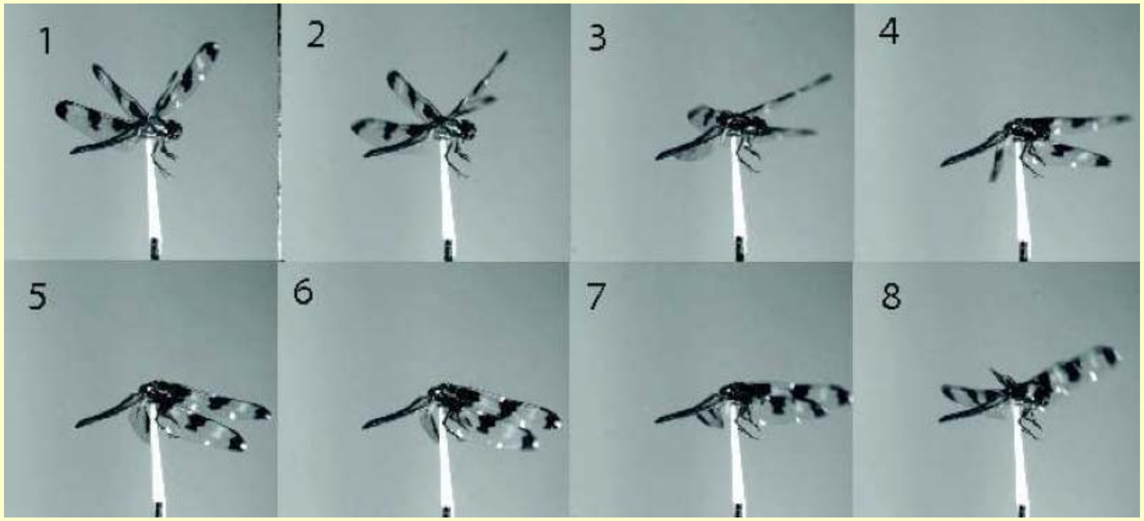
Insect Flight:

Aerodynamics, Efficiency, and Evolution



Z. Jane Wang

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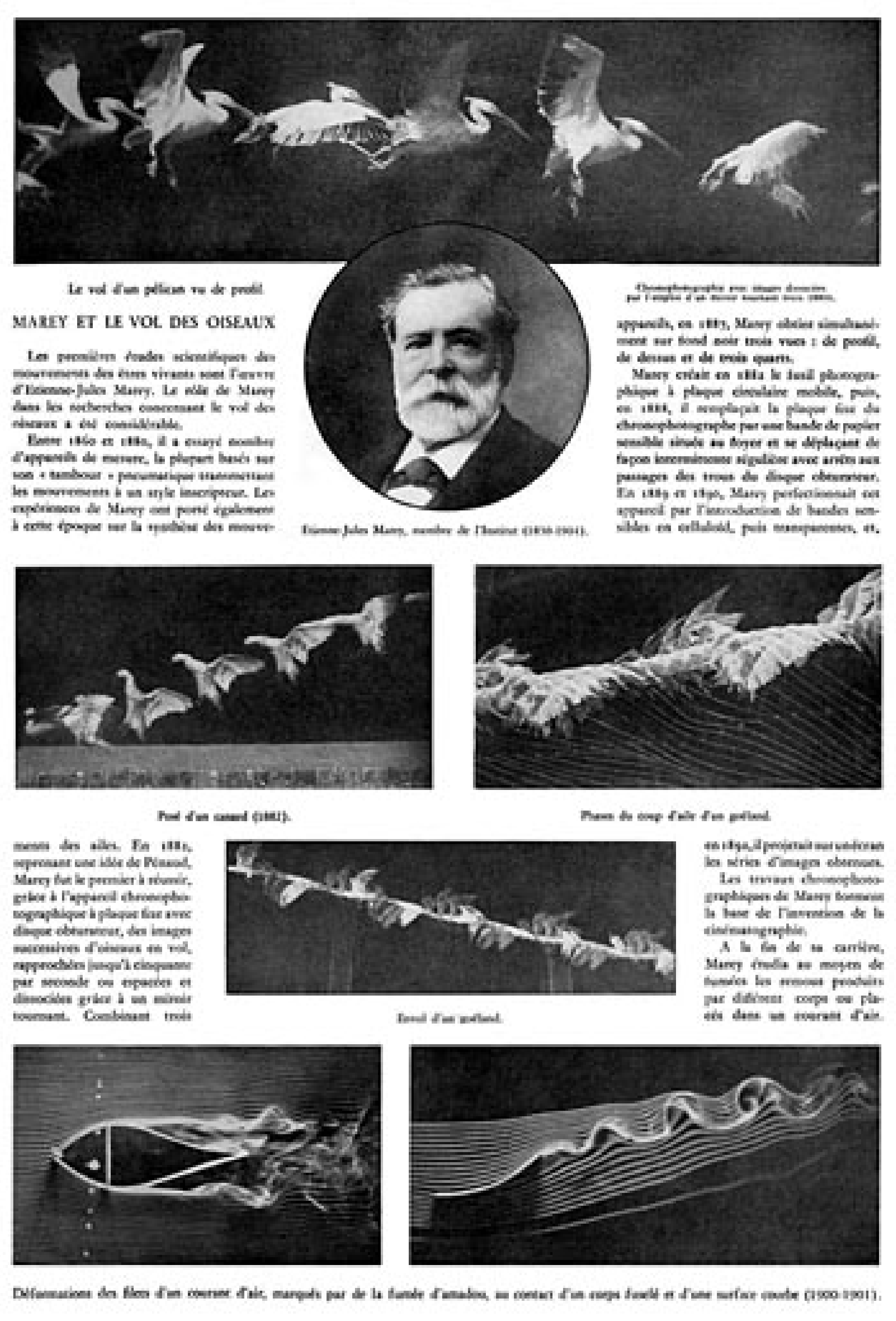


Le vol d'un pélican vu de profil.

Chronophotographie avec images dissociées par l'emploi d'un miroir tournant (vers 1880).

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 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 1887, 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.

