

How do Insects Fly and Turn?



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Taking It Apart

- I. Kinematics and Aerodynamics
 - Energetics and Optimization
- II. Dynamics 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'Etienne-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 stabilité des mouve-



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

Chronophotographie sur disque tournant, par l'exemple d'un moulin à vent (1880).

appareils, en 1883, Marey obtint simultanément sur fond noir trois vues : de profil, de dessus et de trois quarts.

Marey créait en 1884 le fusil photographique à plaque circulaire mobile, puis, en 1888, il remplaçait la plaque fixe du chronophotographe par une bande de papier sensible tirée au foyer et se déplaçant de façon intermittente sigulière avec arête 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,



Profil d'un canard (1881).



Phases du coup d'aile d'un pélican.

ments des ailes. En 1886, reprenant une idée de Pinaud, Marey fut le premier à réunir, 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

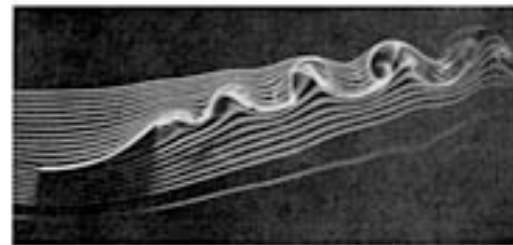
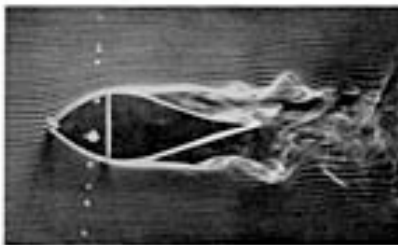


Essai d'un goéland.

en 1894, il projetait sur un écran les séries d'images obtenues.

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

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



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

E. J. Marey
1830-1904

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.

Harper Magazine
1870

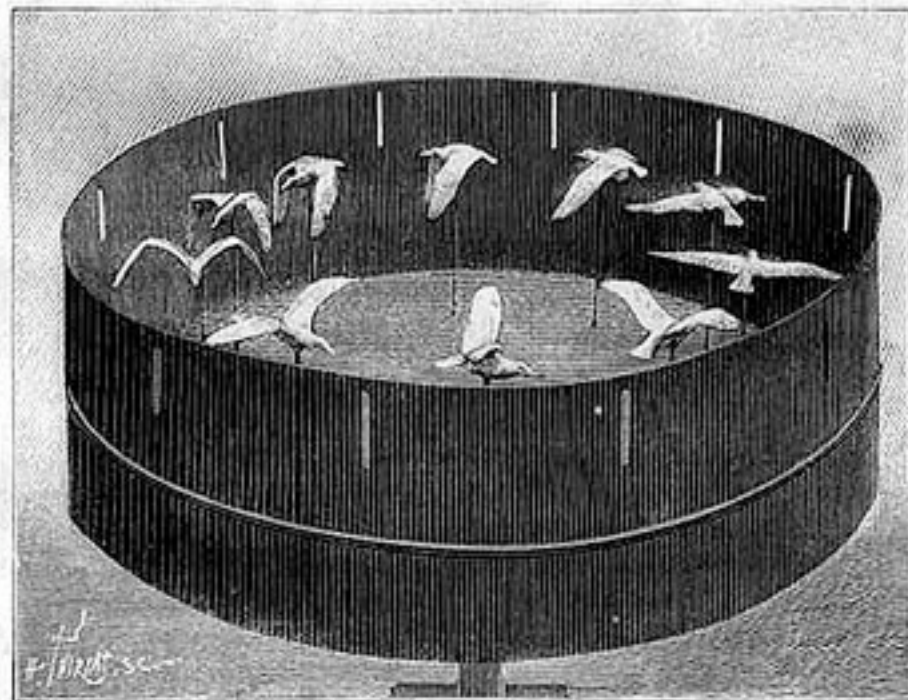
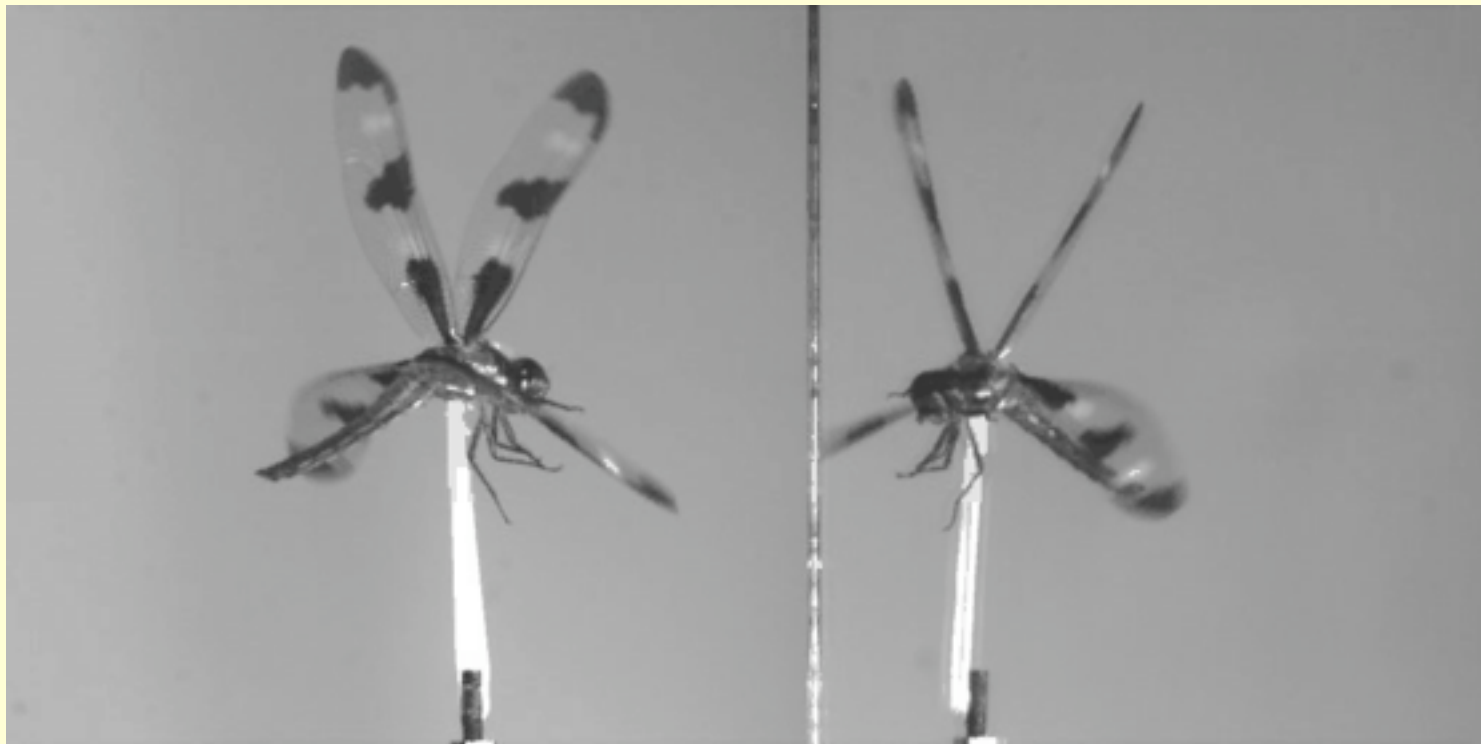


Fig. 9. — Zoetrope dans lequel sont disposées 10 images en relief d'un goéland dans les attitudes successives du vol.

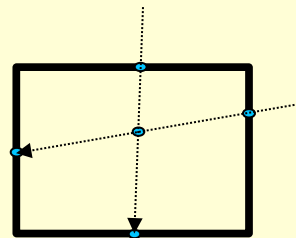
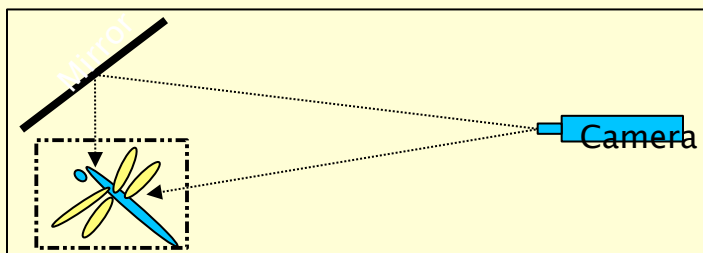
See also:
Weis-Fogh and Jensen (1956)
Ellington (1984)
Fry, Sane, Dickinson (2003)



