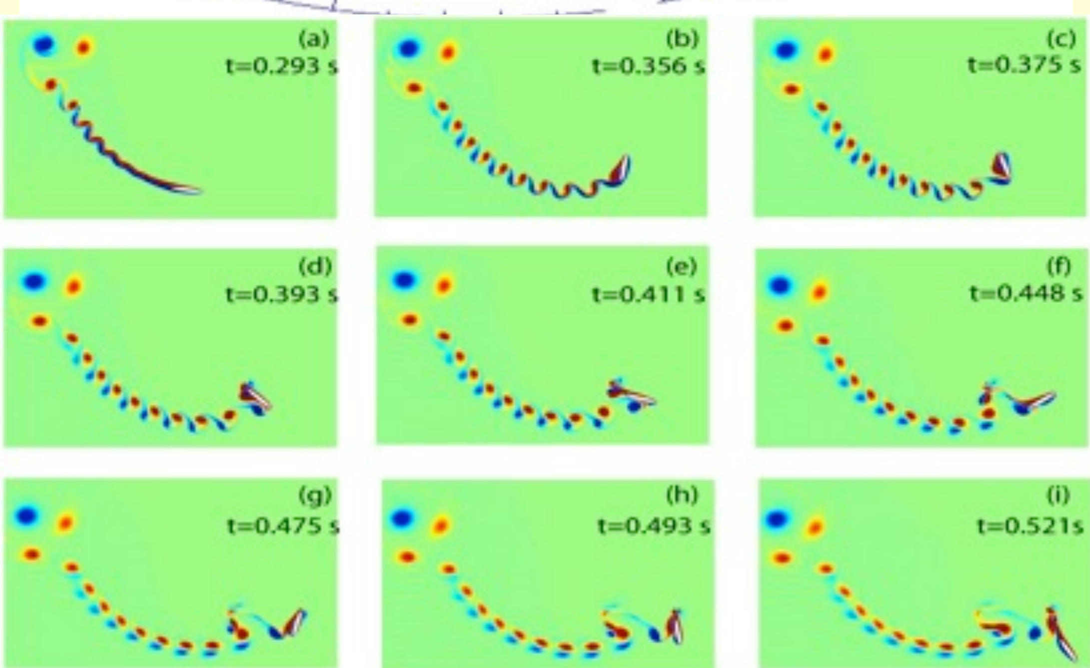
Sharp Edges:

By conformal mapping:

$$x + iy = \cosh(\mu + i\theta)$$

$$S(\mu,\theta) = \cosh^2\mu - \cos^2\theta$$





2D NS equation (Vorticity-Stream Function Formulation) in elliptic coordinates

$$\frac{\partial(S\omega)}{\partial t} + \left(\sqrt{S}u \bullet \nabla\right)\omega = \frac{1}{\mathrm{Re}}\nabla^2\omega$$

$$S\omega = \nabla^2\Psi$$

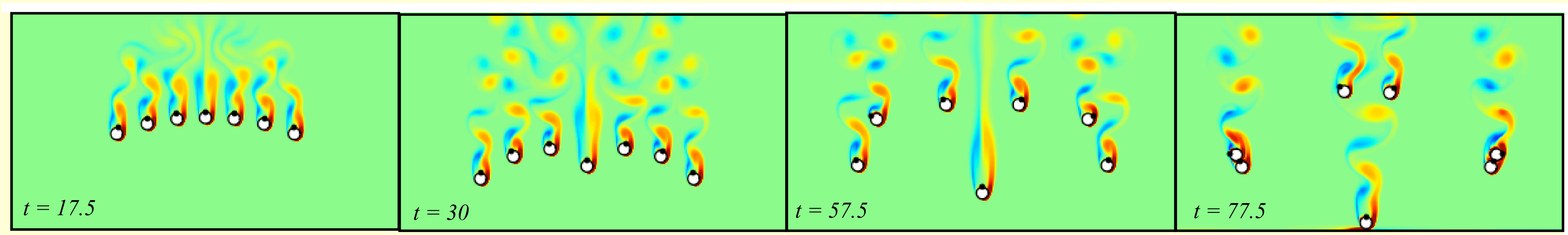
$$\sqrt{S}u = -\nabla \times \Psi$$

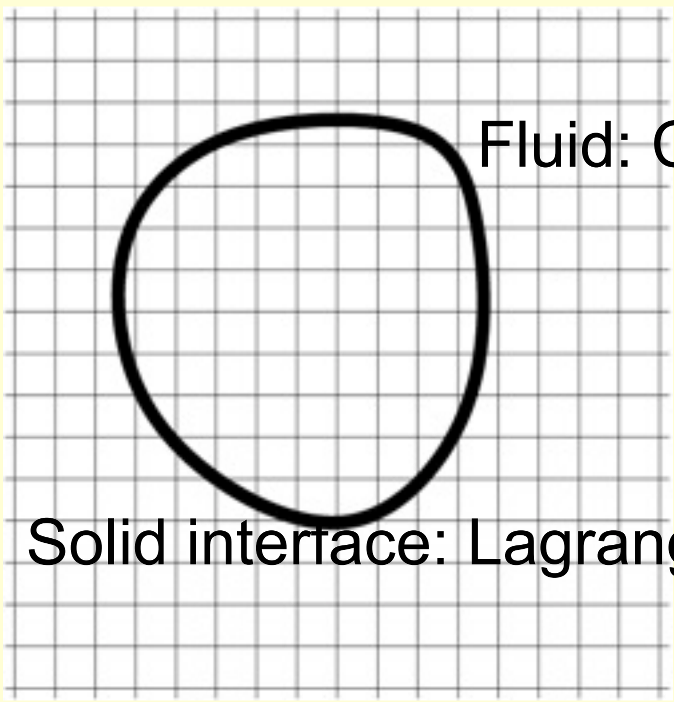
4th order in time (RK)
4th order in space (implicit scheme)
Explicit method (E & Liu 1996)

Solved in noninertial body frame in elliptic coord with far field boundary conditions

Dynamic coupling, PDE optimization
wang (2000) , pesavento & wang 2004, 2009

An immersed interface method for solving multiple moving objects in 2D and 3D (hydrodynamic interactions, collective behavior, flexibility)





$$\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v} = -\nabla p + \frac{1}{Re}\nabla^2\vec{v} + \int_\Gamma \vec{f}(\alpha,t)\,\delta(\vec{x}-\vec{X}(\alpha,t))\,d\alpha$$

$$\nabla\cdot\vec{v} = 0$$

$$\begin{aligned} m_s\ddot{\vec{x}}_c &= \vec{F}_b + \vec{F}_{fl} \\ I\ddot{\vec{\theta}} &= \vec{\tau}_{fl} + \vec{\tau}_b \end{aligned}$$

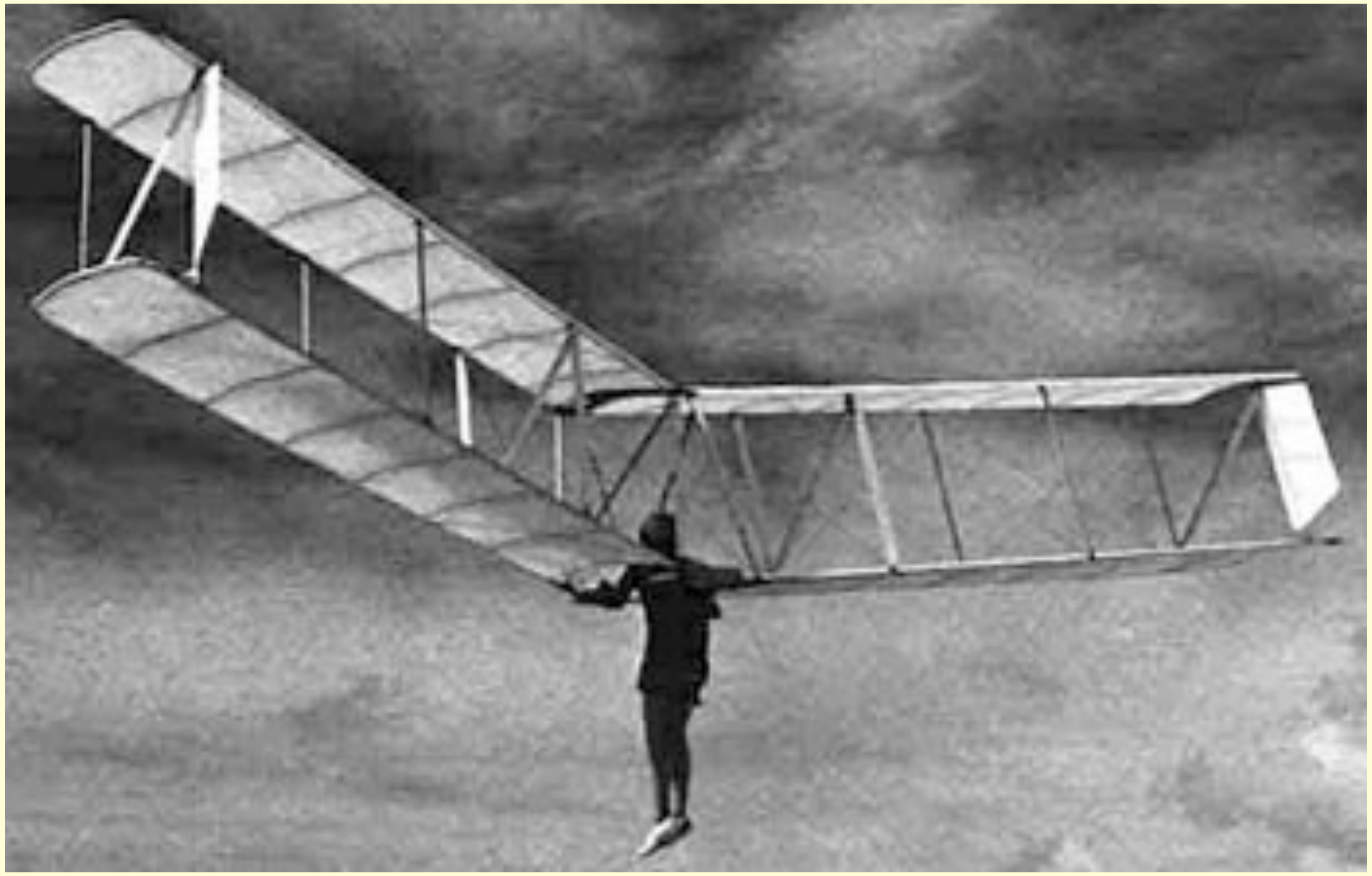
$$f_\tau = -\frac{1}{Re}\left(\vec{\tau}.\frac{\partial\vec{v}}{\partial n}\bigg|_{\Gamma+} - \frac{d\theta}{dt}\right) = -\frac{1}{Re}\left(\omega|_{\Gamma+} - 2\frac{d\theta}{dt}\right)$$

$$f_n = \int\left(\frac{1}{Re}\left[\frac{\partial\omega}{\partial n}\right] + [b_\tau]\right) J\,d\alpha$$

Xu and Wang, SIAM J. Num. Analysis (2006), J. Comp. Phys. (2006), Comp. Meth. Appl. Mech. and Eng. (2008)

‘Birds vs. Plane’

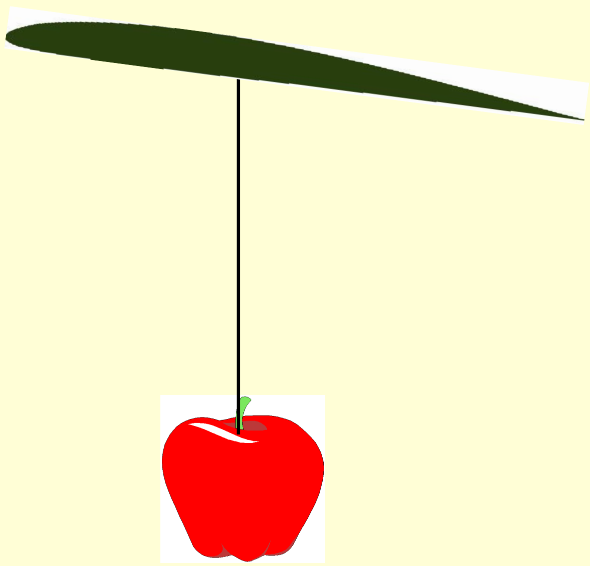
Which is more efficient?
What do we mean by ‘efficient?’