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

Posé 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

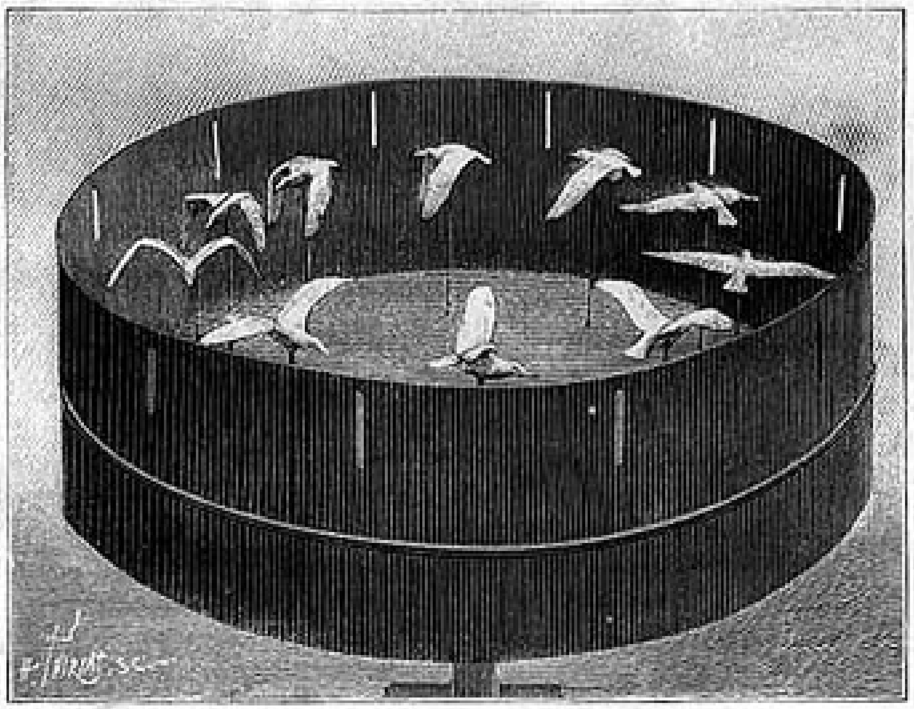
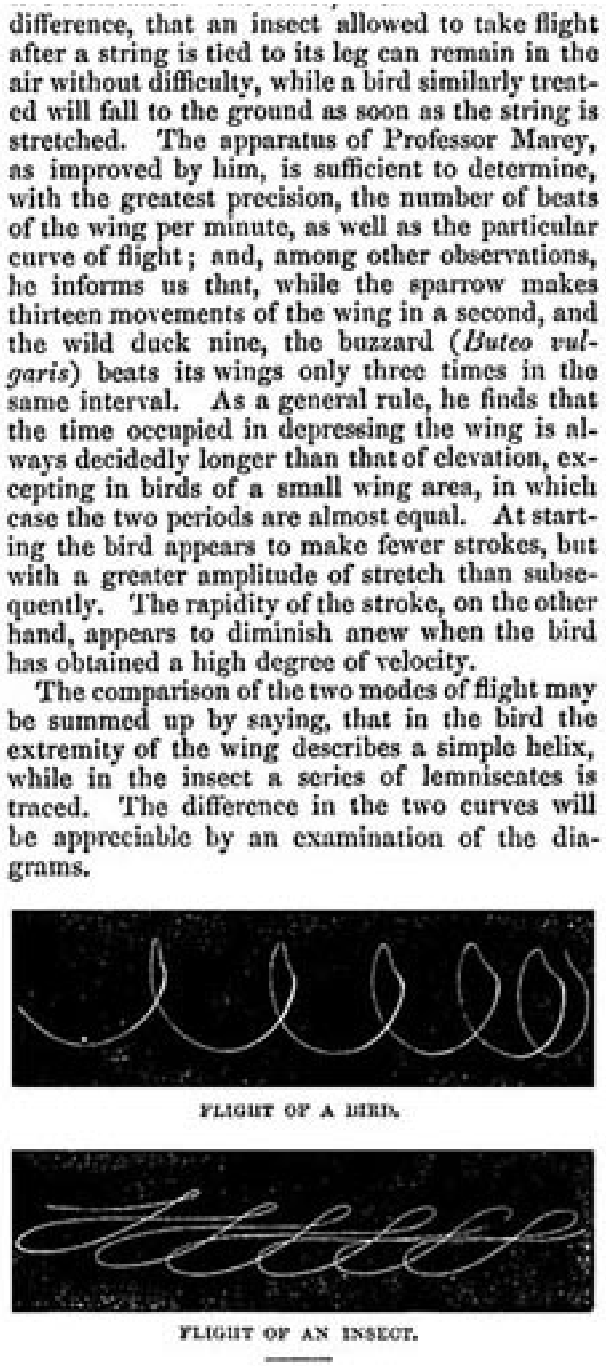


Fig. 9. — Zootrope dans lequel sont disposées 10 images en relief d'un goéland dans les attitudes successives du vol.



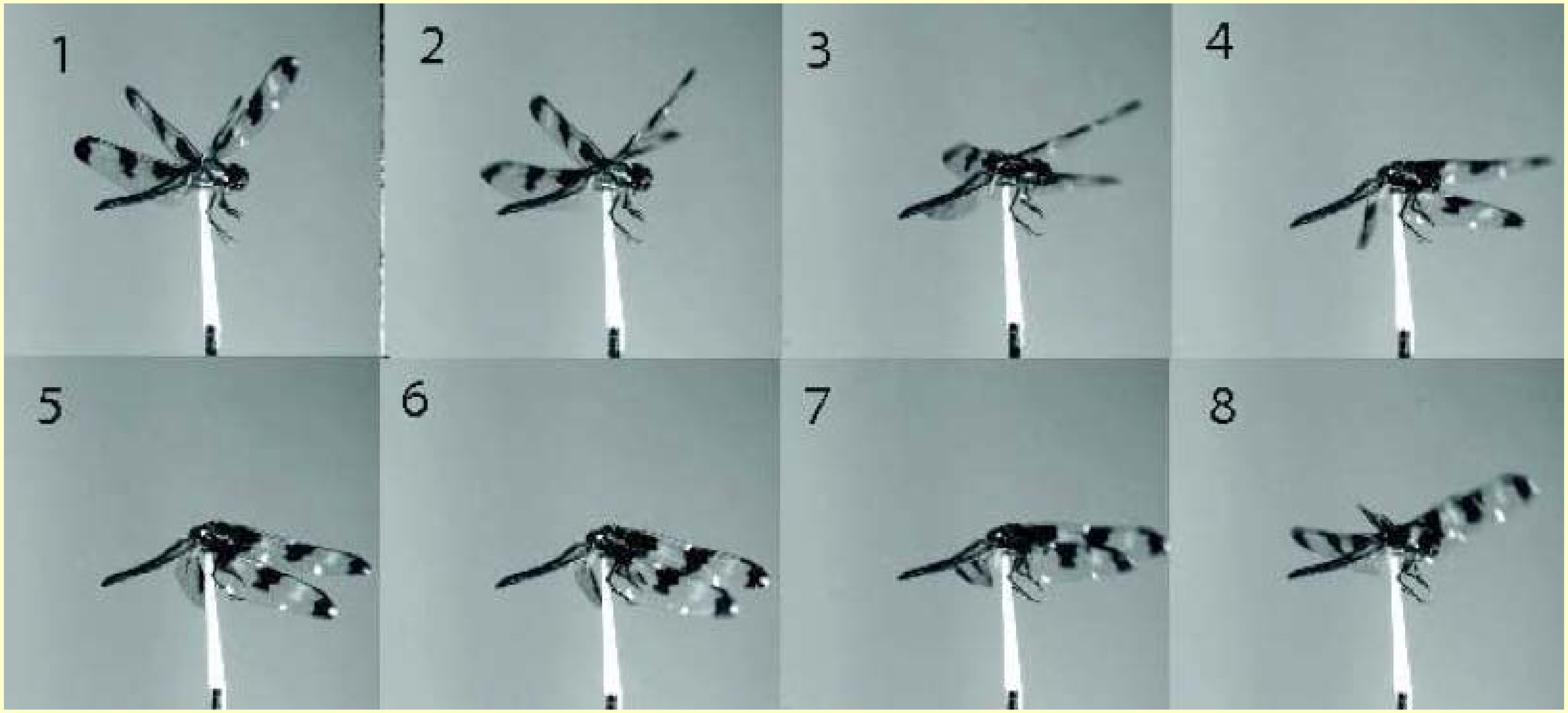
difference, that an insect allowed to take flight after a string is tied to its leg can remain in the air without difficulty, while a bird similarly treated will fall to the ground as soon as the string is stretched. The apparatus of Professor Marey, as improved by him, is sufficient to determine, with 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.