marker based tracking

1600fps, 1024x1024

mirror



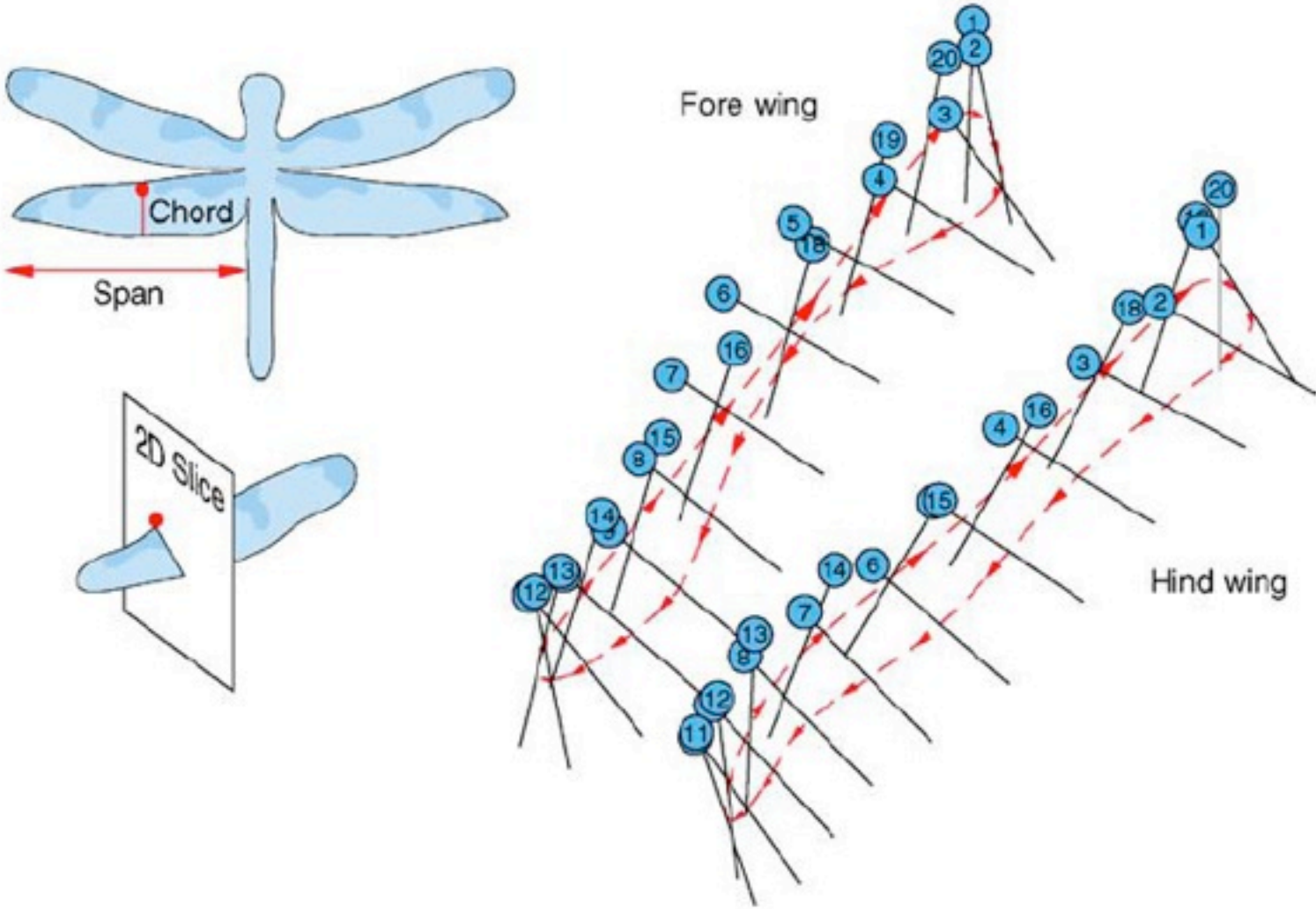
$L \sim 1\text{cm}$

Freq $\sim 40\text{Hz}$

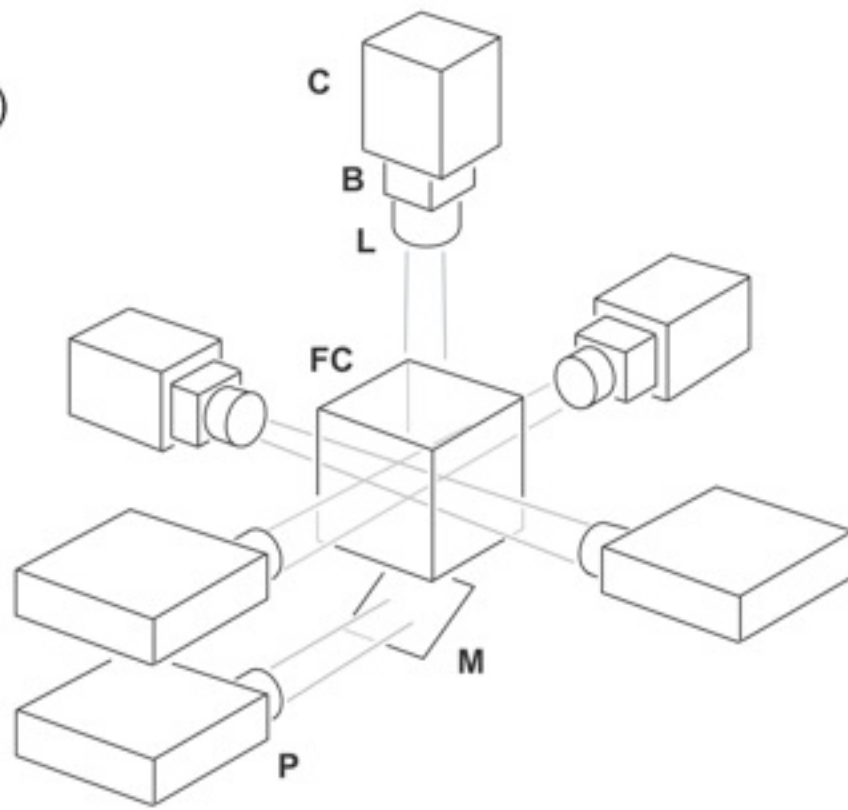
$Re = UL/v \sim 3000$

David Russell (2004, PhD Thesis)

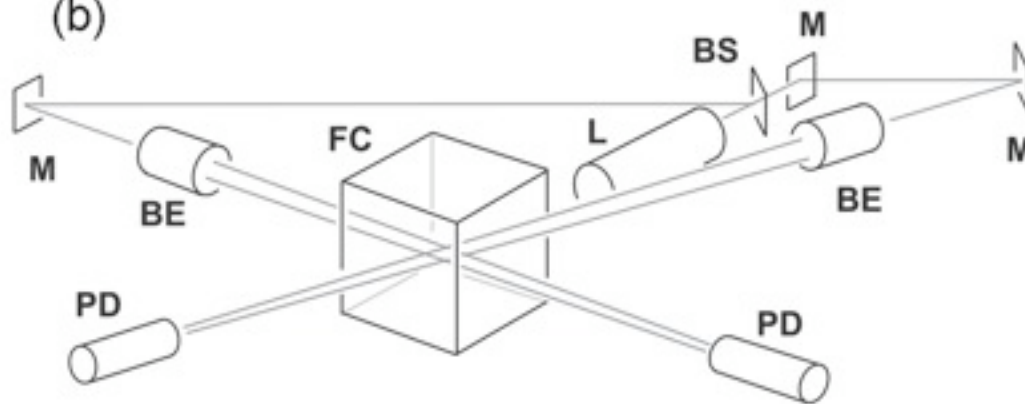
Dragonfly Hovering



(a)



(b)

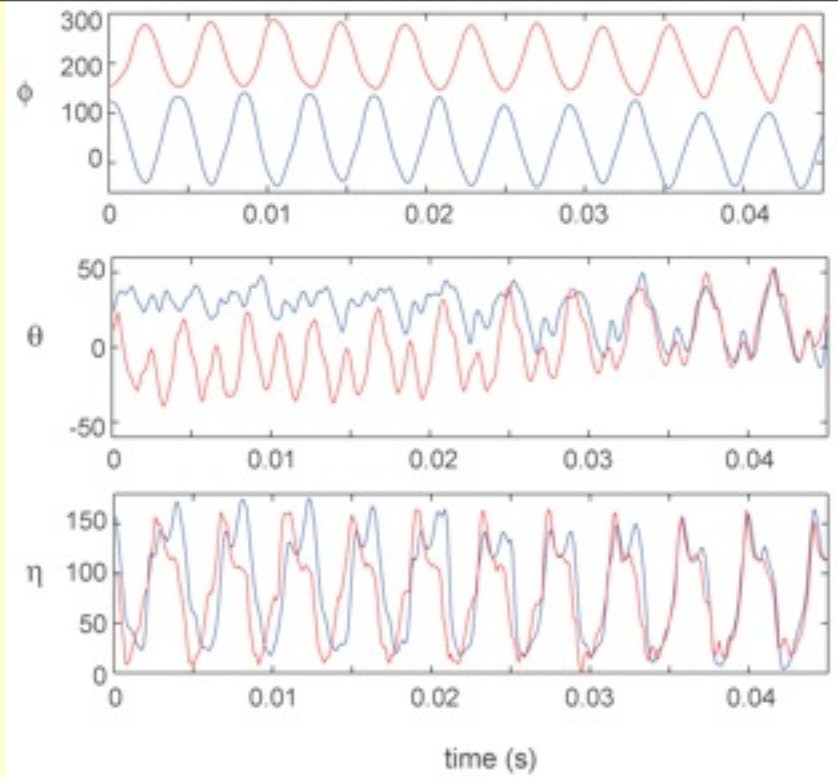
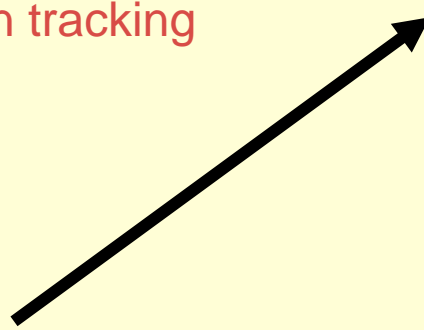