Energy Minimizing Hovering Wing Motion

Problem:

Given a wing and a weight,

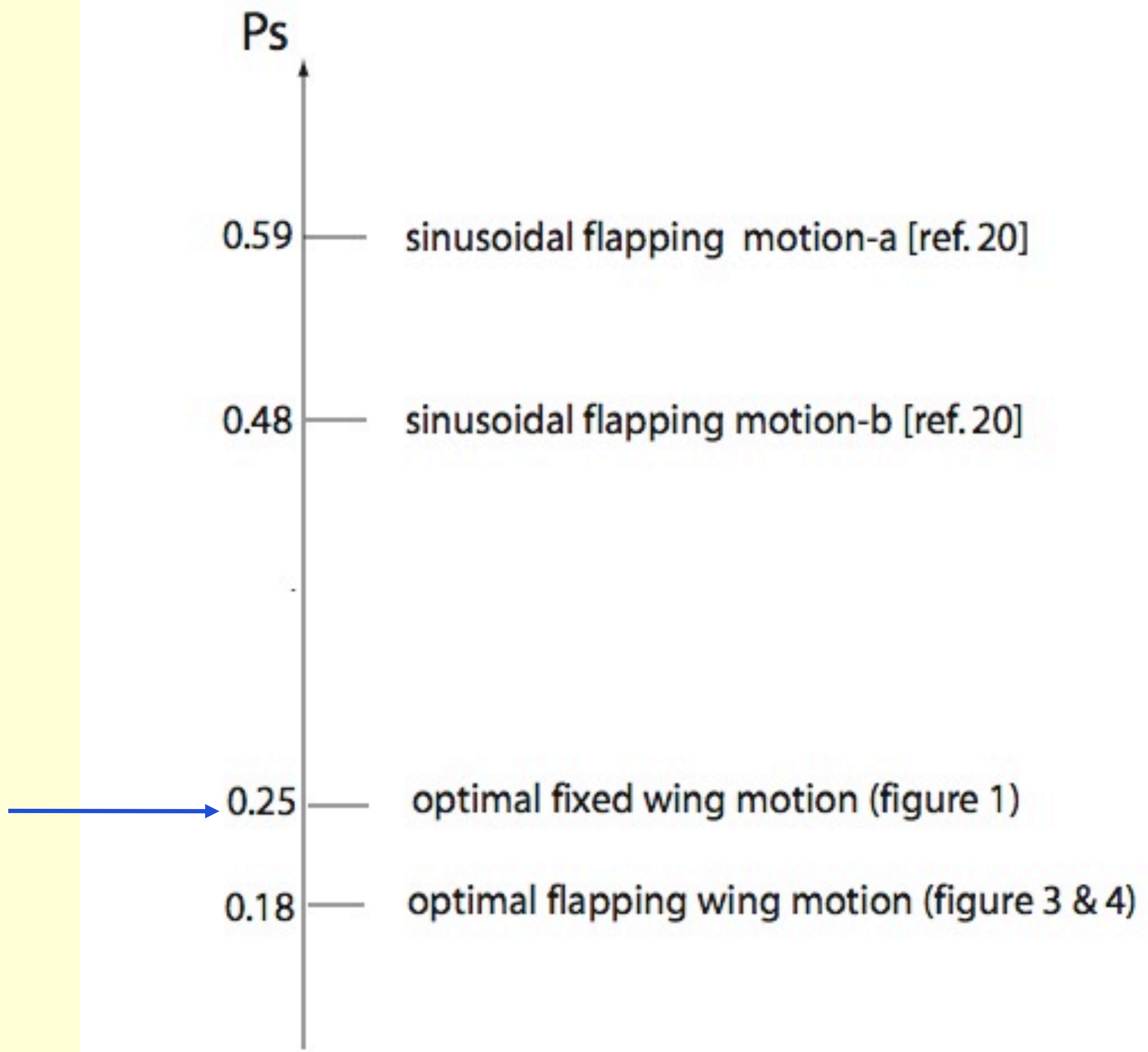


find wing motions

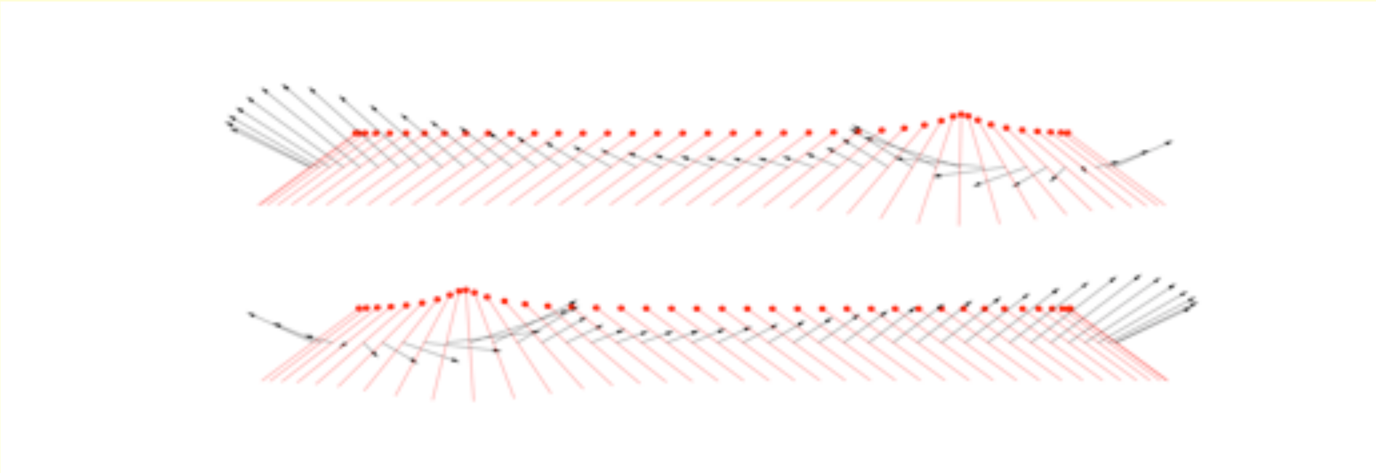
that minimize the aerodynamic power to support the weight

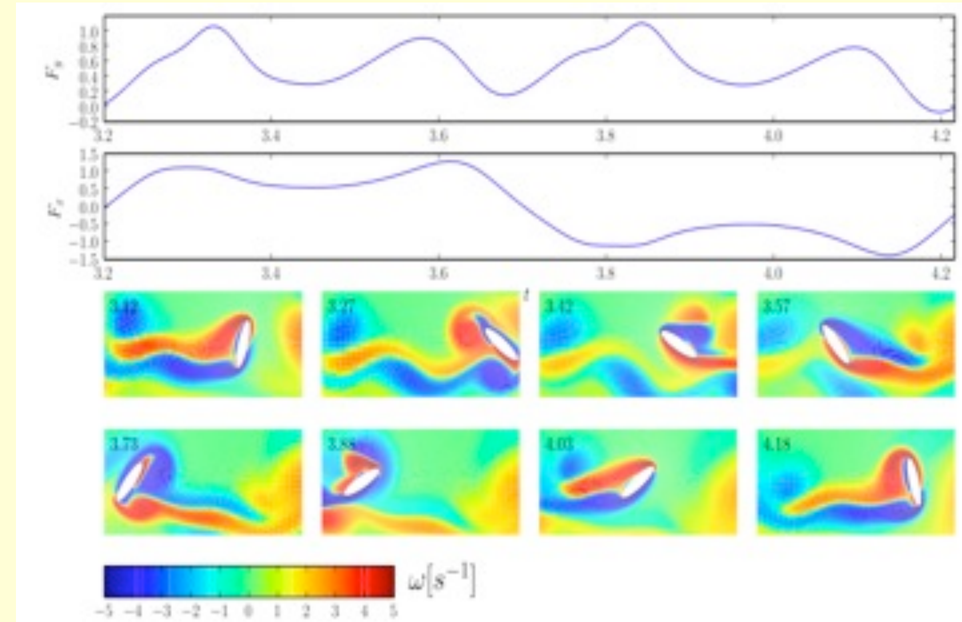
Constrained PDE/ODE optimization

Specific Power



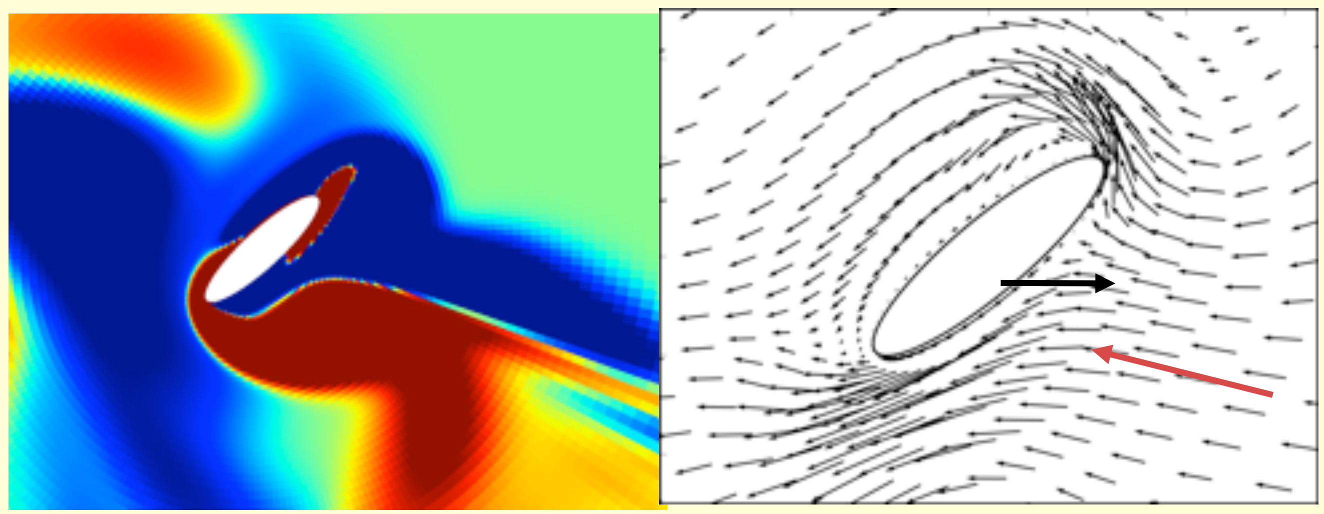
Optimal Flapping Motion



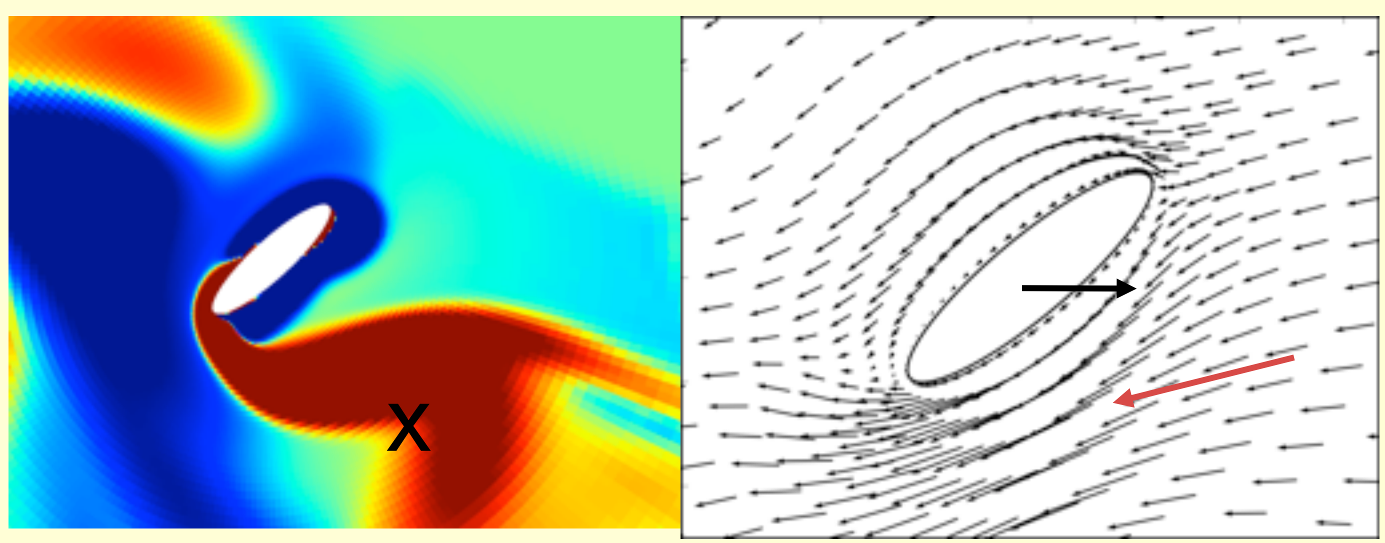


Near
wing reversal:

Unperturbed case:



Remove the leading edge vortex in previous half-stroke:



Pesavento and Wang, PRL 2009

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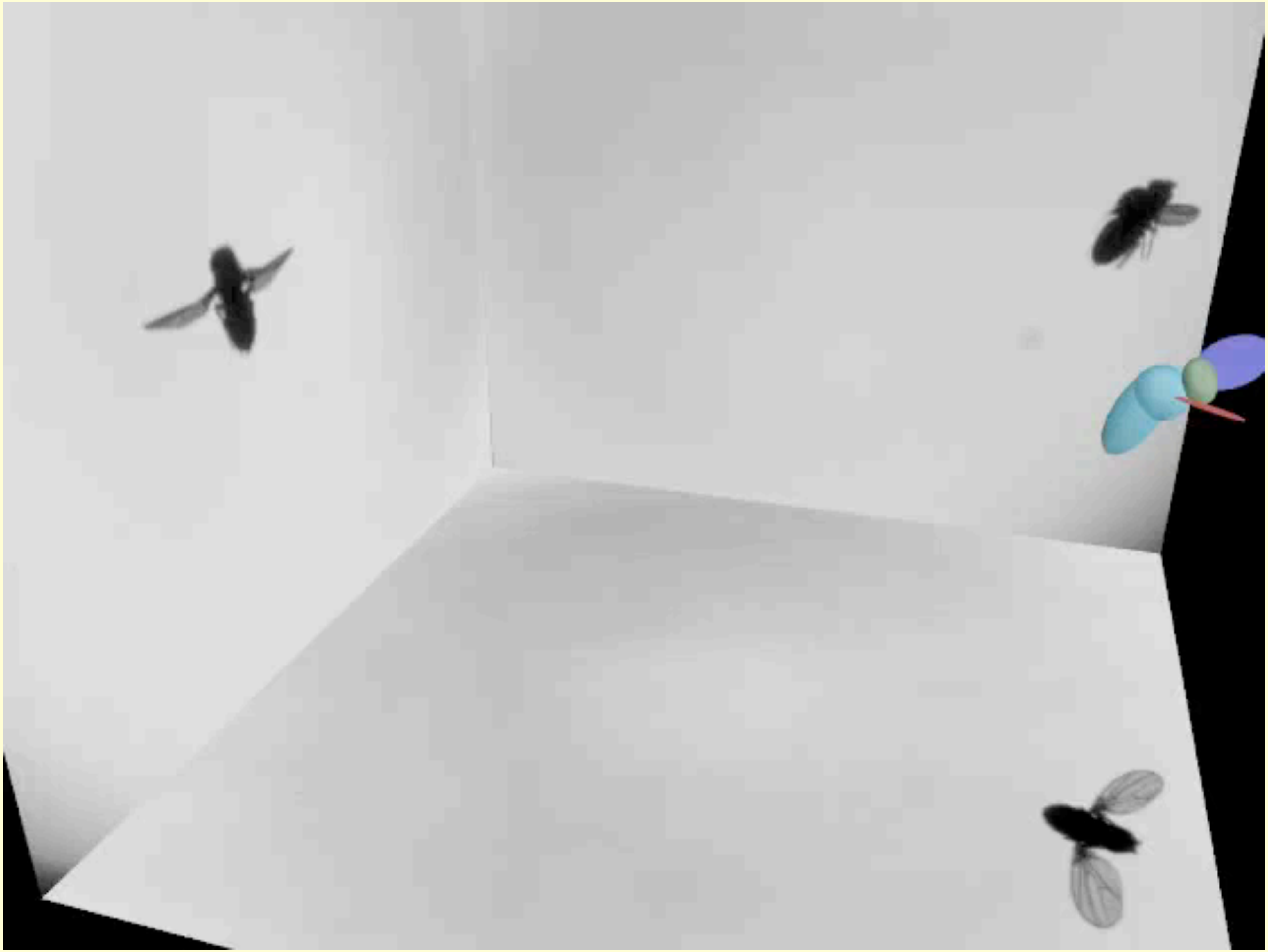
How do fruit flies control their wings to Turn?



sensory feedback loops

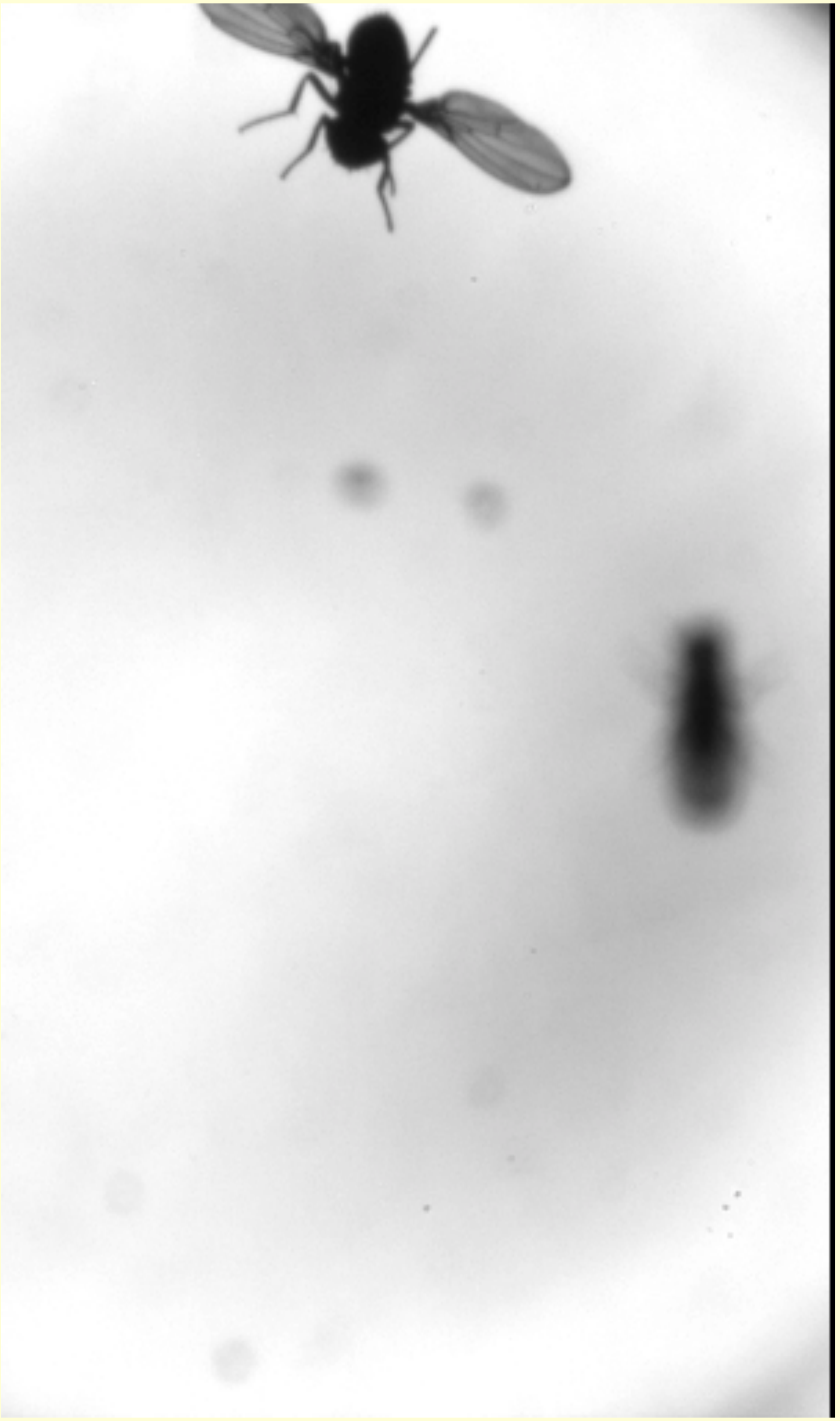
mechanical
visual
...

time scales

fast   compared to ?
slow

Perturbed by Magnetic Field

top view

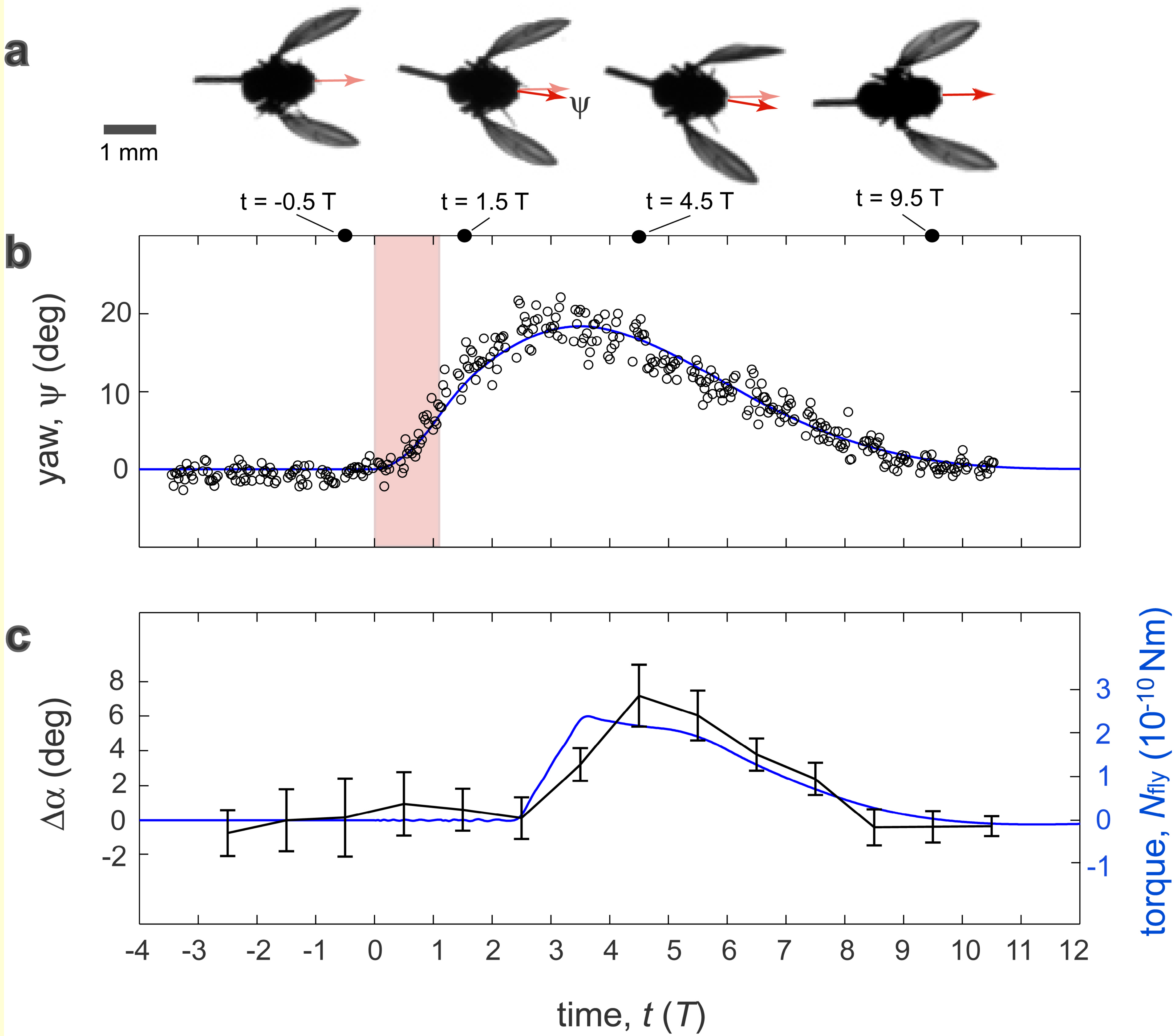


Start

finish

Reset orientation

Ristrohph et al, PNAS (2010)