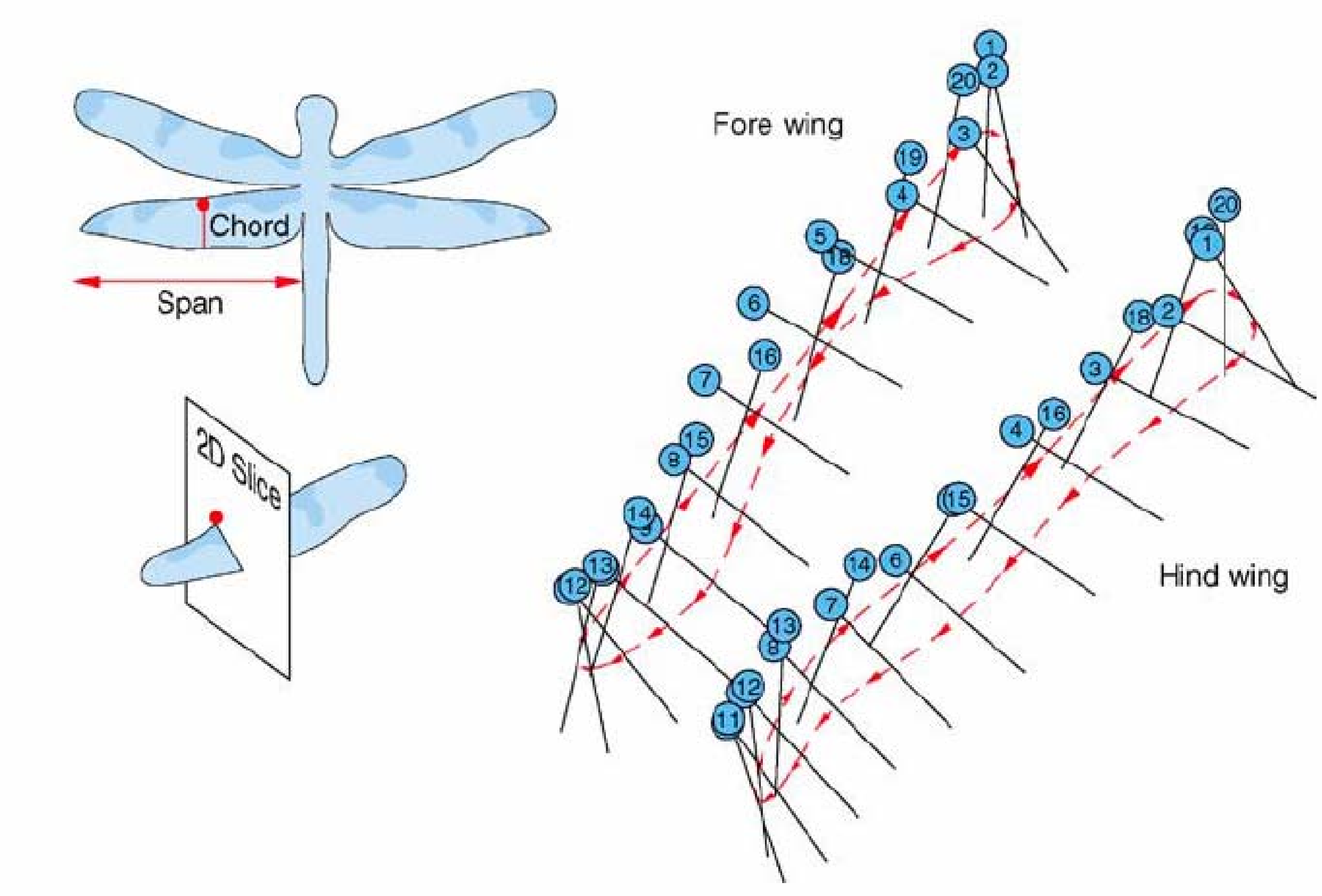
FLIGHT OF A BIRD.

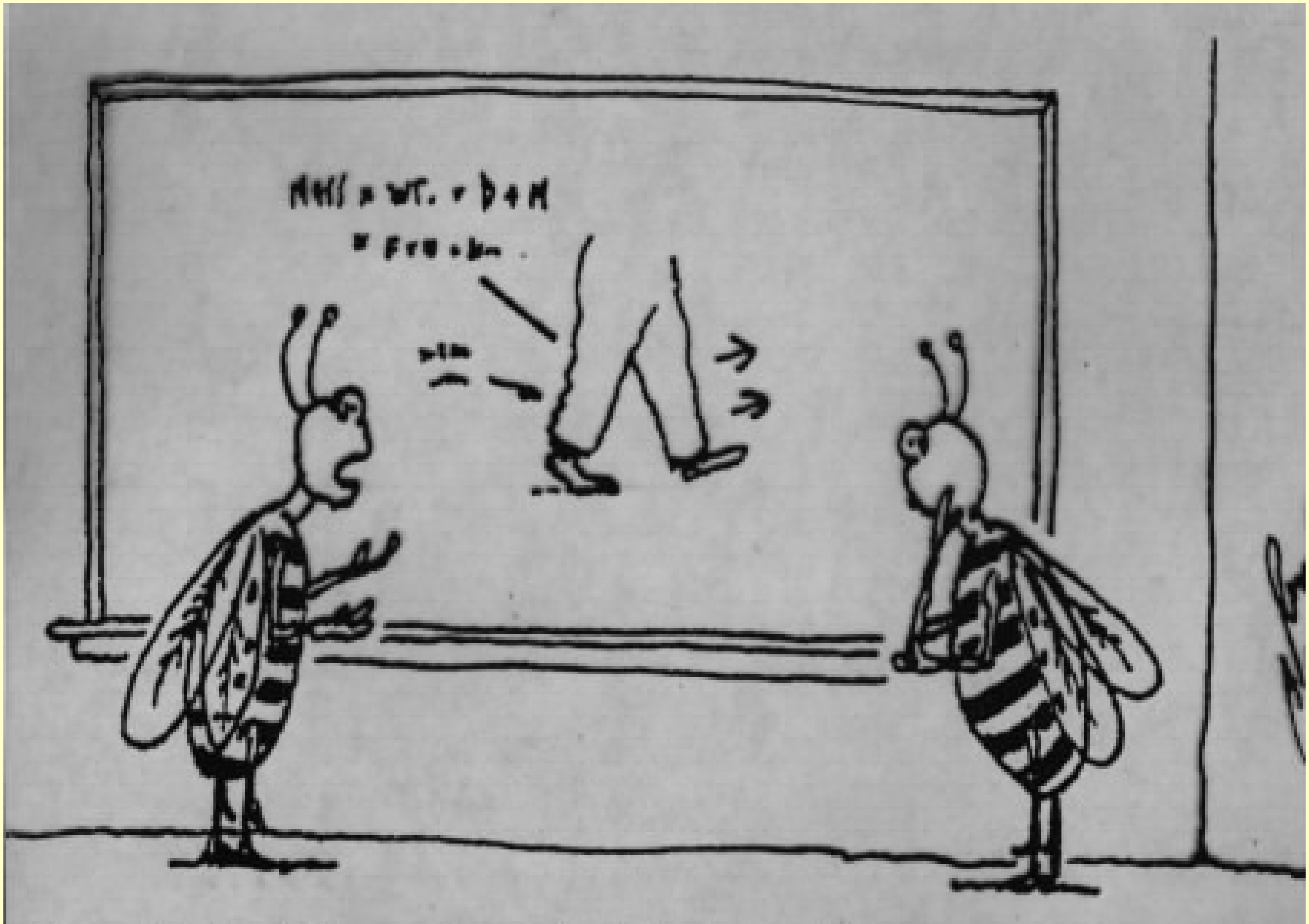
FLIGHT OF AN INSECT.

Harper Magazine
1870



L ~ 1cm
f ~ 40Hz
Re ~ 3000


Chord
Span
2D Slice
Fore wing
Hind wing



“According to all known laws of physics it should be impossible for them to walk

Rayleigh (1842) Kichhoff (1887) ……

Lanchester (1897) Kutta (1903) Joukowski (1903)
Prandtl (1914) Wagner(1925) Karman and Sears (1938) ……

Dragonflies (~350 Millions years ago)

Navier-Stokes Equation Subject to Wing Motions

Incompressible flow:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla P / \rho + \nu \nabla^2 \mathbf{u}$$

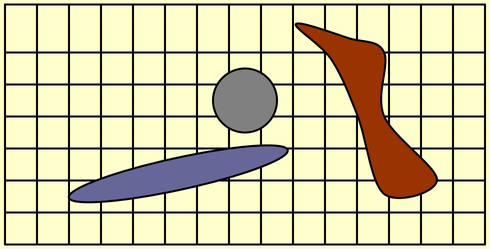
$$\nabla \bullet \mathbf{u} = 0$$

Boundary condition (no-slip):

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

Moving wing:

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



Why compute and which methods?

1. Single rigid wing in prescribed or free motion

   -Co-moving frame, 4th order in time and space (Phys. Rev. Lett. ‘00, ‘04)

2. Multiple rigid wings in prescribed motion

   -Cartesian grid + overset grid, 4th order in time, 2nd order in space

   (J. Comp. Phys.’03)