Ristroph and Cohen

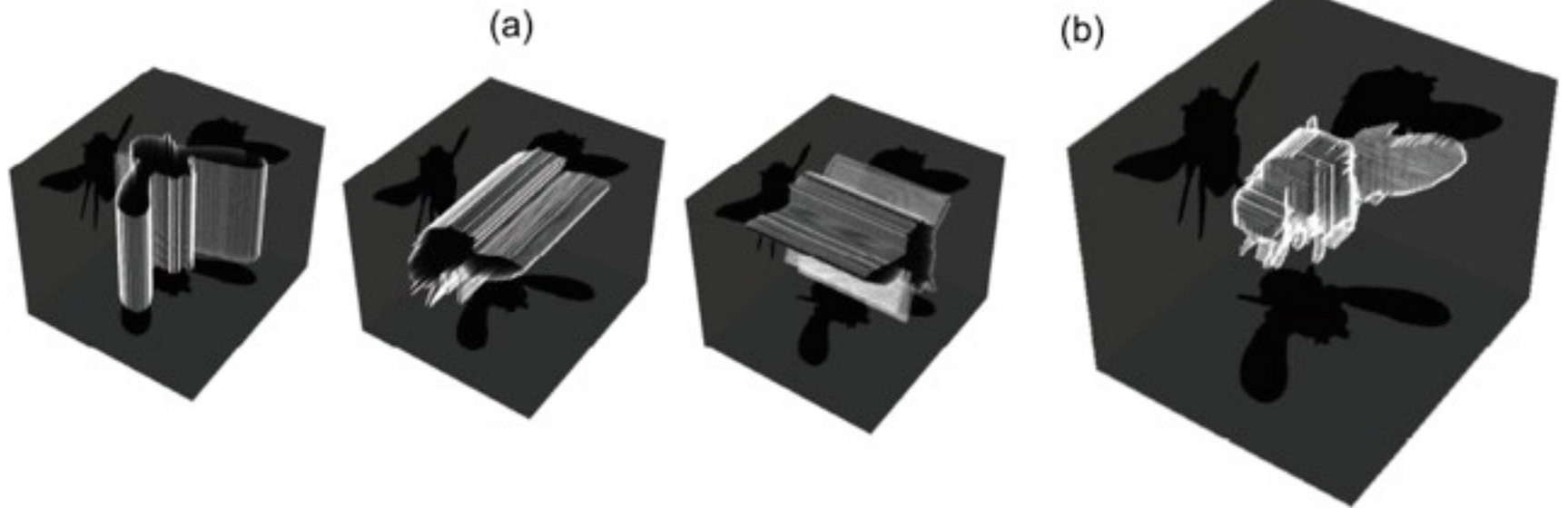
Subtle change of wing kinematics

Lots of data

--> high accuracy & statistics
in tracking



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



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)
 - Principal axes (orientation)

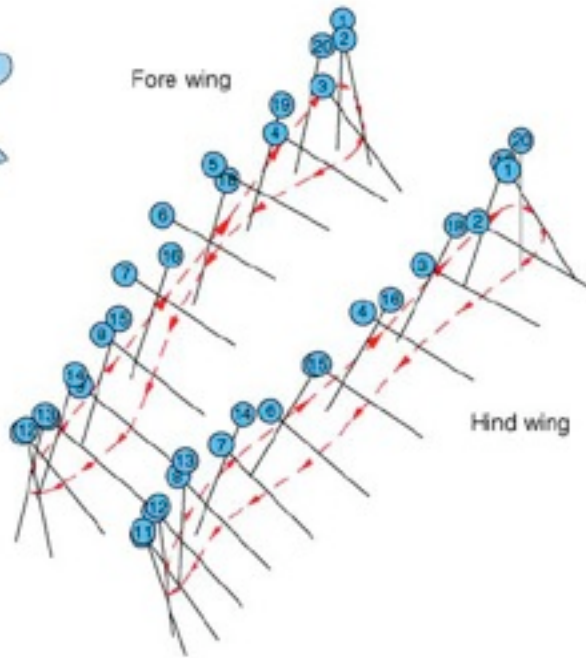
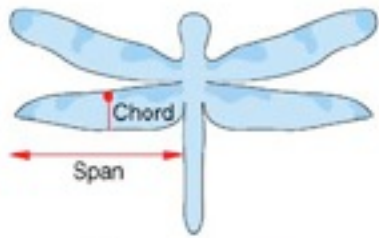
+ camera calibration and etc....

hours

reduced to

minutes

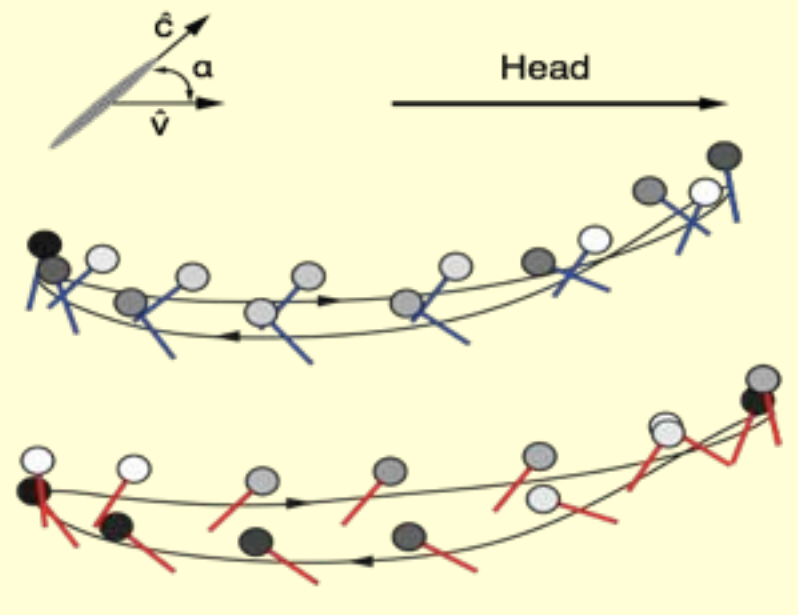
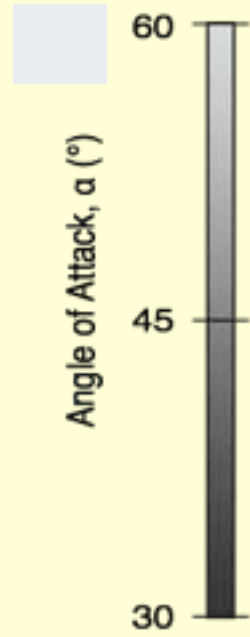
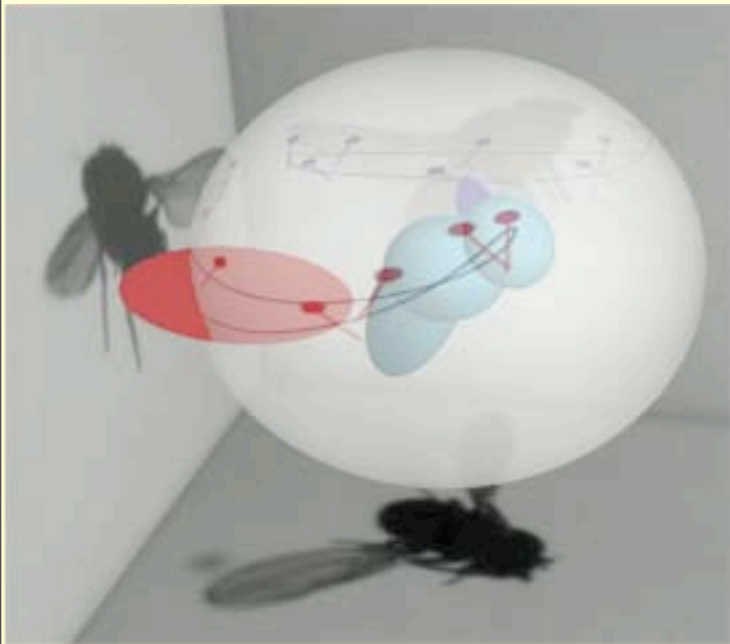
Ristroph et. al, J. Exp. Biol.(2009)



Why the Observed Motions?

dragonfly

fruitfly



Governing Equations

Navier-Stokes equations for incompressible flows:

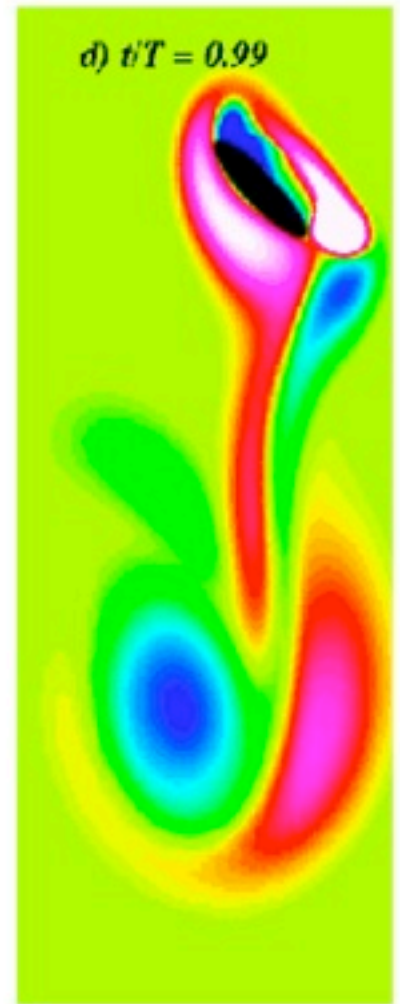
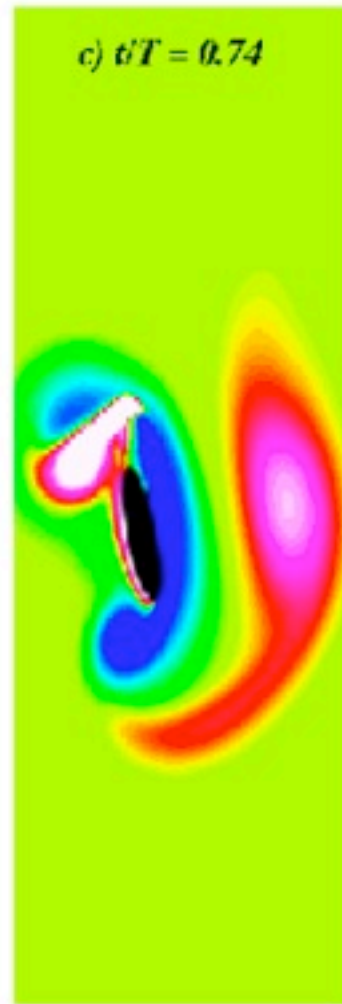
$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{\text{Re}} \nabla^2 \mathbf{u}$$
$$\nabla \cdot \mathbf{u} = 0$$

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

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

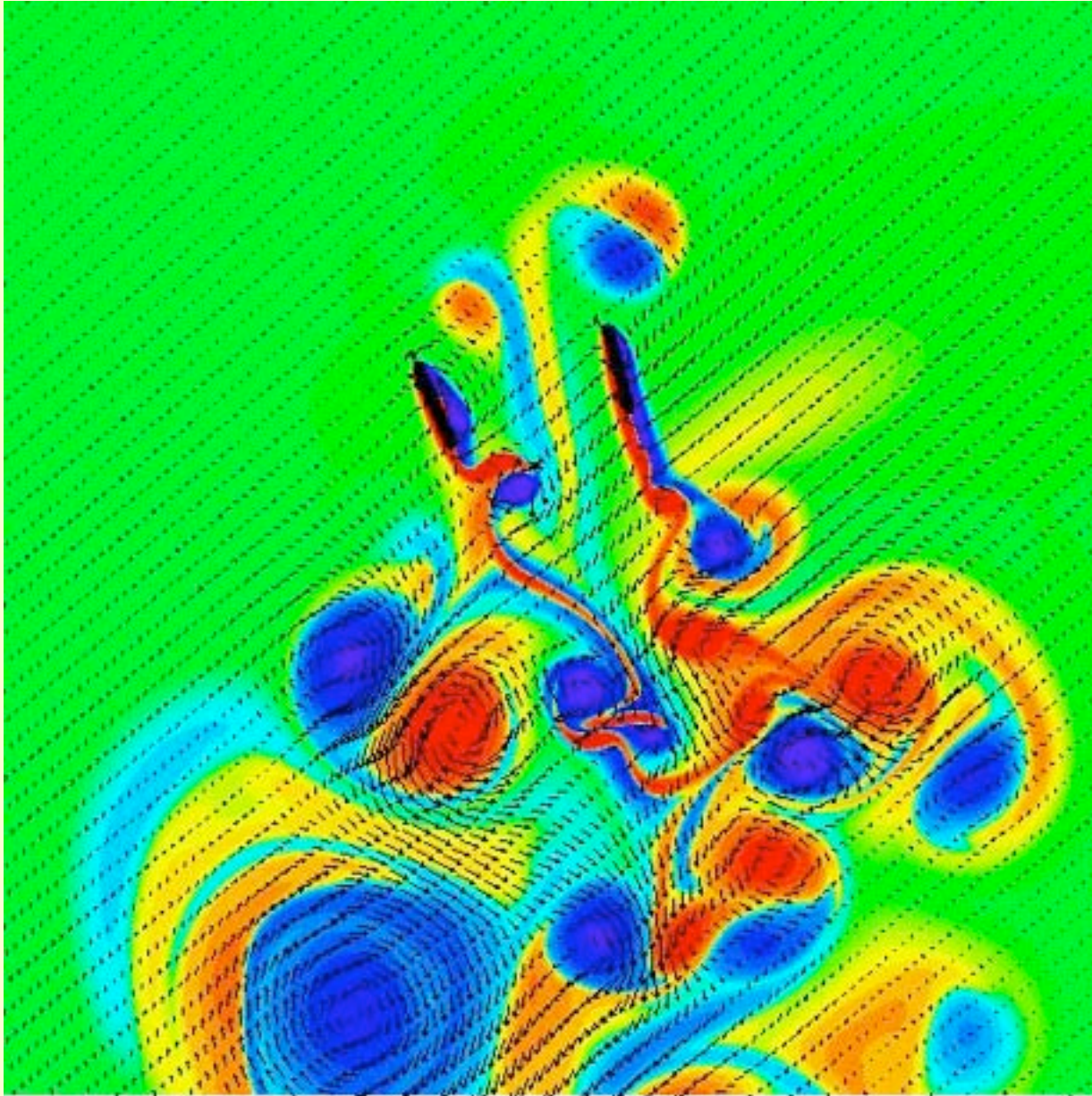
Dynamics of the wing coupled to the fluid:

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



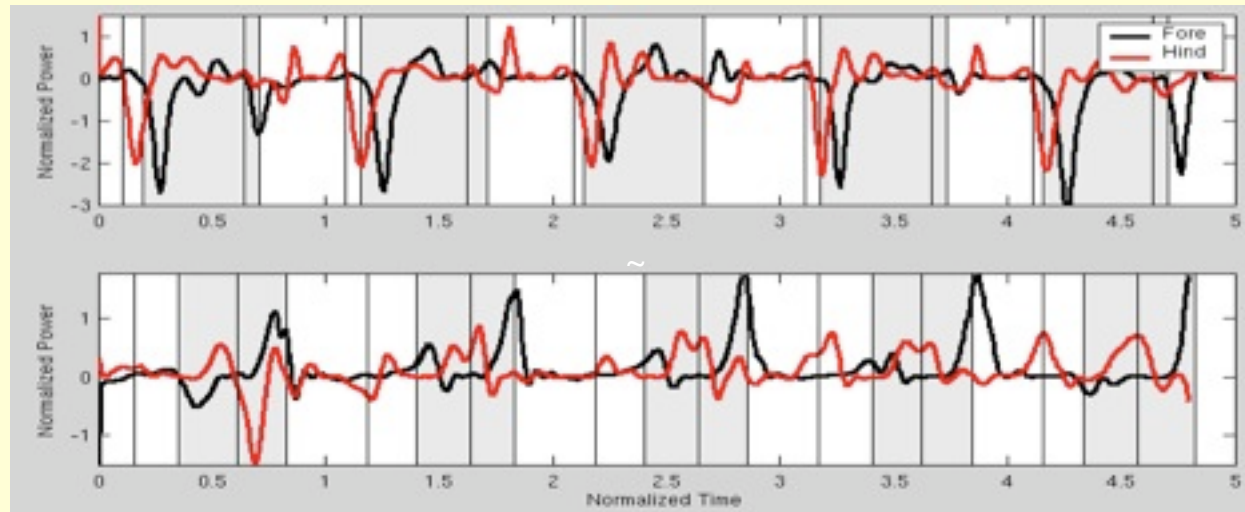
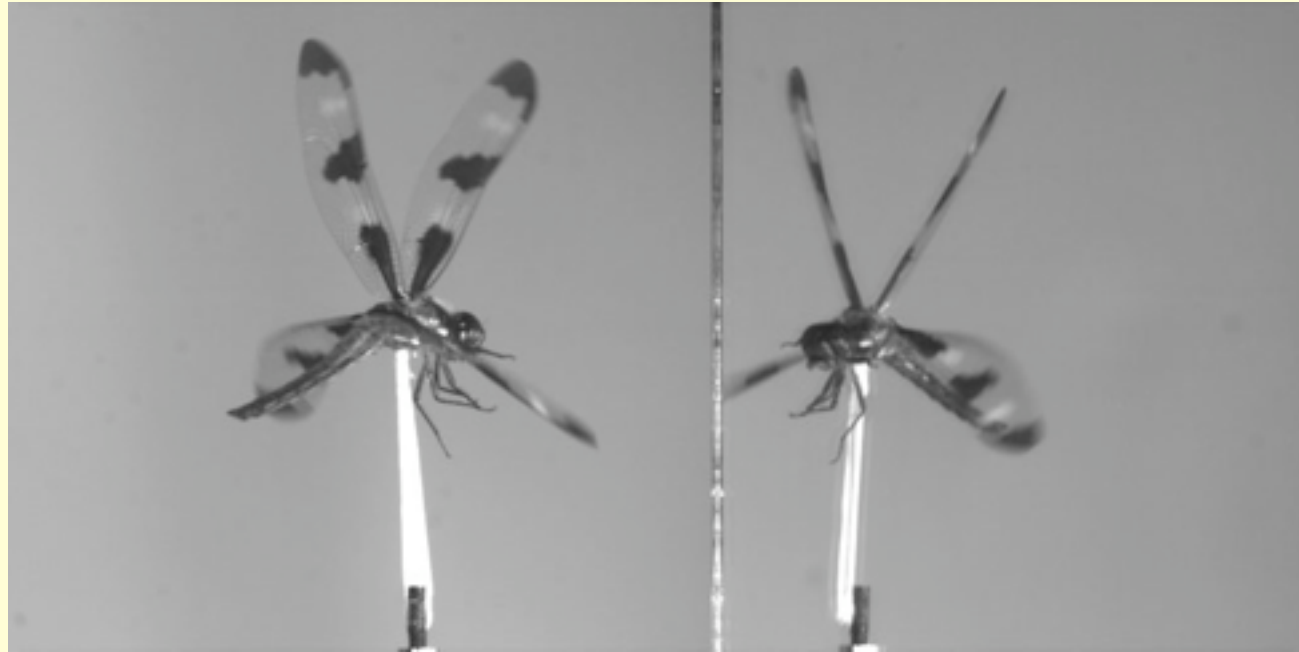
Wang, Physical Review Letters, 2000