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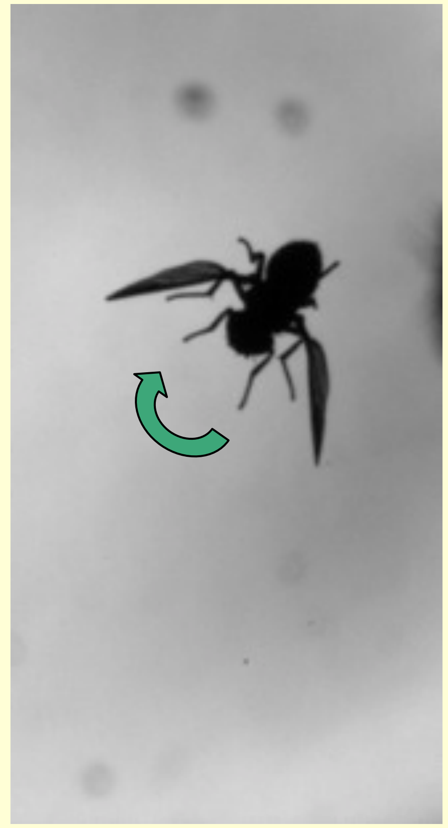
Recovering from an Aerial Stumble

top view

Before perturbation

Symmetric wing motion

~ 4 wing beats

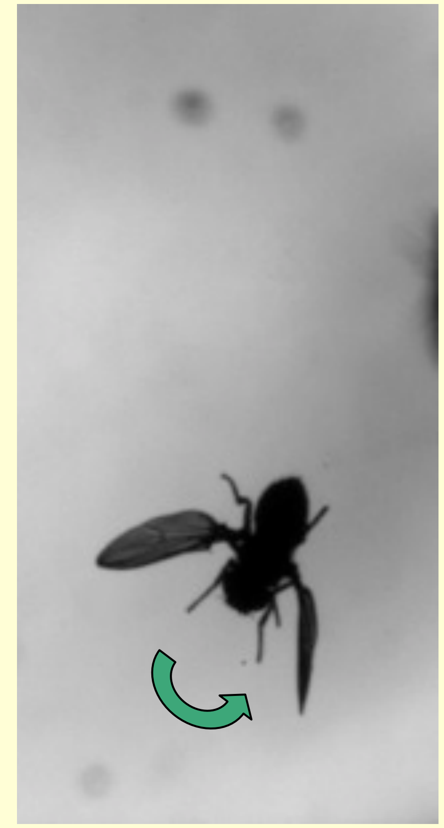


Passive damping

1

Symmetric

~ 4 wing beats

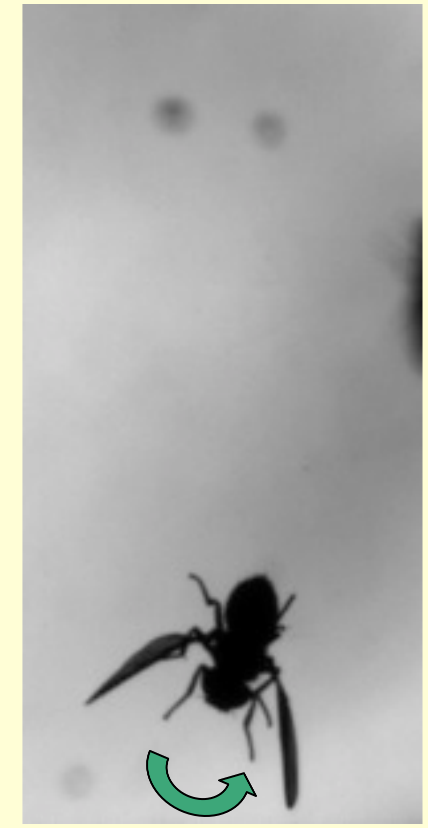


Active recovery

2

Asymmetric

~ 2 wing beats

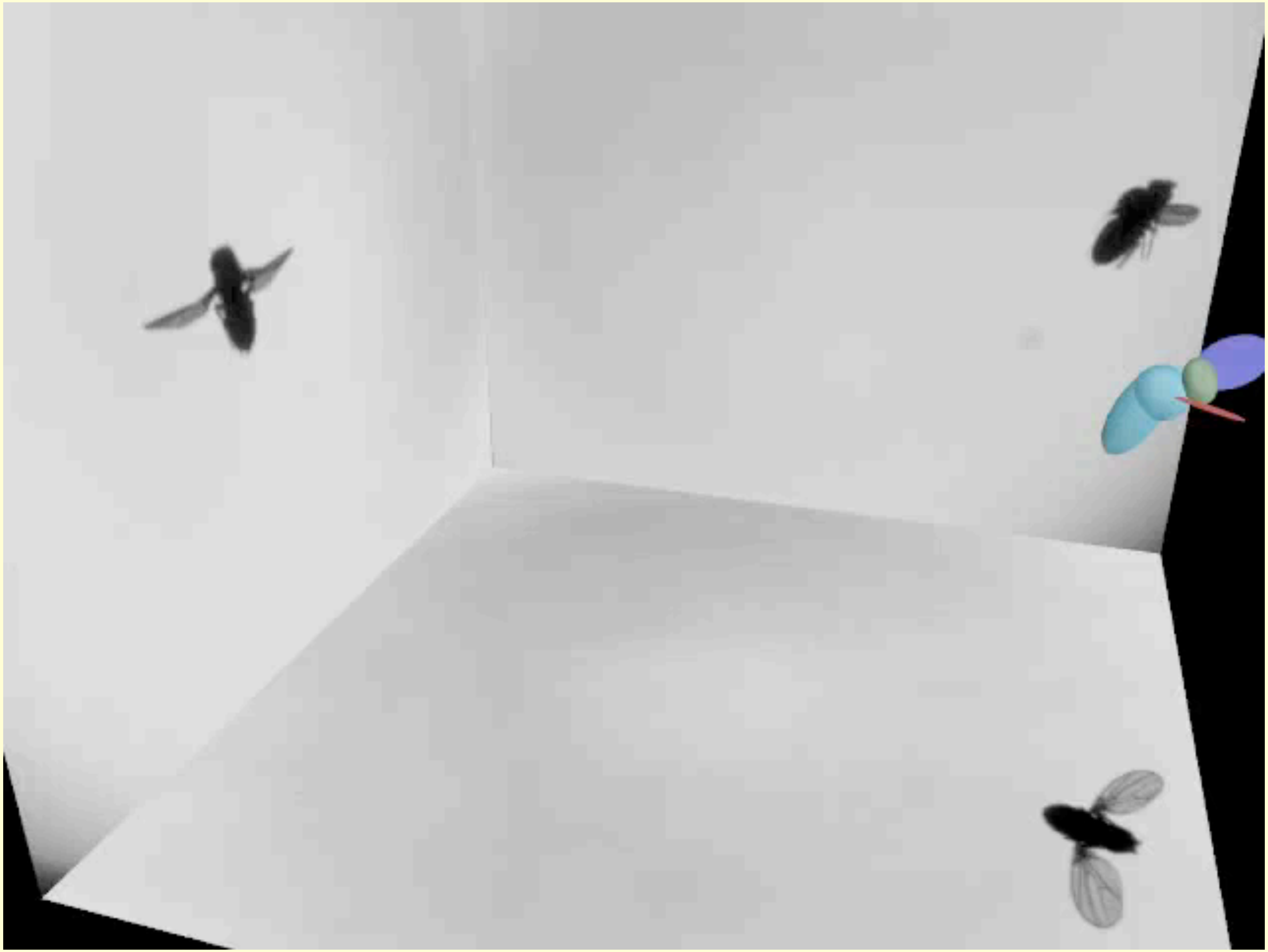


Passive recovery

3

Symmetric

How do fruit flies control their wing to Turn?



How does the insect control its wings to create these asymmetries?

Back and forth motion:

Driven by large indirect muscles

Pitching:

Controlled by steering muscles

However,
the insect cannot adjust the wing stroke every wing beat (4ms)

Inferring (Pitching) Torque

Measure wing kinematics
wing mass, shape, axis of rotation

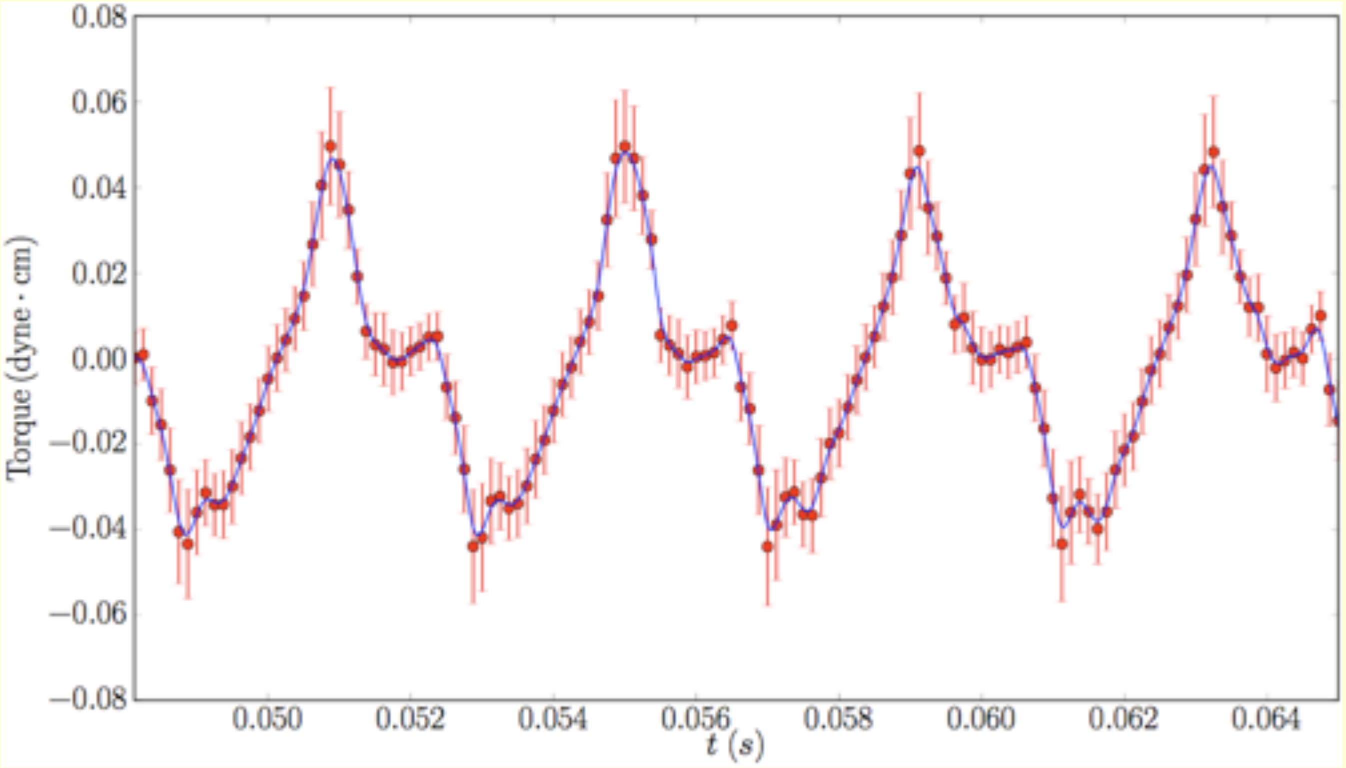
Calculate aerodynamic torque
wing inertia

Deduce torque at the wing base

$$\vec{\tau}^{\mathrm{fly}} = \mathbf{I}_{\mathrm{cm}} \cdot \dot{\vec{\omega}} - \vec{r}_{\mathrm{b}} \times m_{\mathrm{w}} \vec{a}_{\mathrm{cm}} + (\vec{r}_{\mathrm{b}} - \vec{r}_{\mathrm{c}}) \times \vec{F}^{\mathrm{aero}} - \vec{\tau}^{\mathrm{aero}}$$