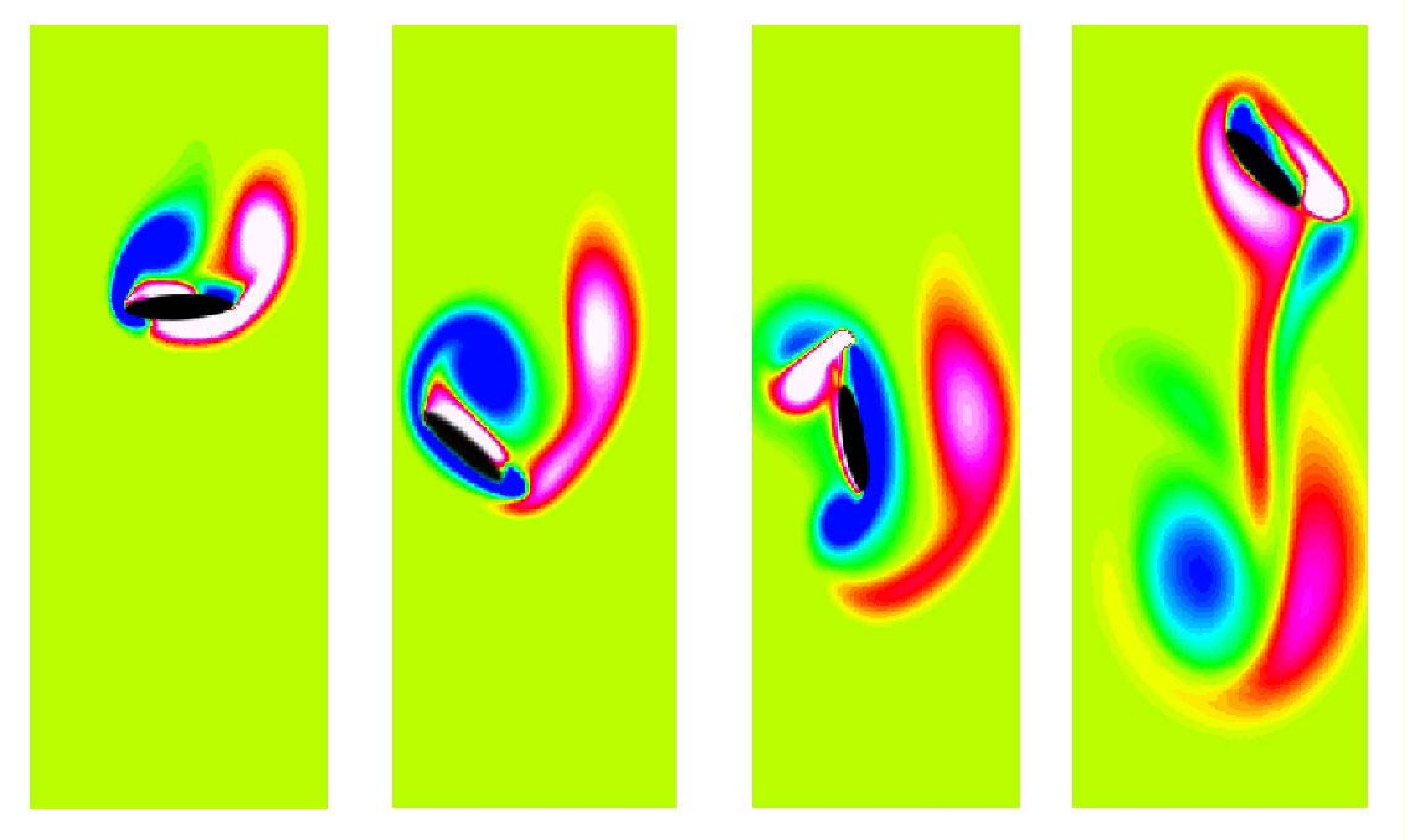
3. Multiple flexible wings in prescribed motion or prescribed force in 2D

   -Immersed Interface Method 2nd order in space and time

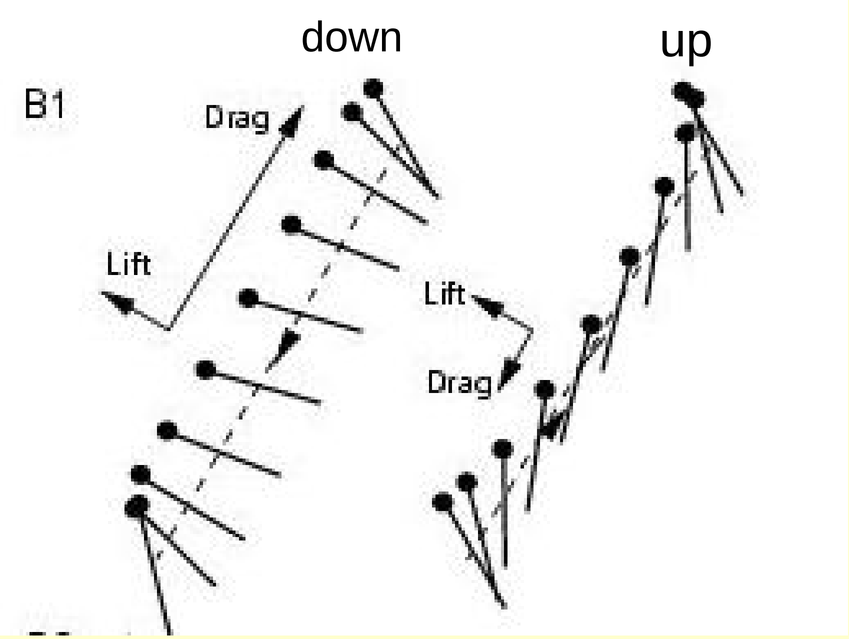
   (SIAM Sci. Comp. ‘05, J. Comp. Phys. ‘05)

4. Multiple flexible wings in 3D

   -Immersed Interface Method 2nd order in +space and time (Comp. Mech. ‘07)