Fore-Hind Wing Interactions Can Save Power



Wang and Russell, Phys. Rev. Lett. 2007

Passive Wing Pitching



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

Taking It Apart

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sensory feedback loops

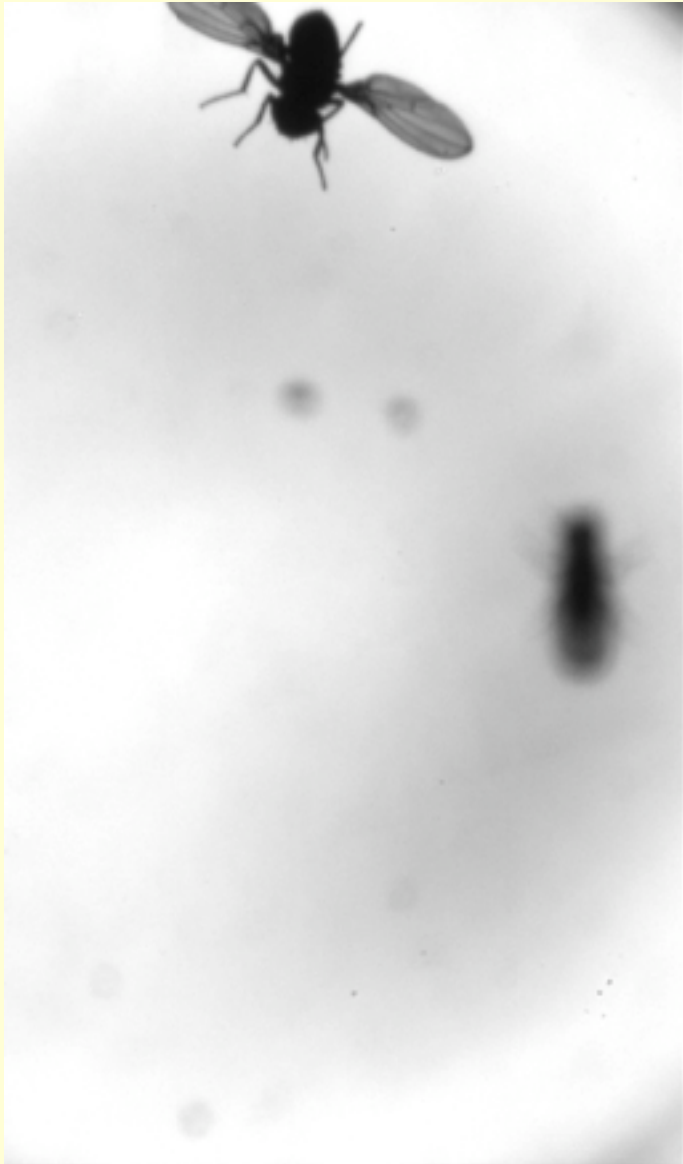
mechanical
visual

time scales

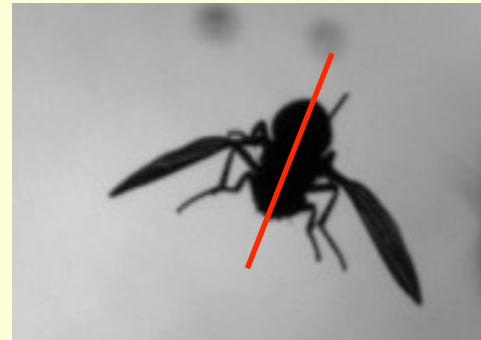
fast compared to ?