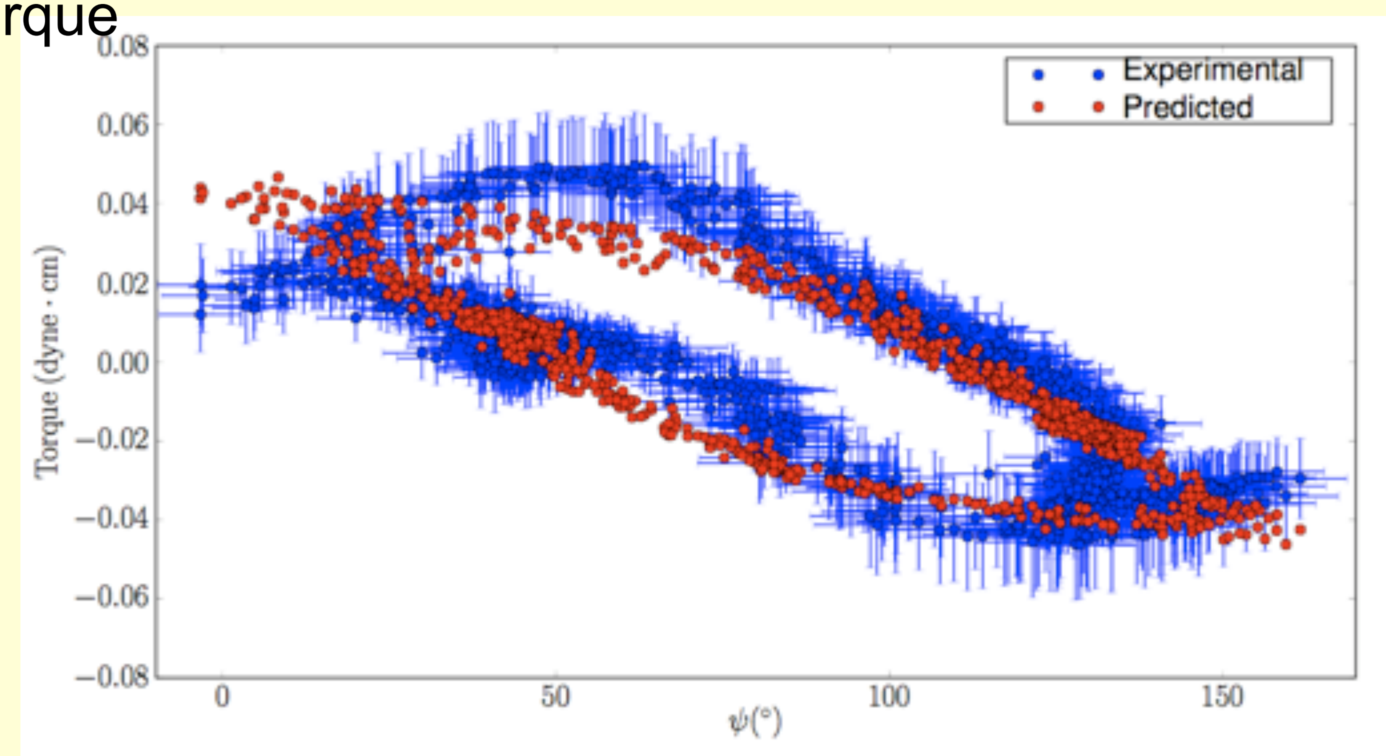
Torsional Spring at the Wing Base

torque



time

torque



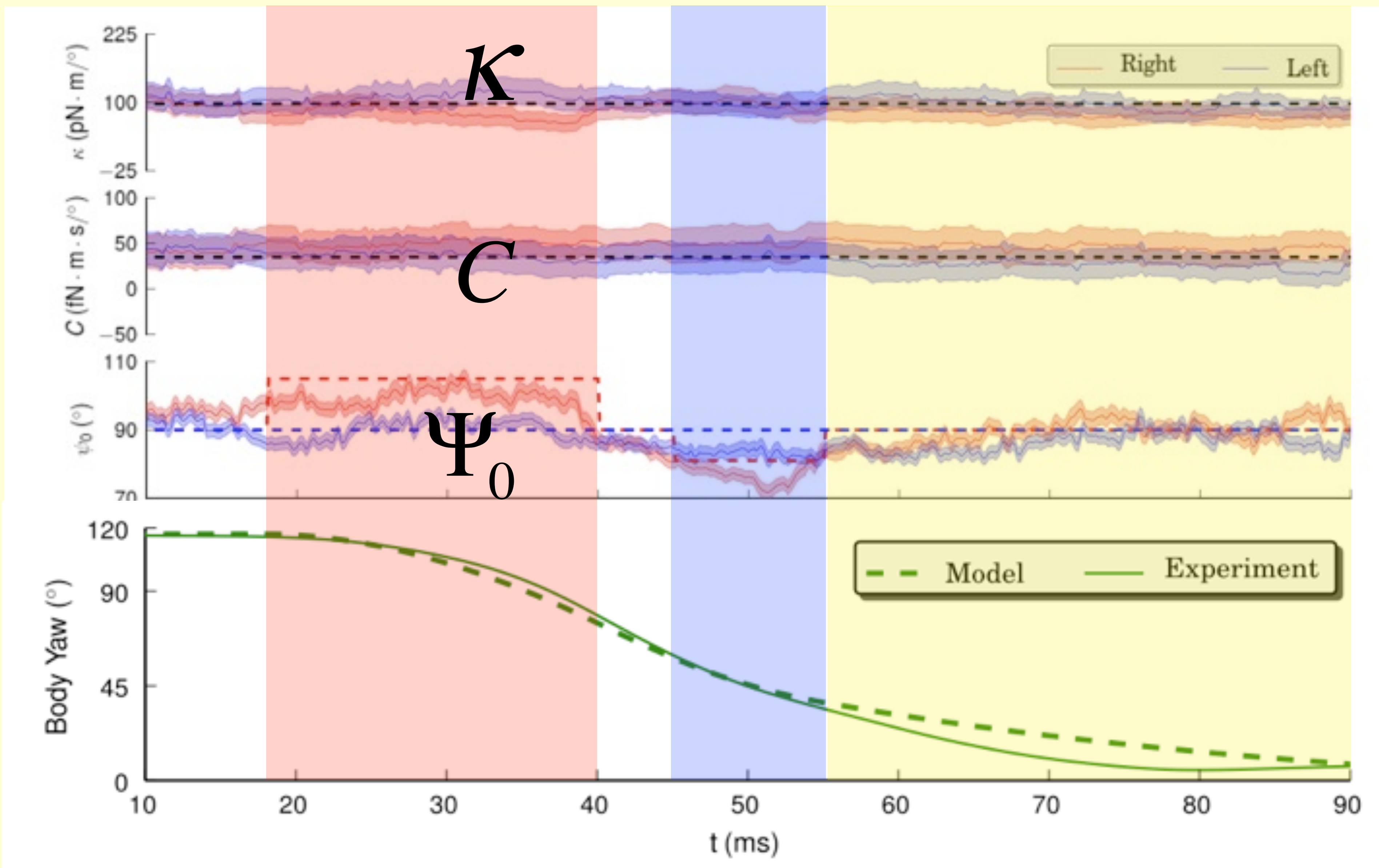
pitching angle

$$\vec{\tau}^{\mathrm{fly}} = -\kappa\left(\psi - \psi_0\right) - C\dot{\psi}$$

κ~ 3 to 5 10^{-2} dyne cm/rad

Determining κ, Ψ_0, C from experimental data

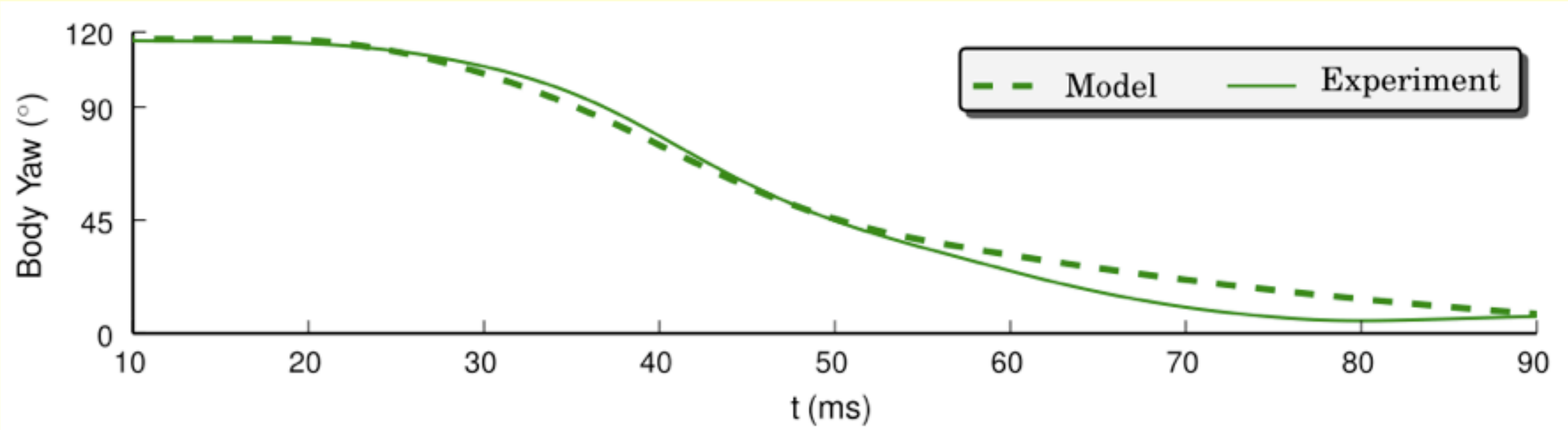
$$\vec{\tau}^{\text{fly}} = -\kappa\left(\psi - \psi_0\right) - C\dot{\psi}$$



Ψ_0 changes over a times scale of ~20ms

Predicts Body Trajectory

Back and forth motion: prescribed
Wing pitch: passive with one control variable



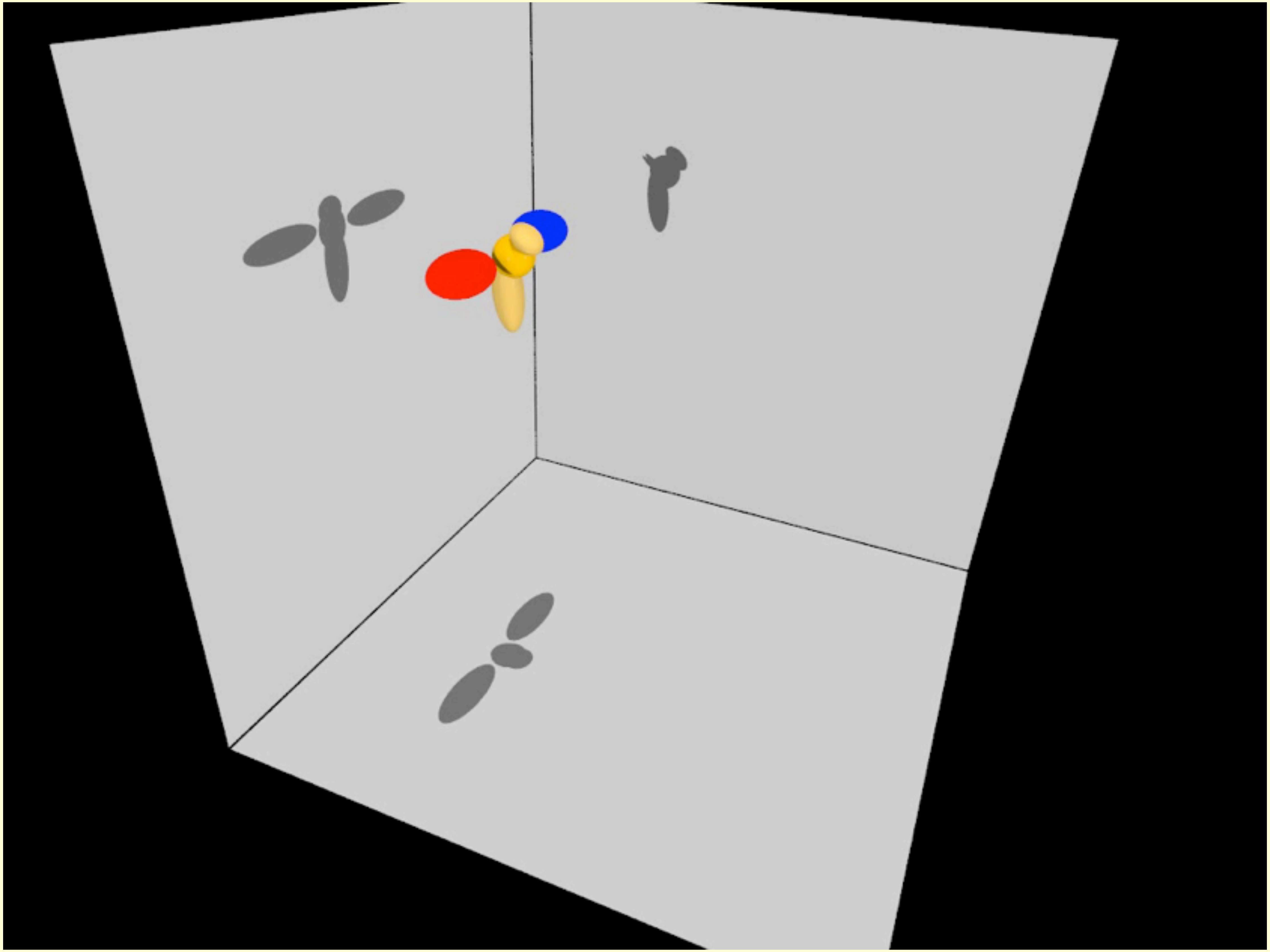
$$I_b\ddot{\phi}_b + 2C_\tau\bar{\omega}\dot{\phi}_b = 2C_\tau\bar{\omega}^2\Delta\psi$$