ZJW, PRL 2000

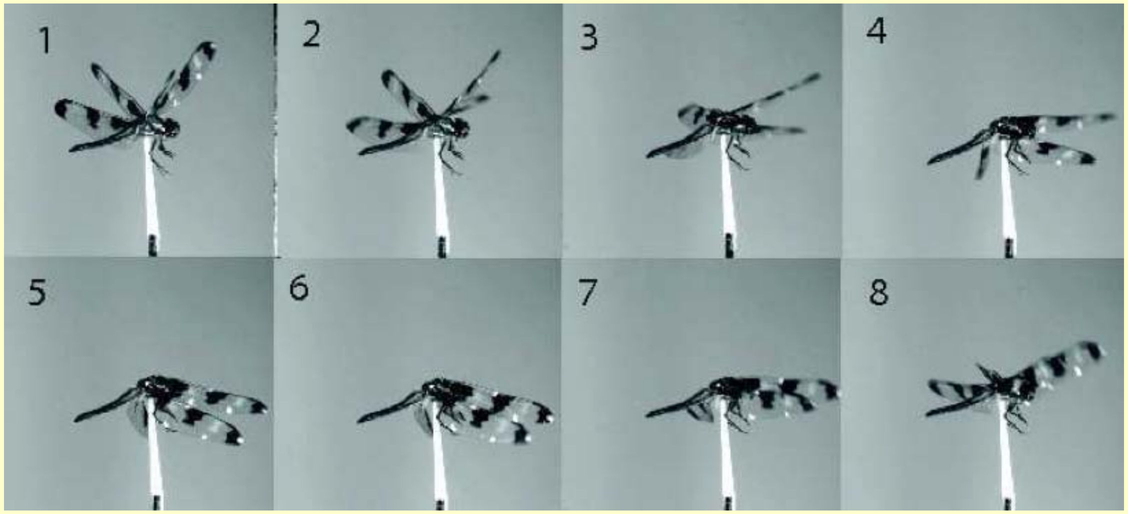


Dragonfly = Drag on Fly

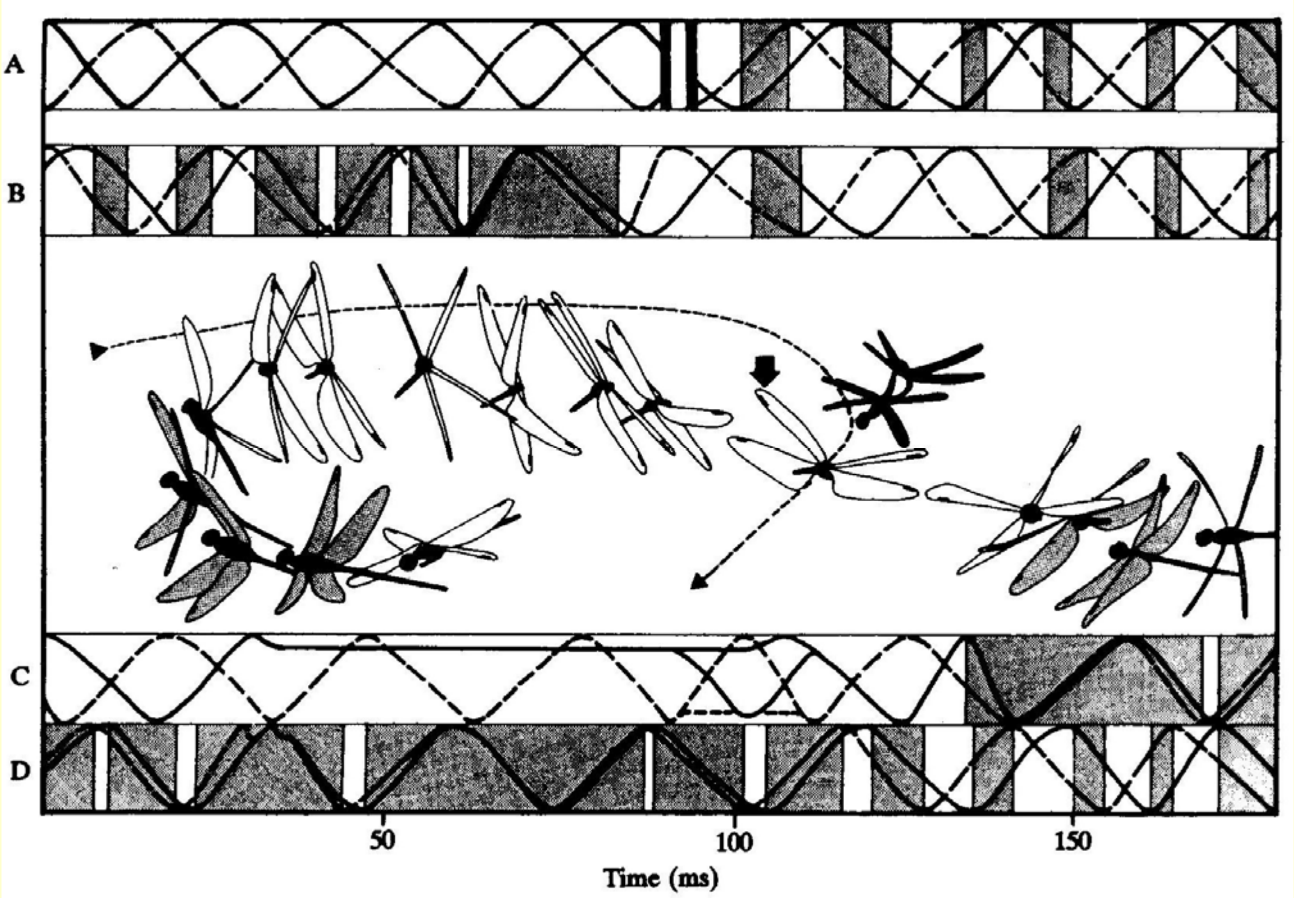
Drag supports majority of the weight.

If drag is neglected, the required lift coefficient ~ 4-5, which is ‘anomalously high’.

Why insects flap their wings the way they do?

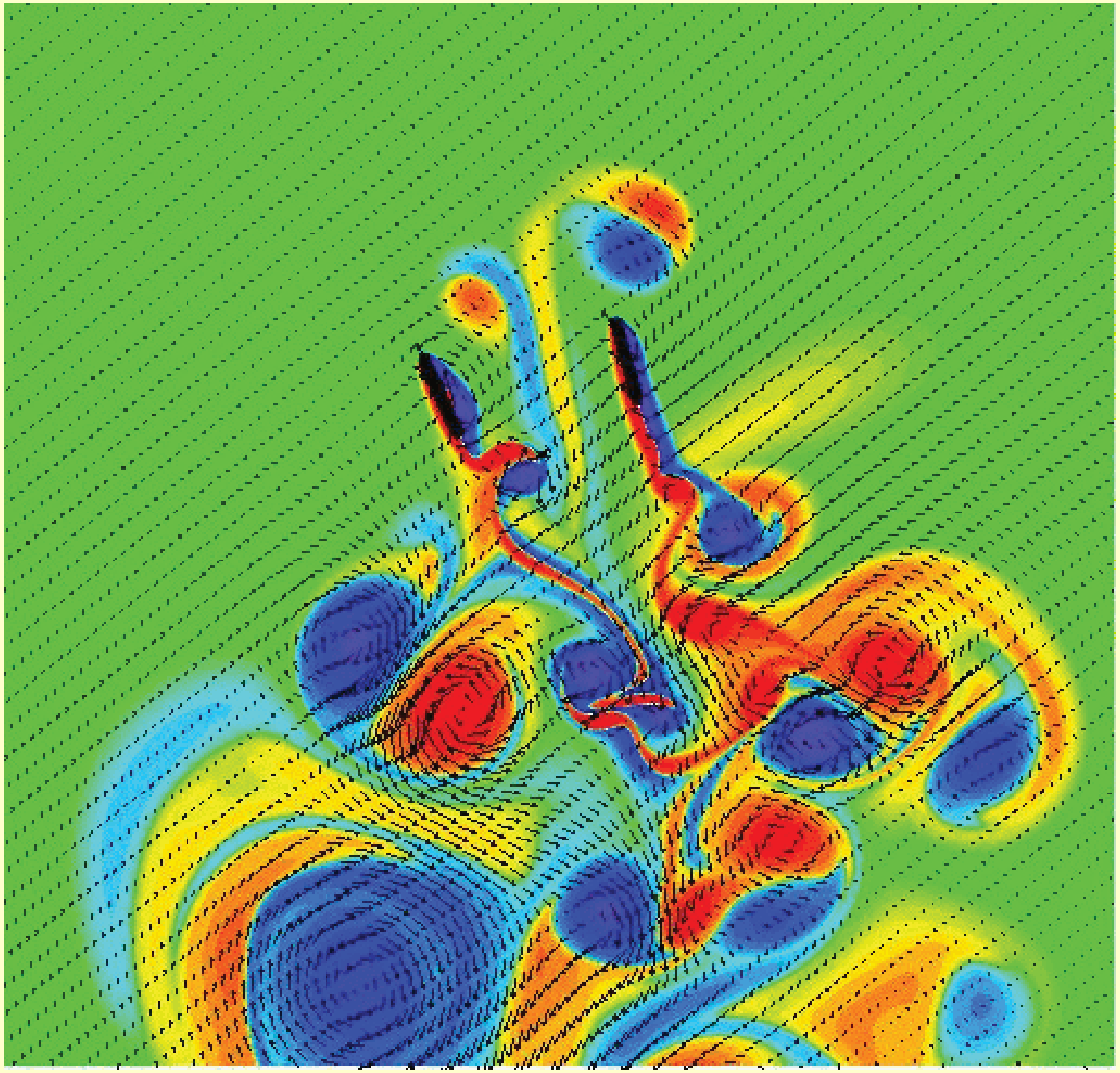


Fore-hind Wing Interactions

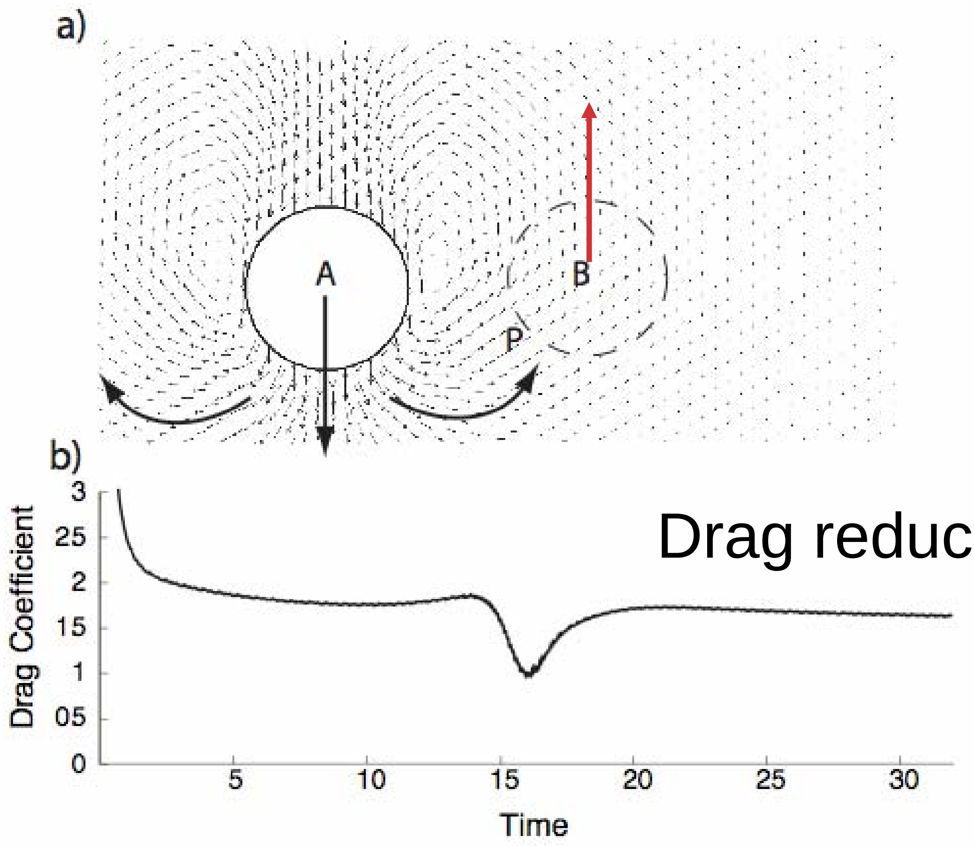


~180° phase difference during hovering.
~90° phase difference in forward flight.
~0° phase difference for large forces.