slow

Perturbed by Magnetic Field

top view



Start

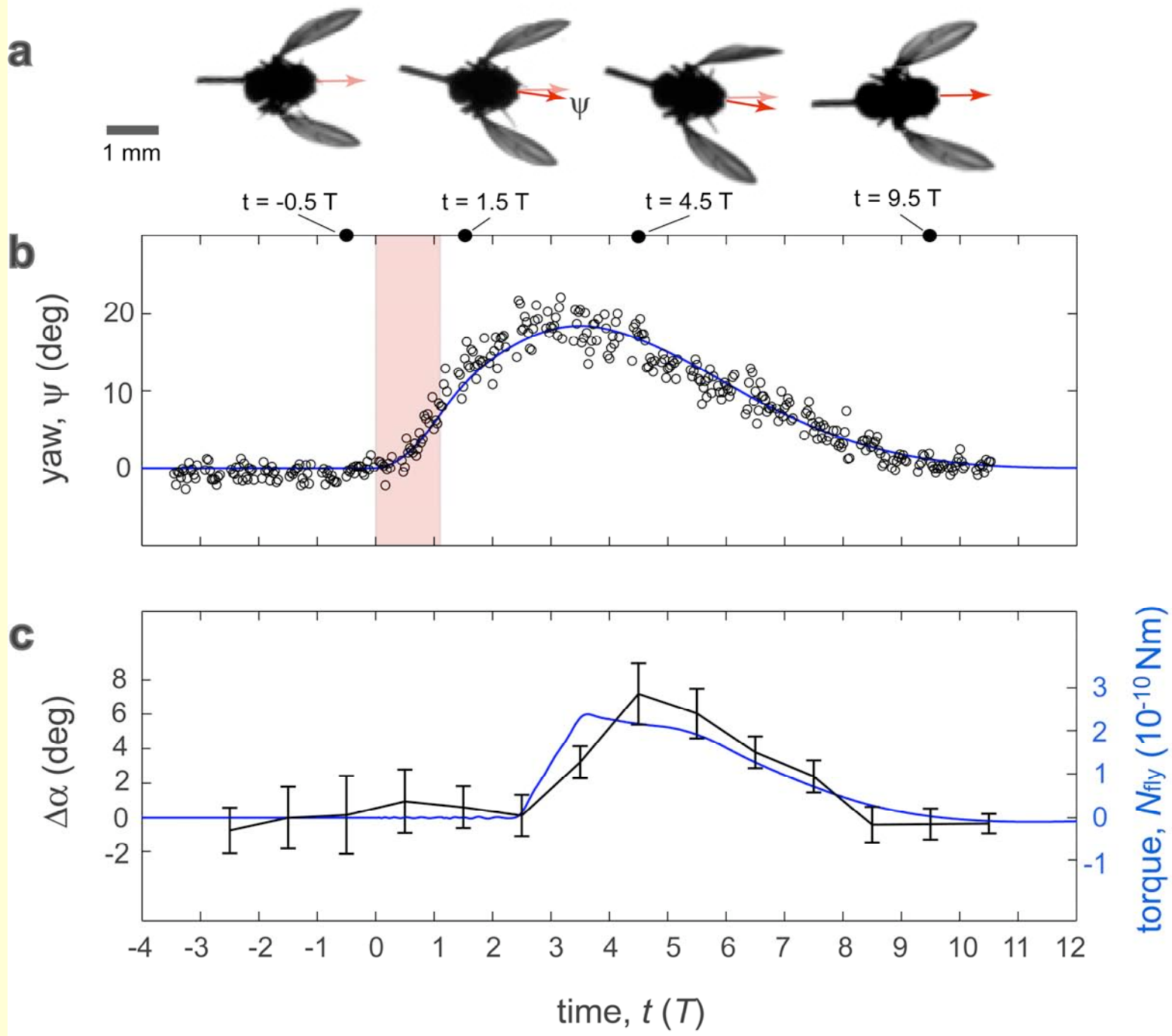


finish

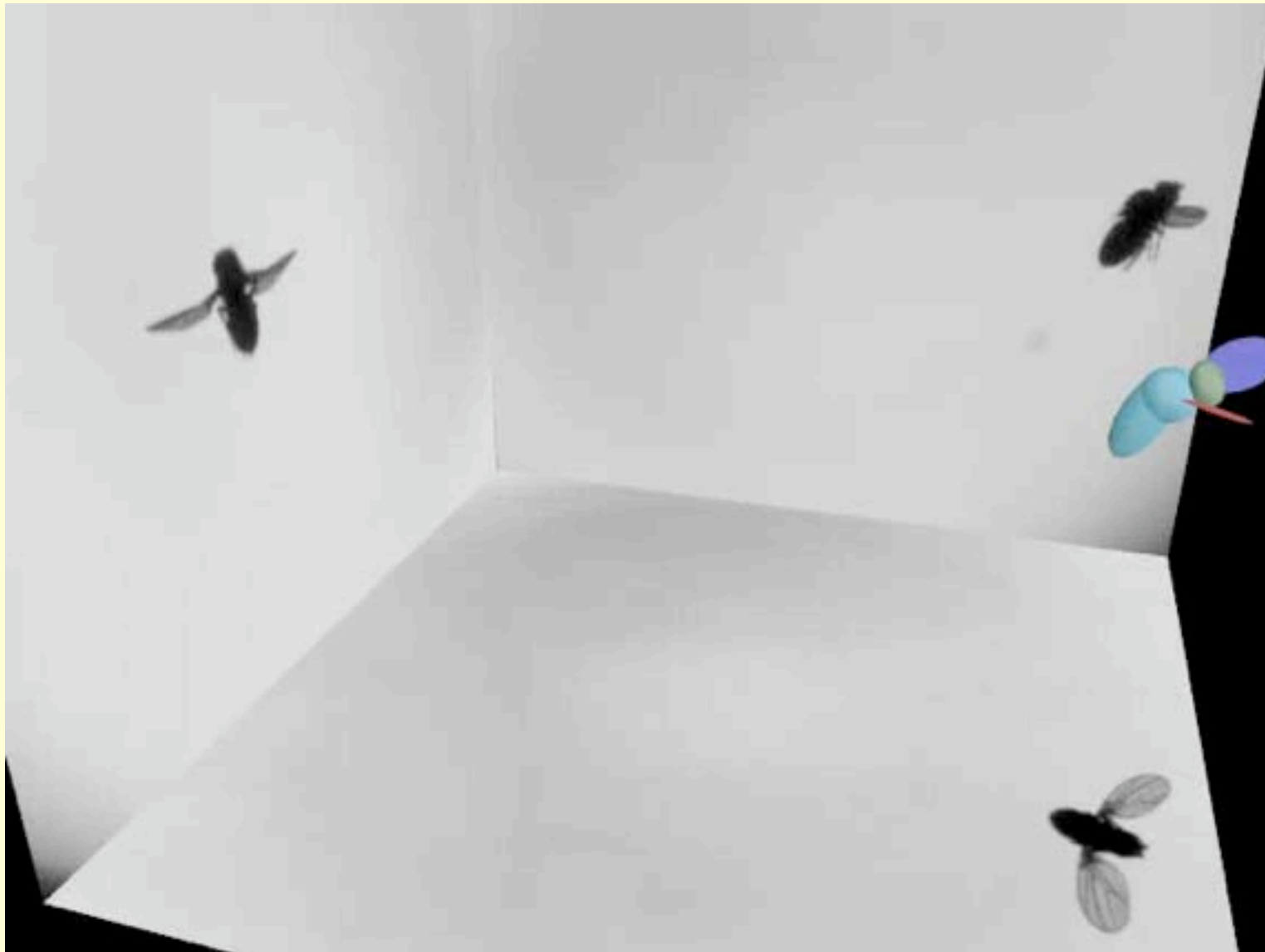


Reset
orientation

Ristroph et al, PNAS (2010)

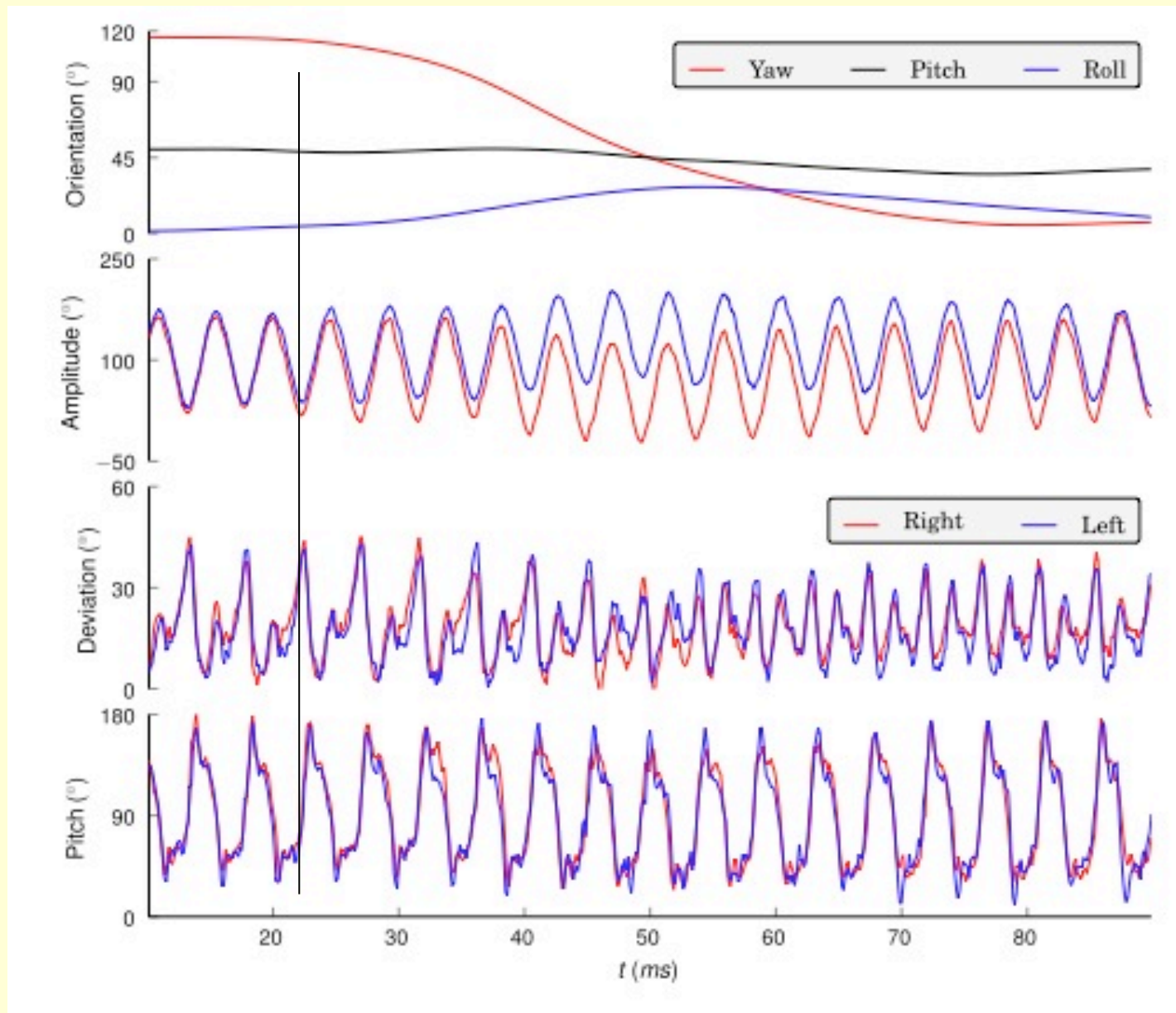


How do fruit flies control their wing to Turn?



Bergou et al., Phys. Rev. Lett. 2010

Body and Wing Kinematics



How is the wing controlled?