damping   driving

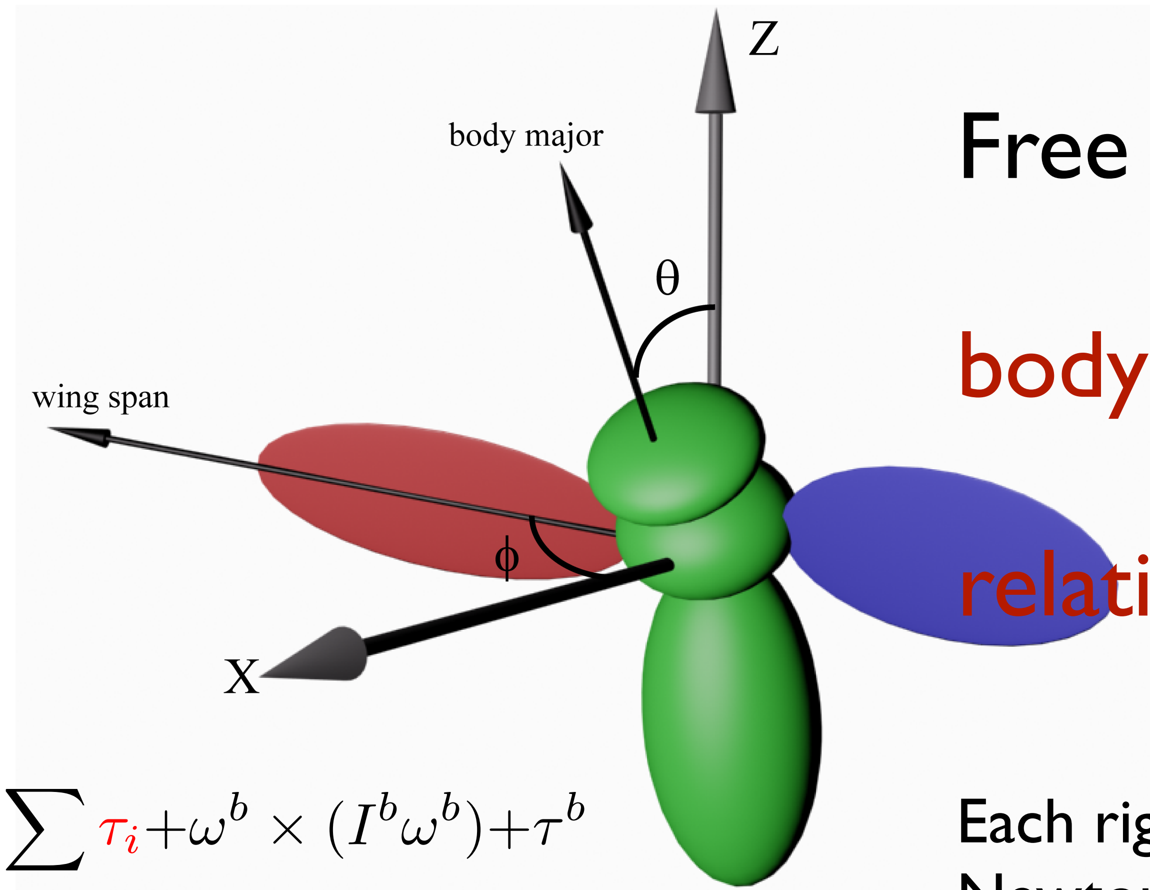
Bergou,Ristroph,Guckenheimer, Cohen, Wang, Phys. Rev. Lett. 2010

Balancing in Air

Flapping Flight is almost always unstable



Dynamic Stability Analysis of Free Flight



Free Flight Simulation

body-wing coupling

relatively fast simulations

$$I^b \beta^b = \sum \tau_i + \omega^b \times (I^b \omega^b) + \tau^b$$

$$I_i^w \beta_i^w = (-\tau_i) + \omega_i^w \times (I_i^w \omega_i^w) + \tau_i^b$$

$$\beta_i^w - \beta^b = \beta^{\mathrm{pre}}$$

$$m^b a^b = (\sum f_i) + m^b g + F^b$$

$$m_i^w a_i^w = (-f_i) + m_i^w g + F_i^w$$

$$r^b + r_i^b = r^w + r_i^w$$

Each rigid body satisfies the Newton-Euler Equation.

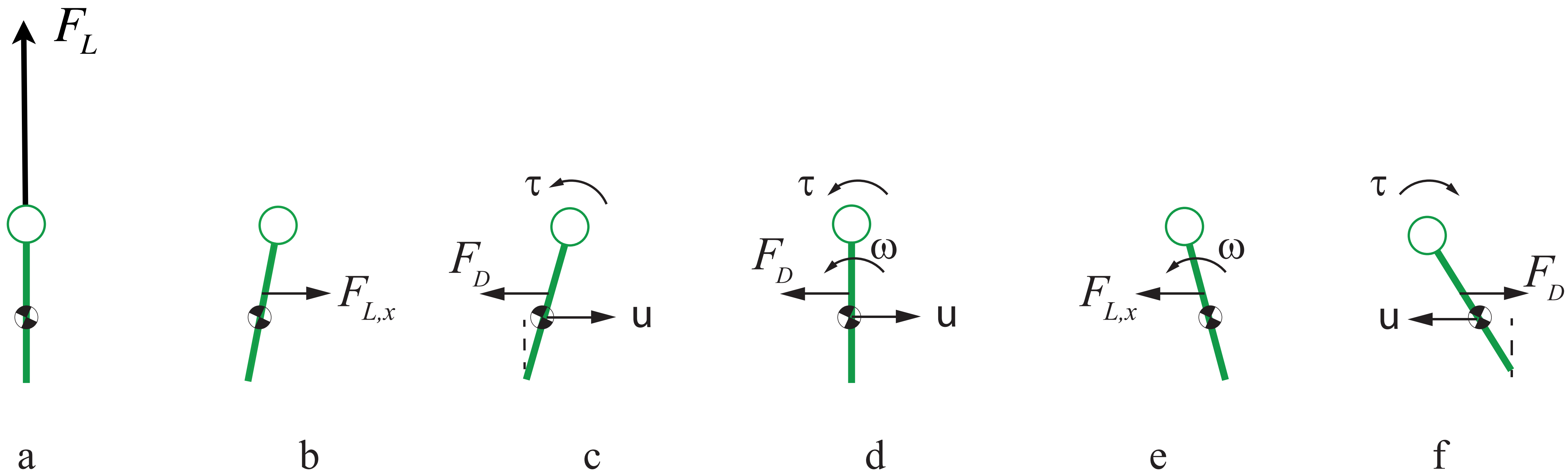
The coupling is enforced through the dynamic constraints at the joints.

Morphological parameters based on insects

The aerodynamics are approximated by a quasi-steady model.

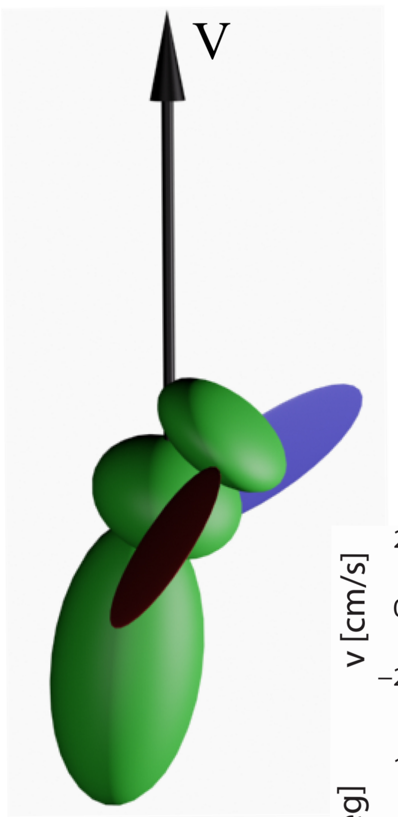
Pitching Instability

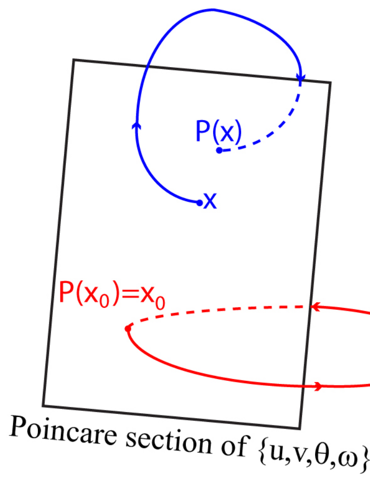
due to coupling between forward and pitching motion