Ruppell (1989)



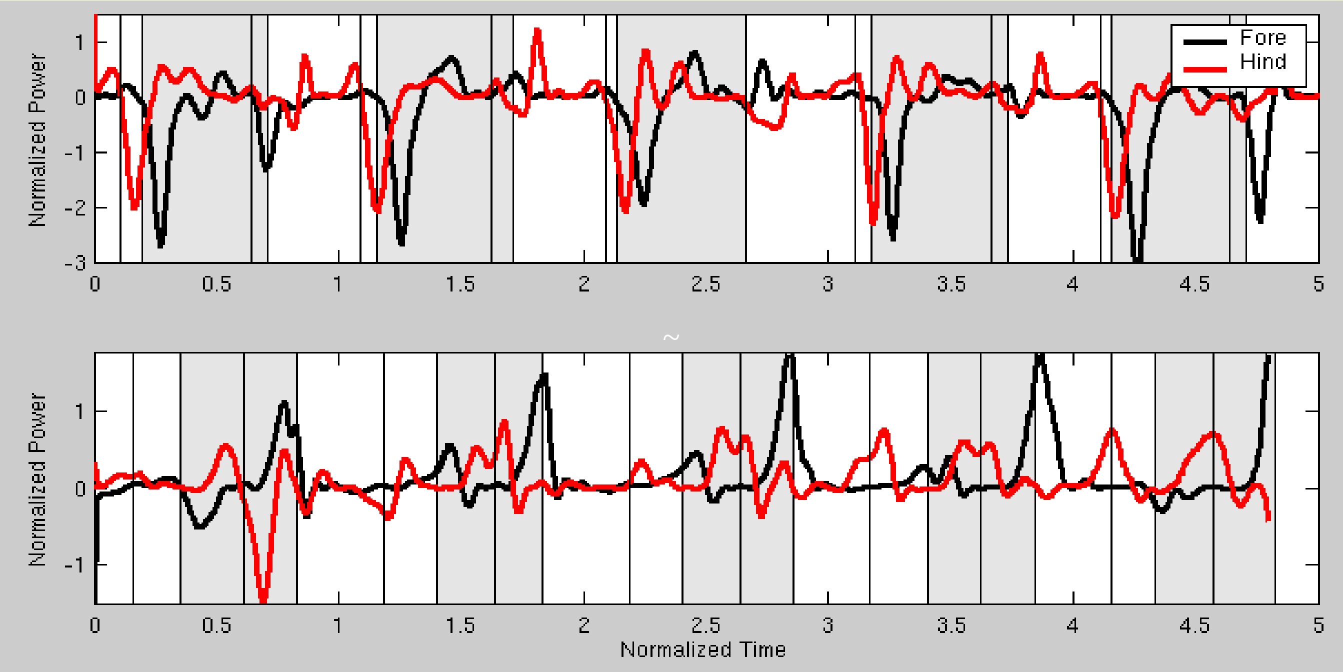
Fore-Hind Wing Interaction
Can Reduce Power for Hovering



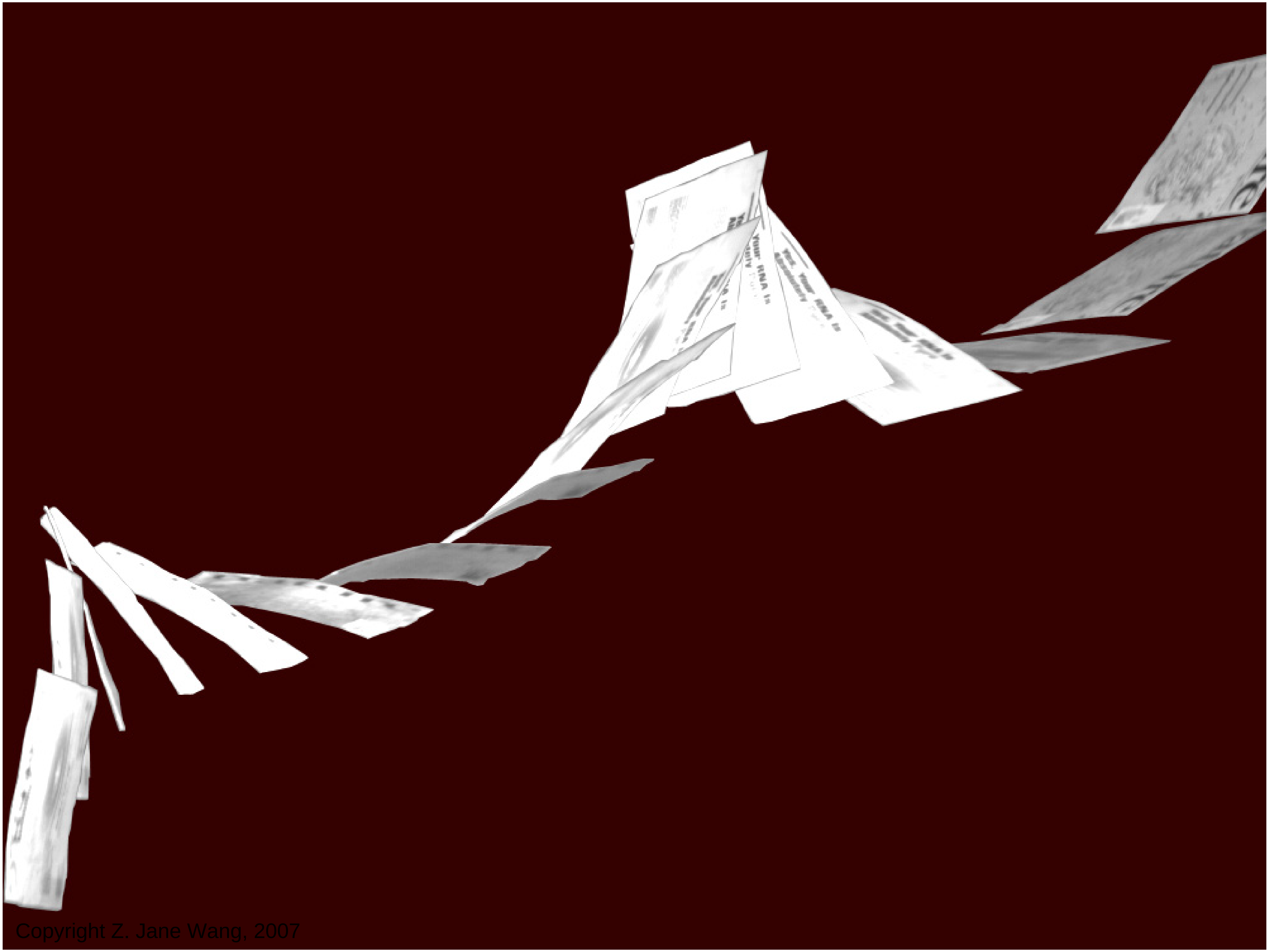
Drag reduction

ZJW, D. Russell, PRL 07

Passive Wing Pitching



A. Bergou, S. Xu, ZJW, J. Fluid Mech., 2007



Are Insect Wing Motions Optimal ?

Why should nature optimize?

Optimize what?

Do Insect Wing Motions

Minimize Energetic Cost?

Why should they?

Which energy?

Do Insect Wing Motions Minimize Mechanic Power in Hovering?