Back and forth motion:

Driven by large indirect muscles

Pitching:

Controlled by steering muscles

Inferring (Pitching) Torque

Measure wing kinematics
wing mass, shape, axis of rotation

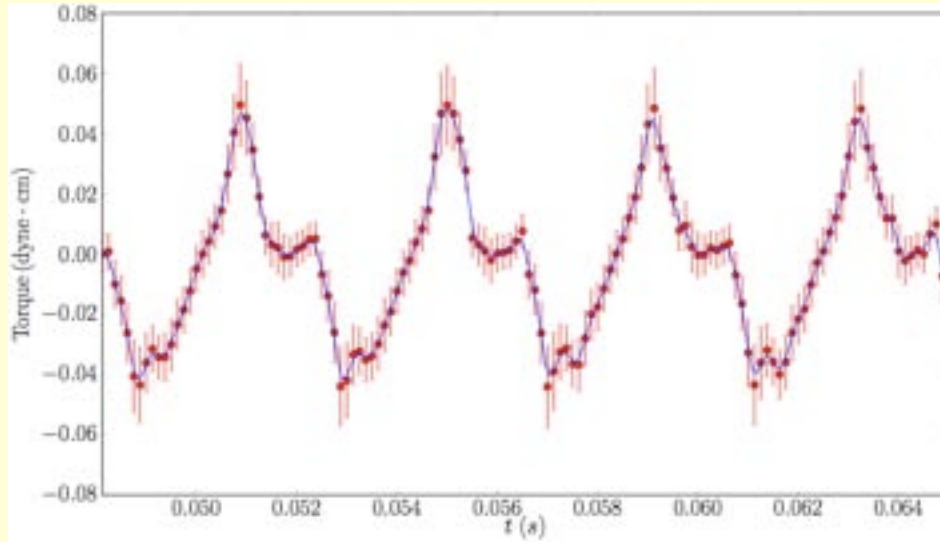
Calculate aerodynamic torque
wing inertia

Deduce torque at the wing base

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

Torsional Spring at the Wing Base

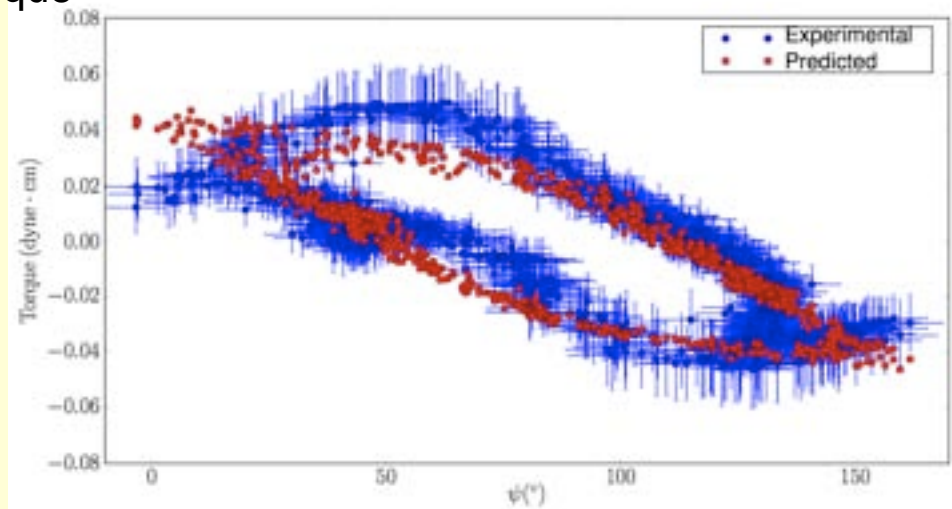
torque



time

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

torque

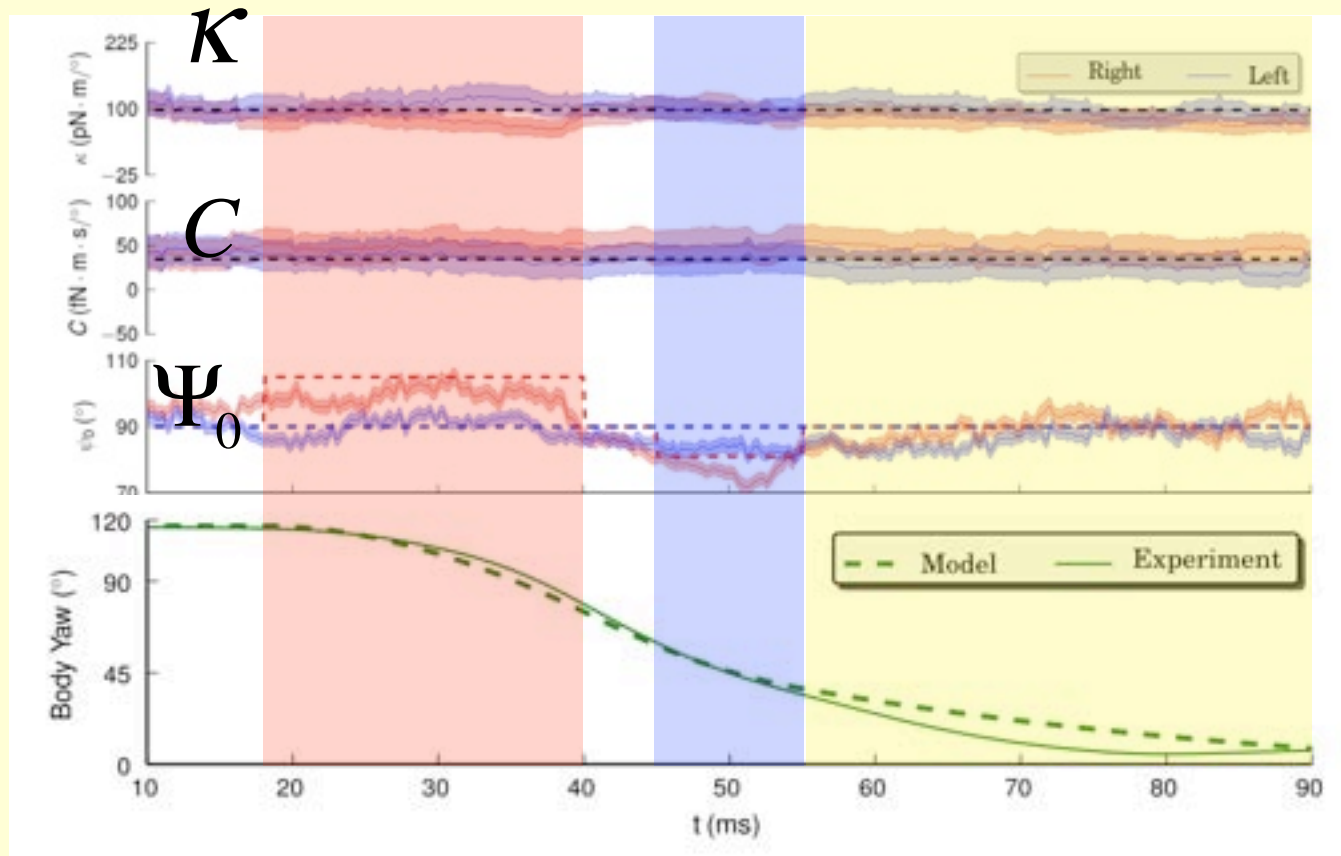


stroke angle

$$\kappa \sim 3 \text{ to } 5 \times 10^{-2} \text{ dyne cm/rad}$$

Determining κ, Ψ_0, C from experimental data

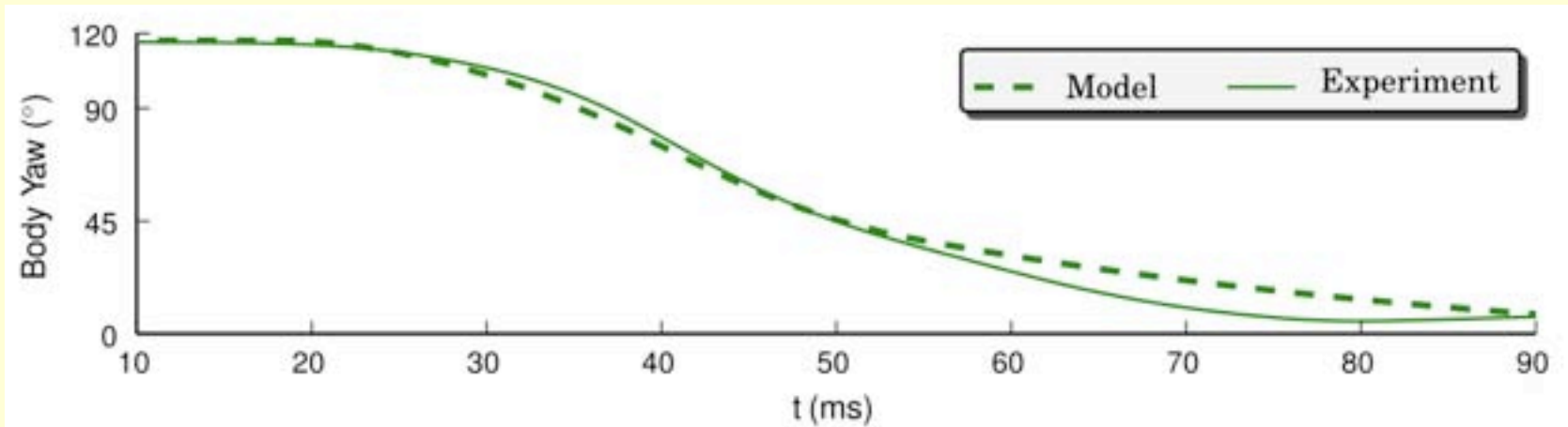
$$\vec{\tau}^{\text{fly}} = -\kappa(\psi - \psi_0) - C\dot{\psi}$$