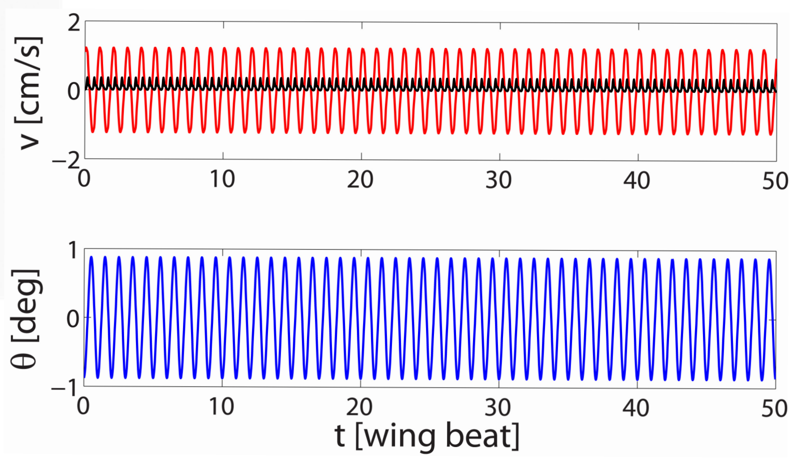


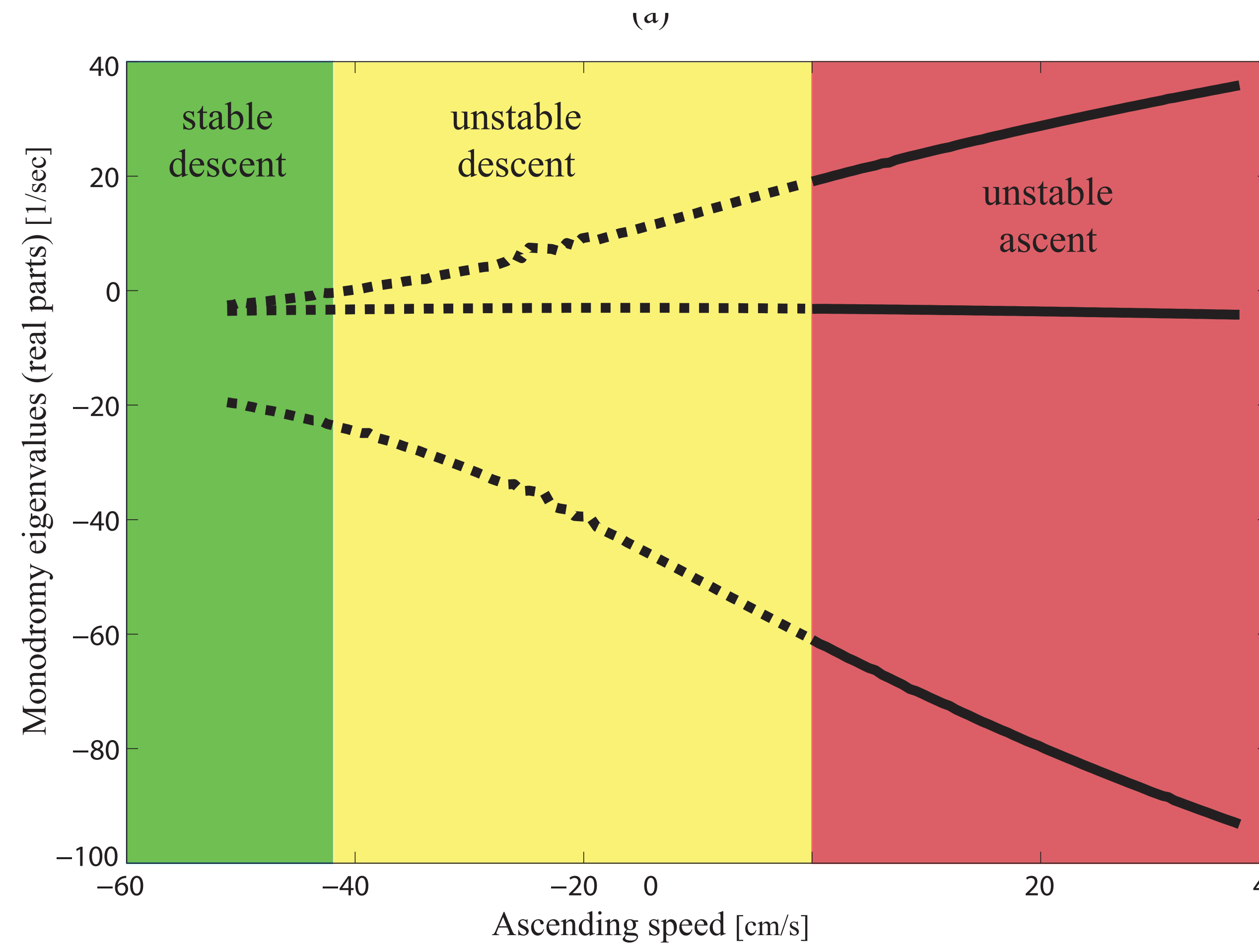
The Stability of the Periodic States

Eigenvalues based on Poincare Map





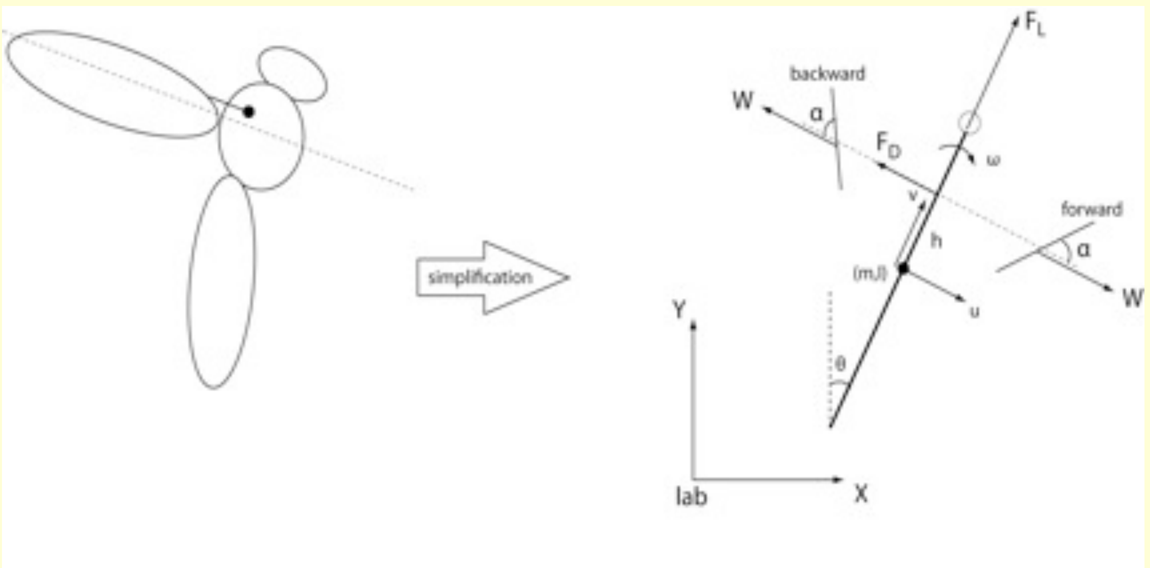




Always unstable, unless in fast descent.

In contrast, ascending model excluding the pitching motion, the flight is stable

Linear Stability Analysis of the Longitudinal Flight $(\theta, \dot{\theta}, u)$



(a) Schematic draw of the lateral view of the fruit fly. The dashed line represents the mean stroke plane.

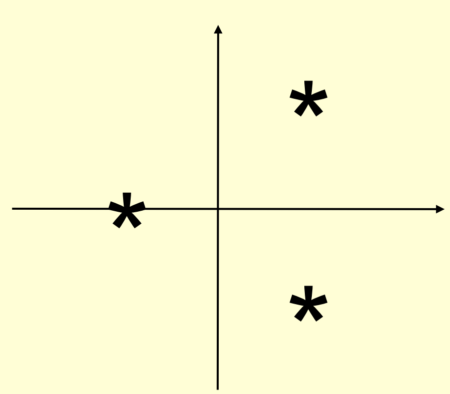
(b) A simplified model for longitudinal flight. The forward and backward strokes are modeled as airfoil translating with constant velocity and constant angle of attack. The body is simplified to a single rigid body parameterized with mass m and moment of inertia I.

$$\begin{aligned}
\dot{u} &= \omega v + \frac{1}{m} F_\xi + g \sin\theta \\
\dot{v} &= -\omega u + \frac{1}{m} F_\zeta - g \cos\theta \\
\dot{\theta} &= \omega \\
\dot{\omega} &= \frac{h}{\mathbf{I}} F_\xi
\end{aligned}$$

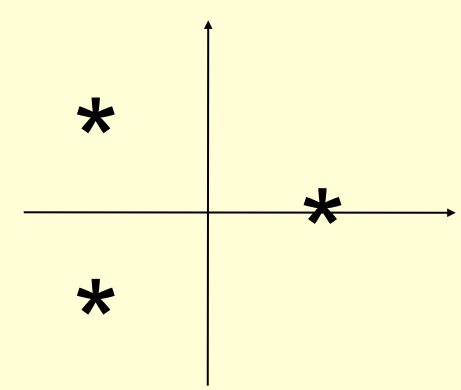
$$\lambda^3 + 2a\lambda^2 + 2ah/L = 0$$

Eigenvalues:

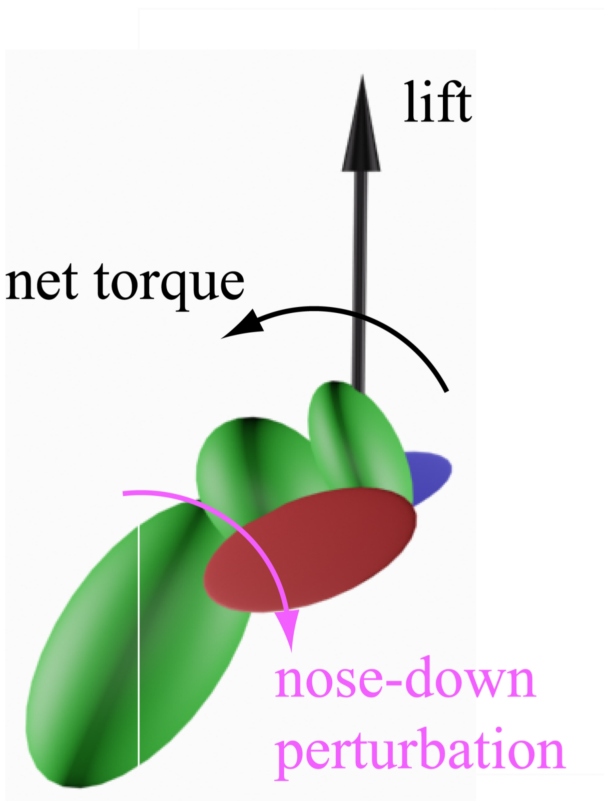
$h < 0$



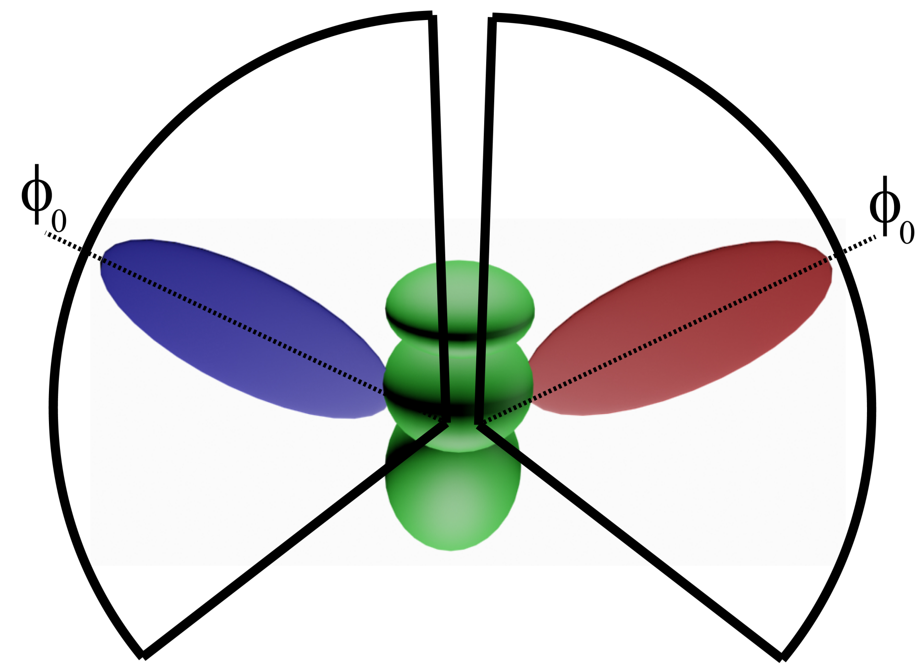
$h > 0$



The pitch instability can be controlled by adjusting the center of the stroke ϕ_0