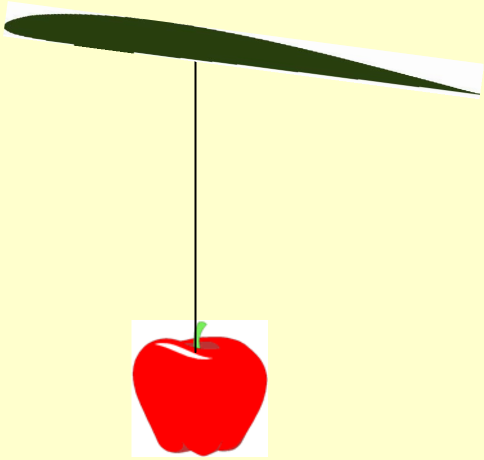
Why should they?

Do they?

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

Optimized Wing Kinematics vs. Observation

Fruitfly:

$f = 230 Hz$

$\eta_m = 70.2^o$

$C_\eta = 2.724$

$\Phi_\eta = -72.3^o$

$K = .727$

$\phi_m = 89.0^o$

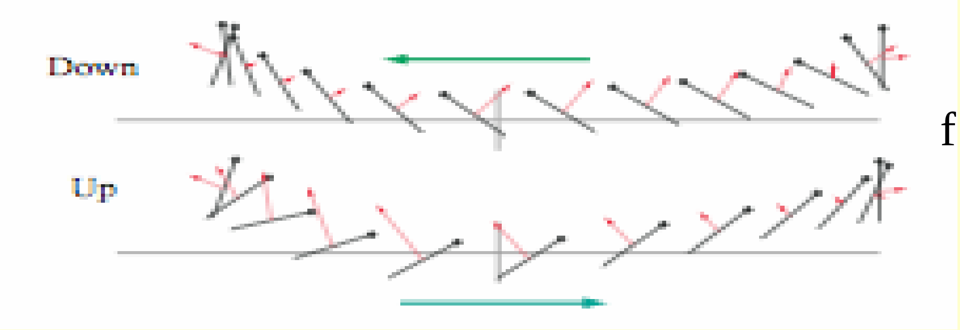
$\theta_m = 2.86^o$

$\Phi_\theta = -98.0^o$

$\theta_0 = 1.75^o$

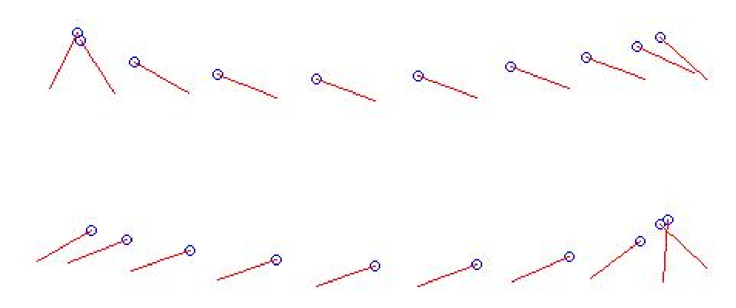
$N = 2$

$\eta_0 = 89.6^o$



f = 225 Hz

Fry, Sayaman, and Dickinson, JEB (2005)



f = 230 Hz

$$P^* = 14.8 \frac{W}{kg}$$

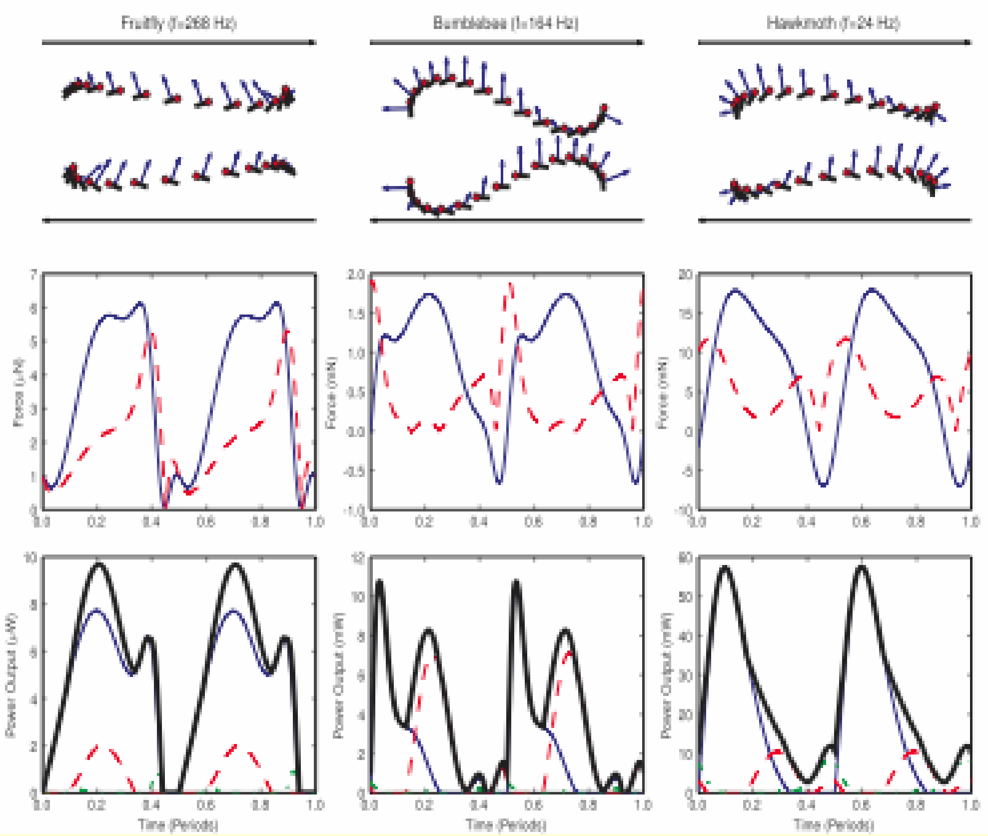
$$L - 1 = 4.1 \cdot 10^{-10}$$

Optimization Results for Insects

Fruitfly

Bumblebee

Hawkmoth

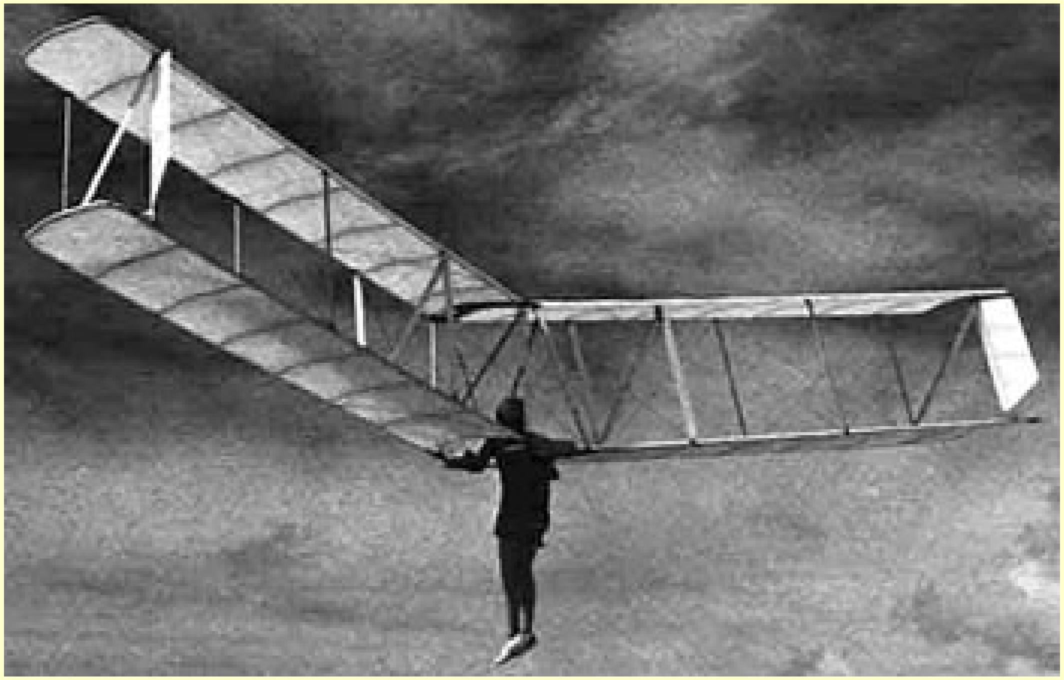


Berman and ZJW, J. Fluid Mech. (2007)