Predicts Body Trajectory

Back and forth motion: prescribed

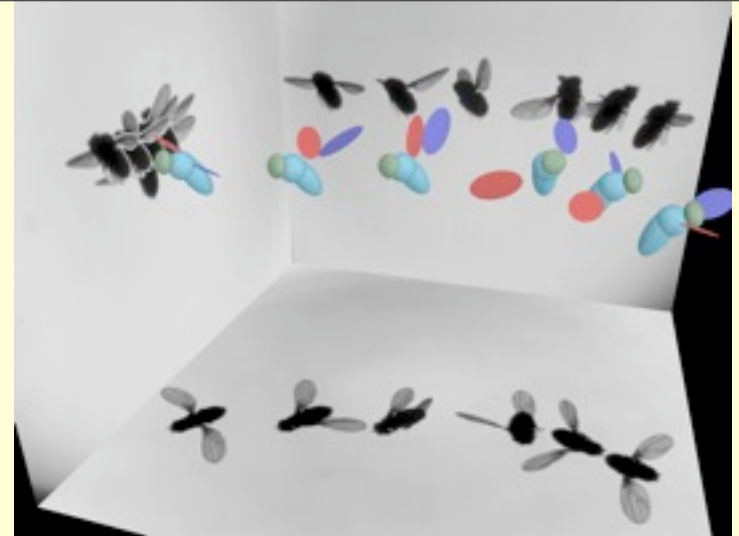
Wing pitch: passive with one control variable



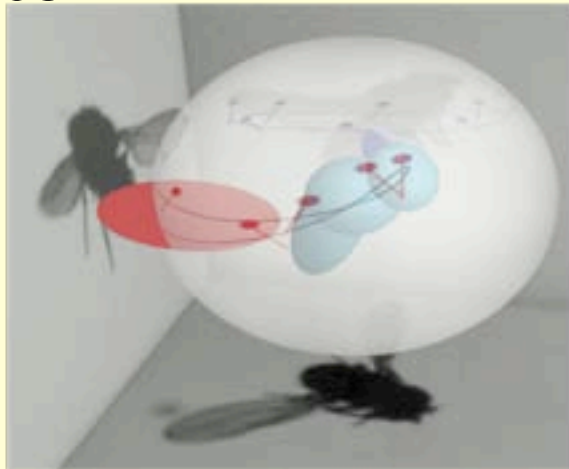
$$I_b \ddot{\phi}_b + \underbrace{2C_\tau \bar{\omega}}_{\text{damping}} \dot{\phi}_b = \underbrace{2C_\tau \bar{\omega}^2}_{\text{driving}} \Delta\psi$$

Putting It Together

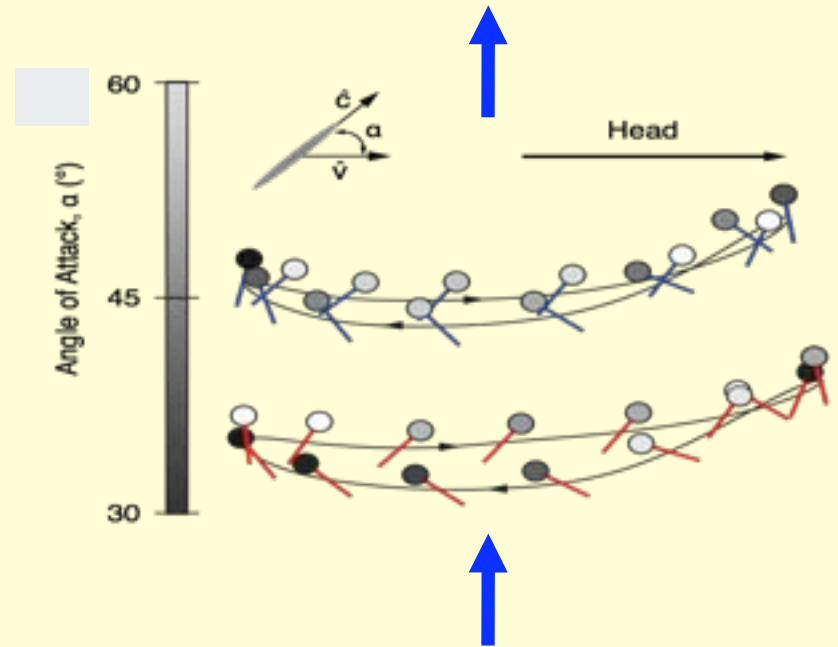
body trajectory



wing kinematics

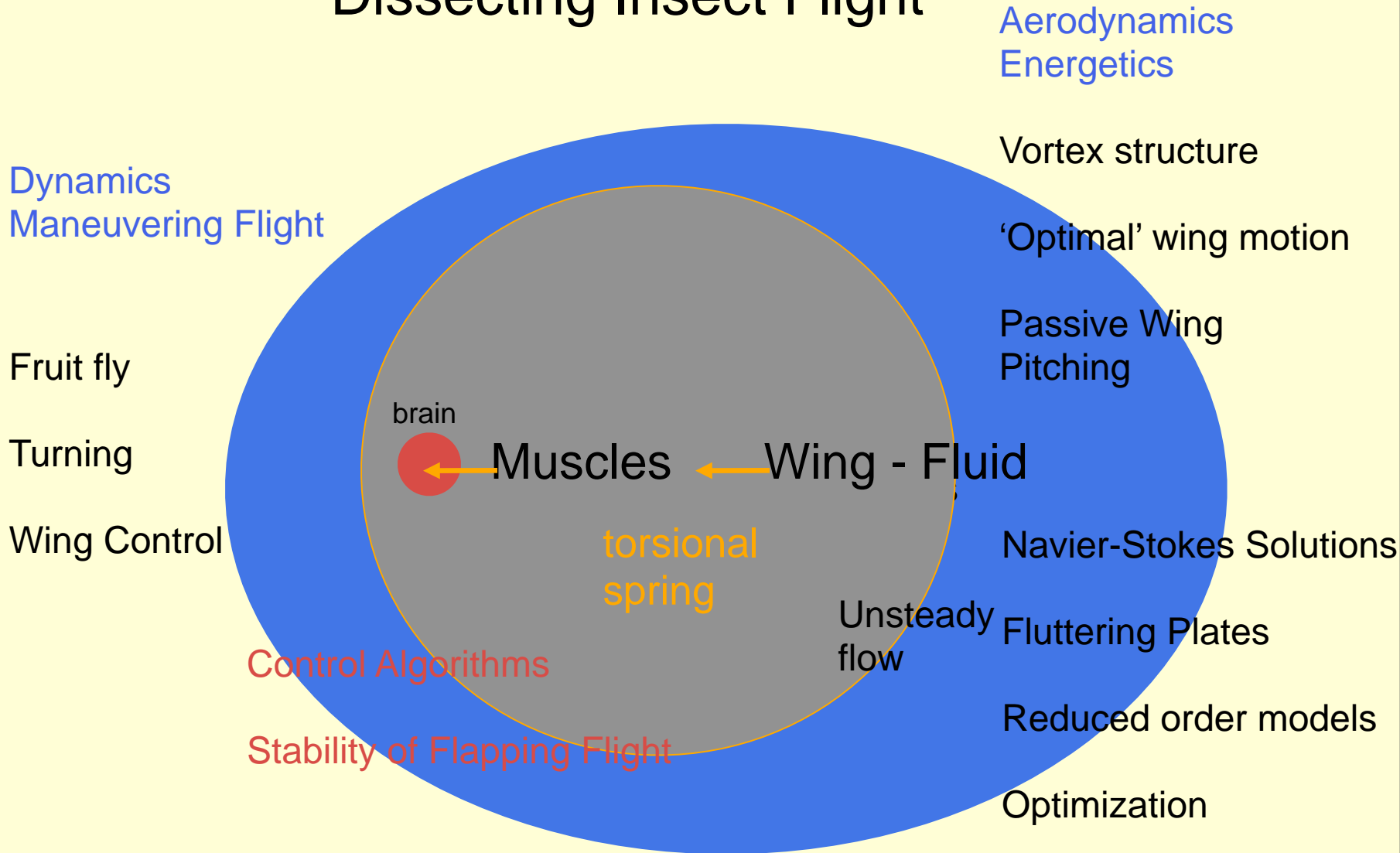


'muscle-wing'



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

Dissecting Insect Flight



Collaborators:

Dragonfly Flight: David Russell

Fruitfly Flight: Leif Ristroph, Attila Bergou, Gordon Berman
Itai Cohen, John Guckenheimer

Papers:

Annual Review of Fluid Mechanics, 2005

Physics Today, Oct. 2008

HRMT (auto-tracking), J. Exp. Biology 2009

Magnetic Field Perturbation, PNAS 2010

Wing Pitch Control, Phys. Rev. Lett. 2010

<http://dragonfly.tam.cornell.edu>

Support: NSF, AFOSR, Packard Foundation