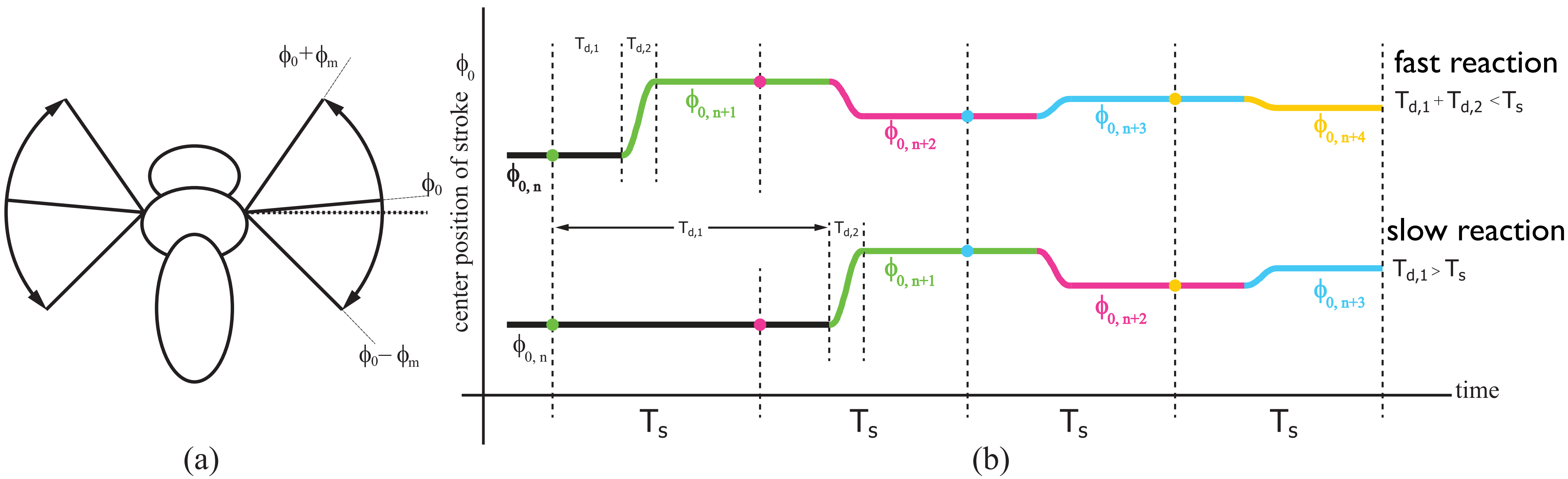


Top View



Adjust ϕ_0

Designing a linear controller

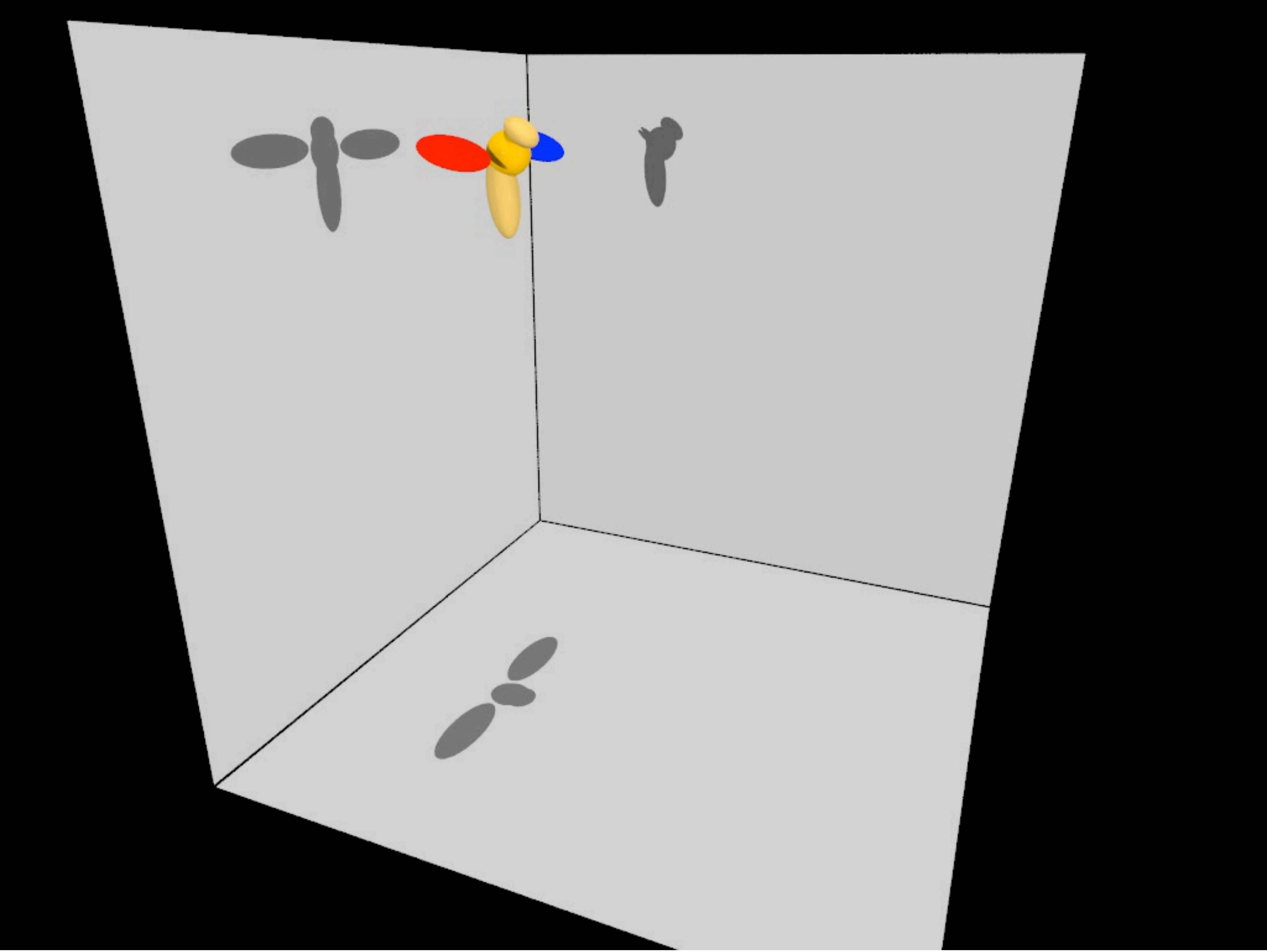


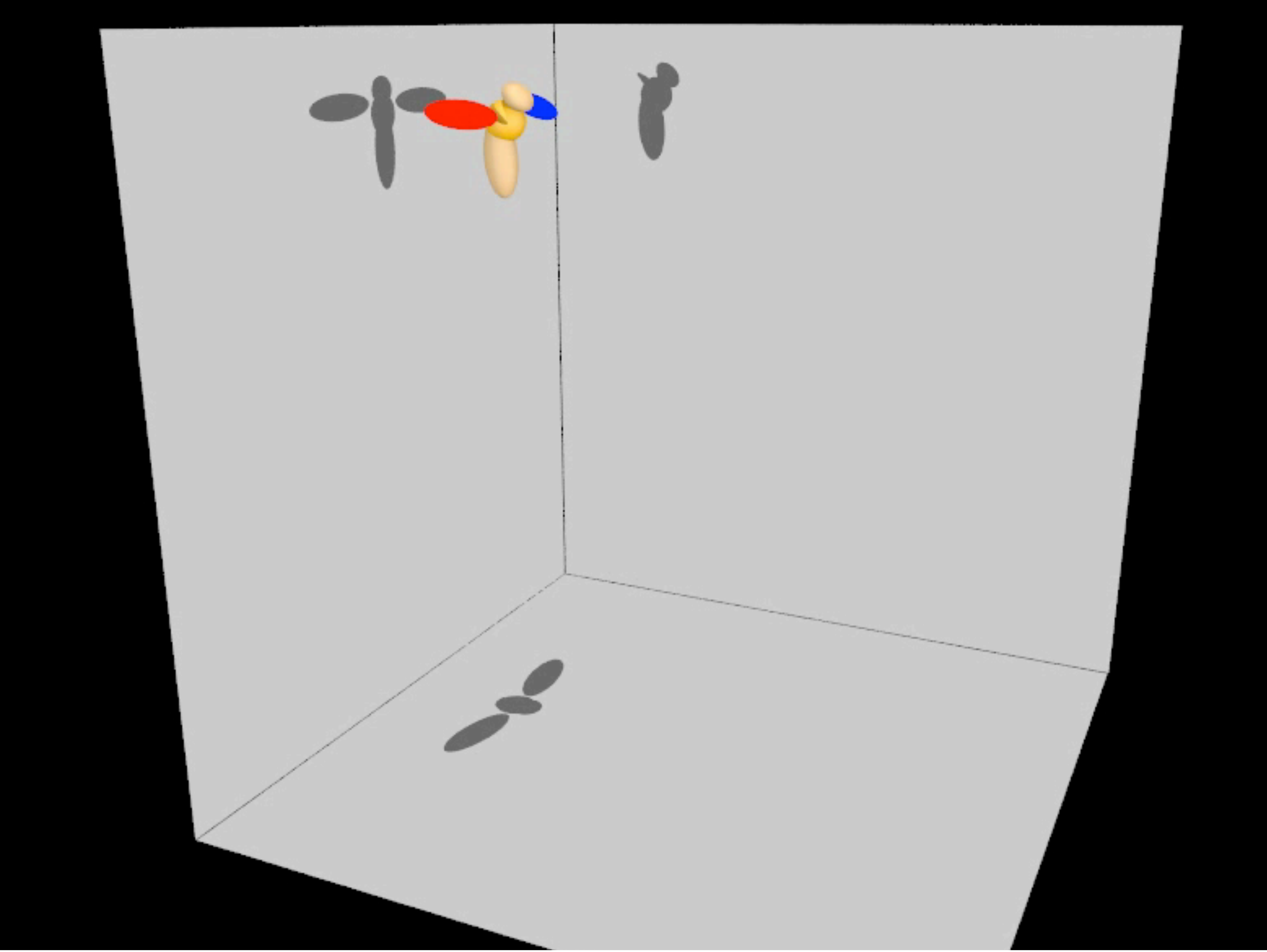
I. time-delay (due to sensing and actuation time) T_d

II. discrete sampling rate $\tau_n - \tau_{n-1} = T_s$

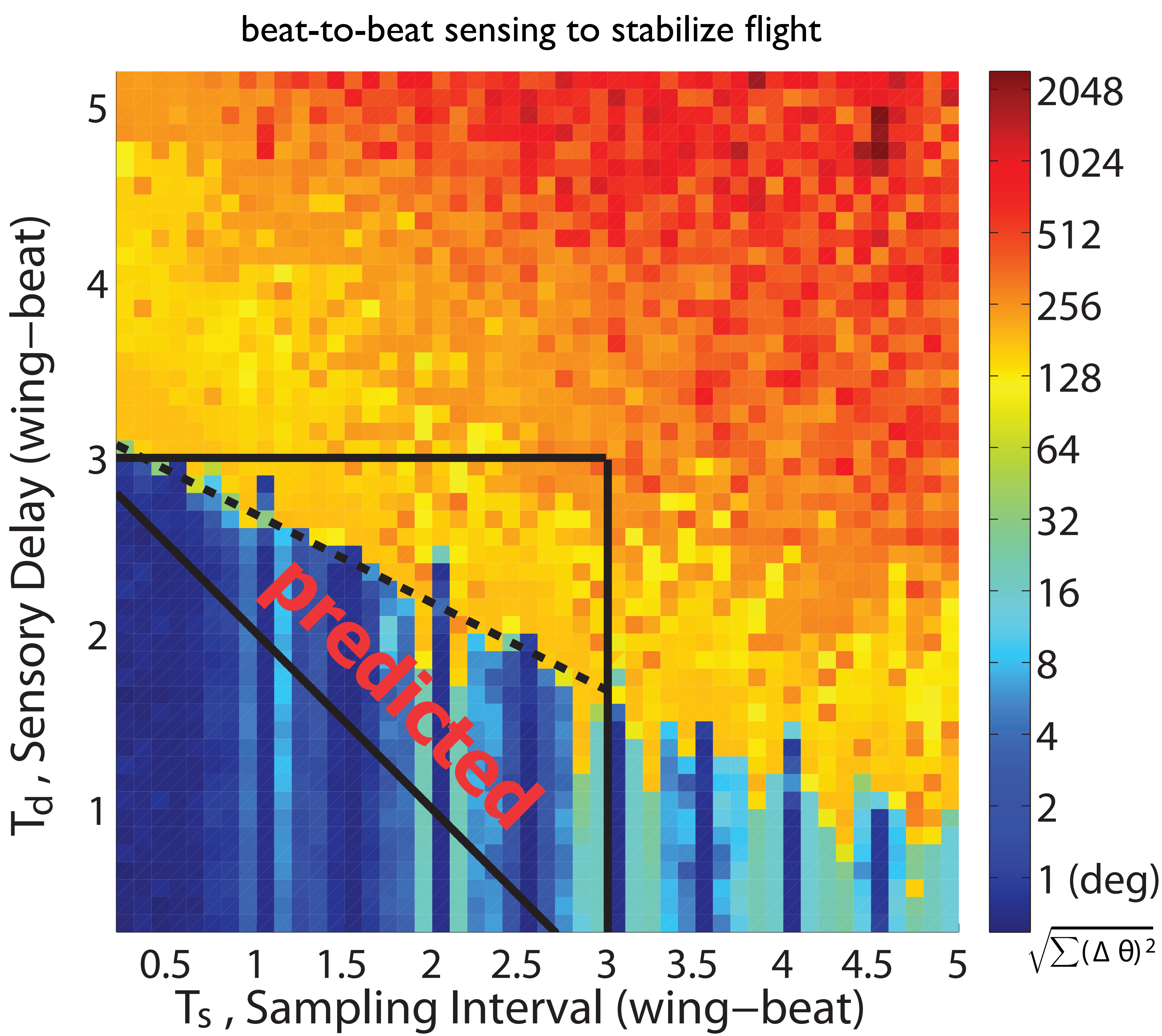
III. a linear controller

interested in the effect of T_d and T_s





Predicting Sensing Rate



Chang & Wang, submitted

Conjecture

Fruit flies sense their state every wing-beat in order to stabilize themselves

Quantitative Study of Organismal Behavior

from flight dynamics to neural dynamics

neural science

visual stimulus

visual neurons

motor neurons

muscle actuation

wing motion

body motion

physics of flight

aerodynamics

3D flight dynamics