12 Species of *Drosophila* (fruit-flies)
Wild-type and Mutants

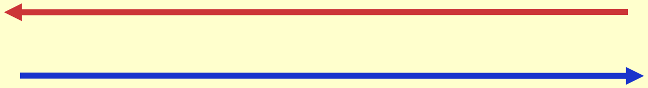
With I. Cohen Group

‘Birds’ vs. Plane

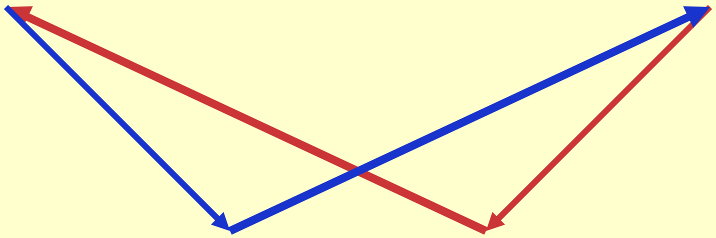


In Classical Aerodynamics Limit

Hovering with



vs

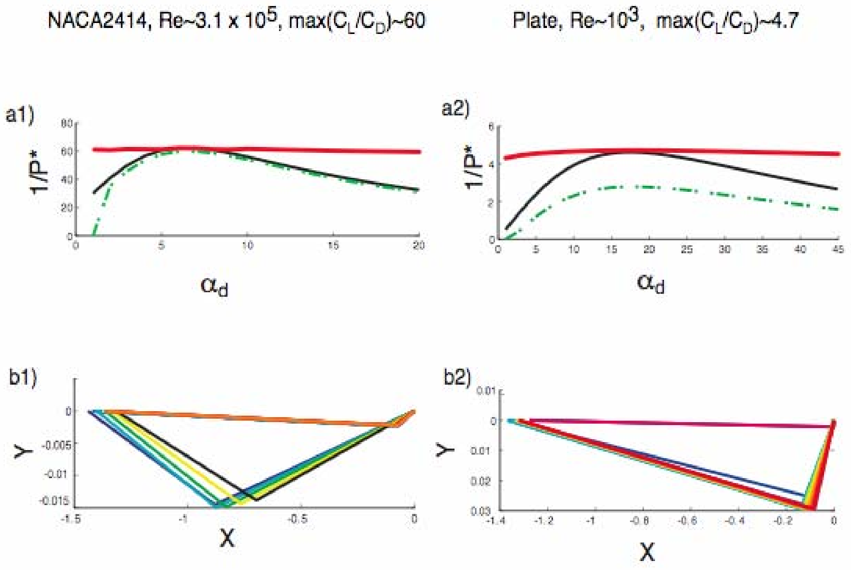


(no need for additional propulsion□)

same wing, same weight

In Classical Aerodynamics Limit

CL/CD ~ 60 CL/CD ~4.7



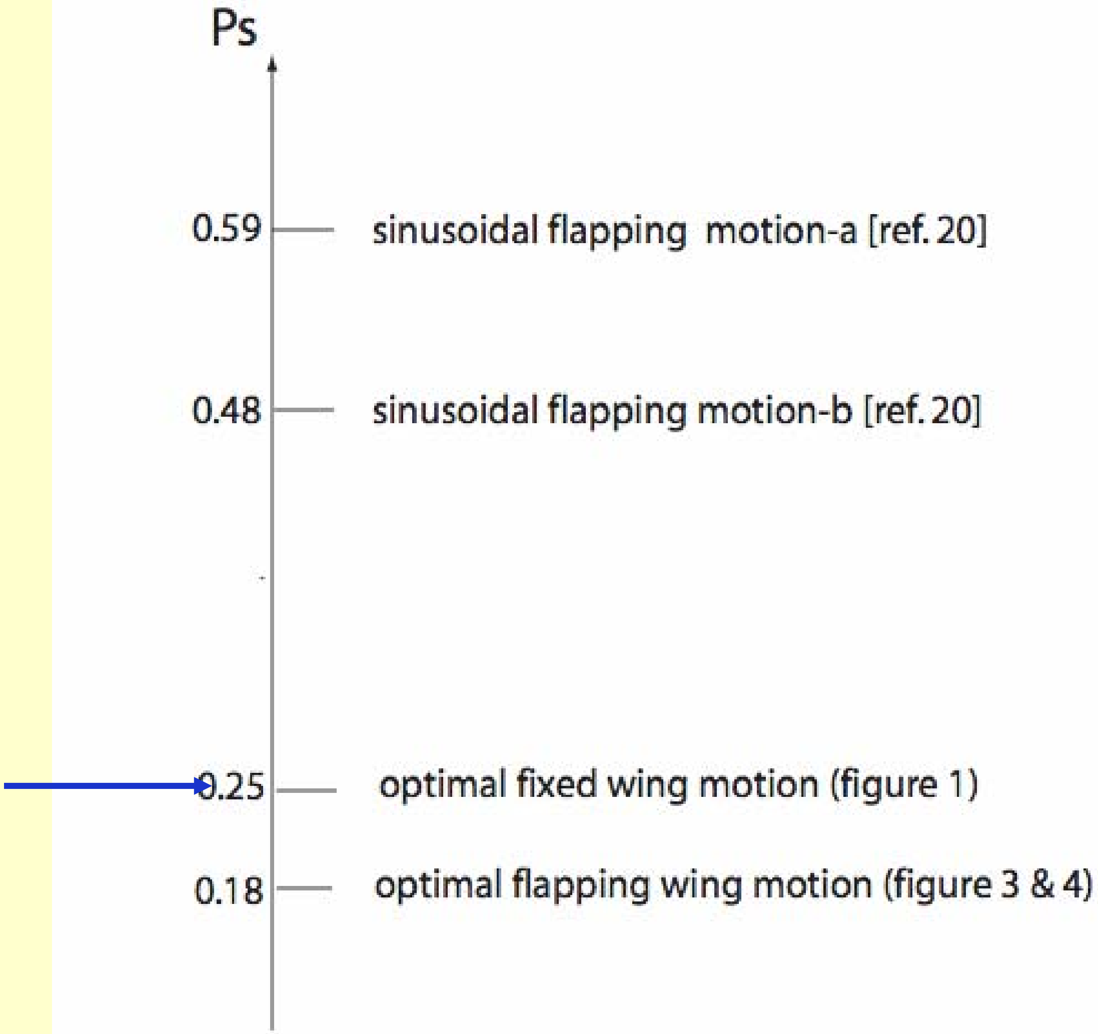
Optimal Steady Flight
Sets the Bar

Independent of Re

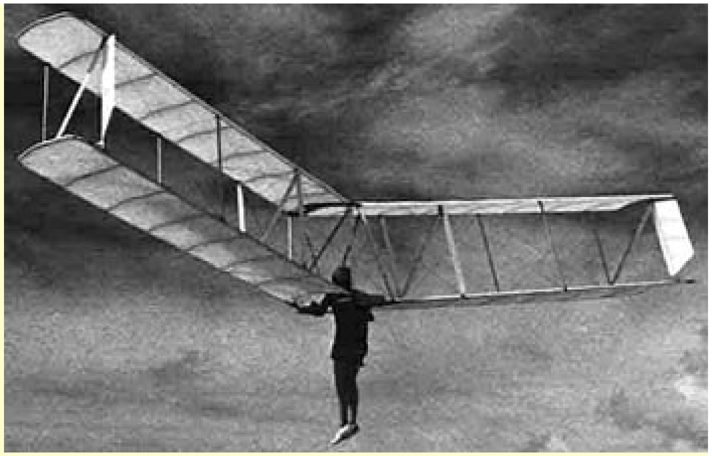
Independent of Wing Shape

Including Unsteady Aerodynamics

Flapping Flight can be Less Costly



U. Pesavento and ZJW, Preprint



Fly Group:

Fore-hind wing interactions in dragonfly flight : David Russell

Passive wing pitch reversal: Attila Bergou

Optimization: Gordon Berman

Flapping vs. fixed wing flight: Umberto Pesavento

Fruitfly Exp: Itai Cohen and Leif Reistroph

Falling Paper: Anders Andersen, UP☐

Immersed Interface Methods: Sheng Xu

http://dragonfly.tam.cornell.edu