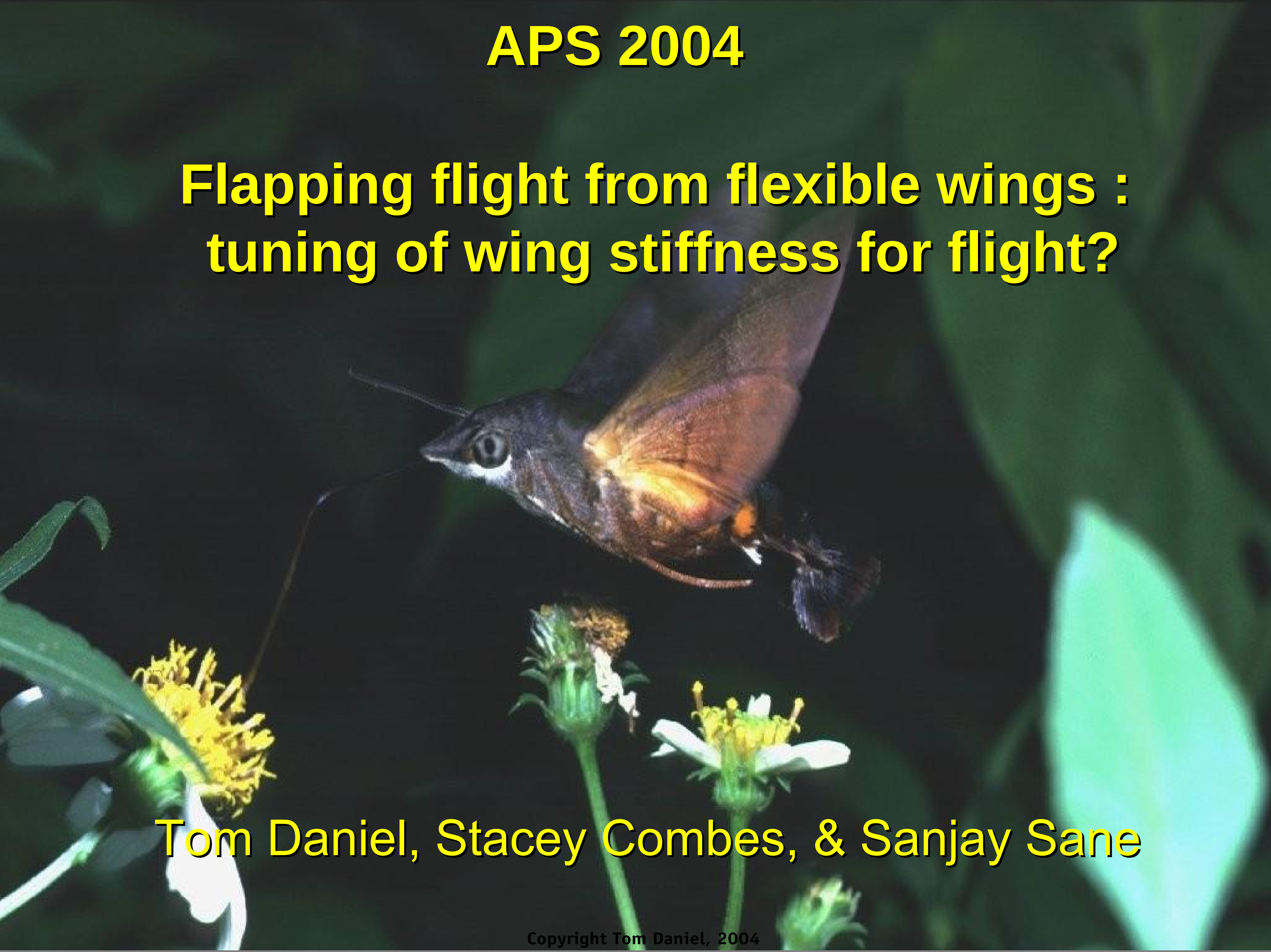
APS 2004
Flapping flight from flexible wings : tuning of wing stiffness for flight?
Tom Daniel, Stacey Combes, & Sanjay Sane
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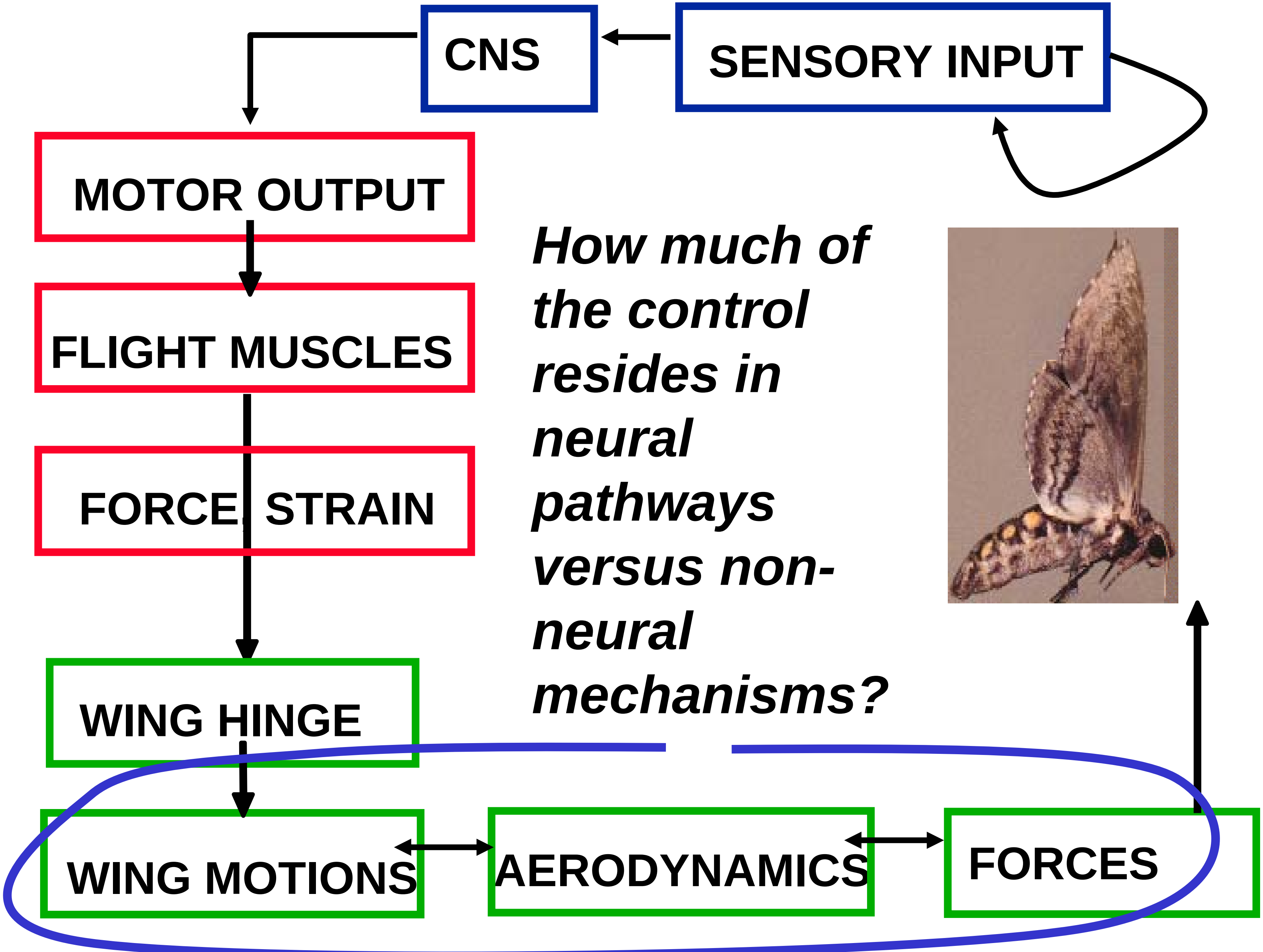

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A summary of insect flight issues

A thought experiment about wing or fin inertia

The coupled problem of fluid-solid interactions

Under what conditions can we ignore such interactions in air?

When we can ignore them, how might we proceed to analyze flight with compliant wings?

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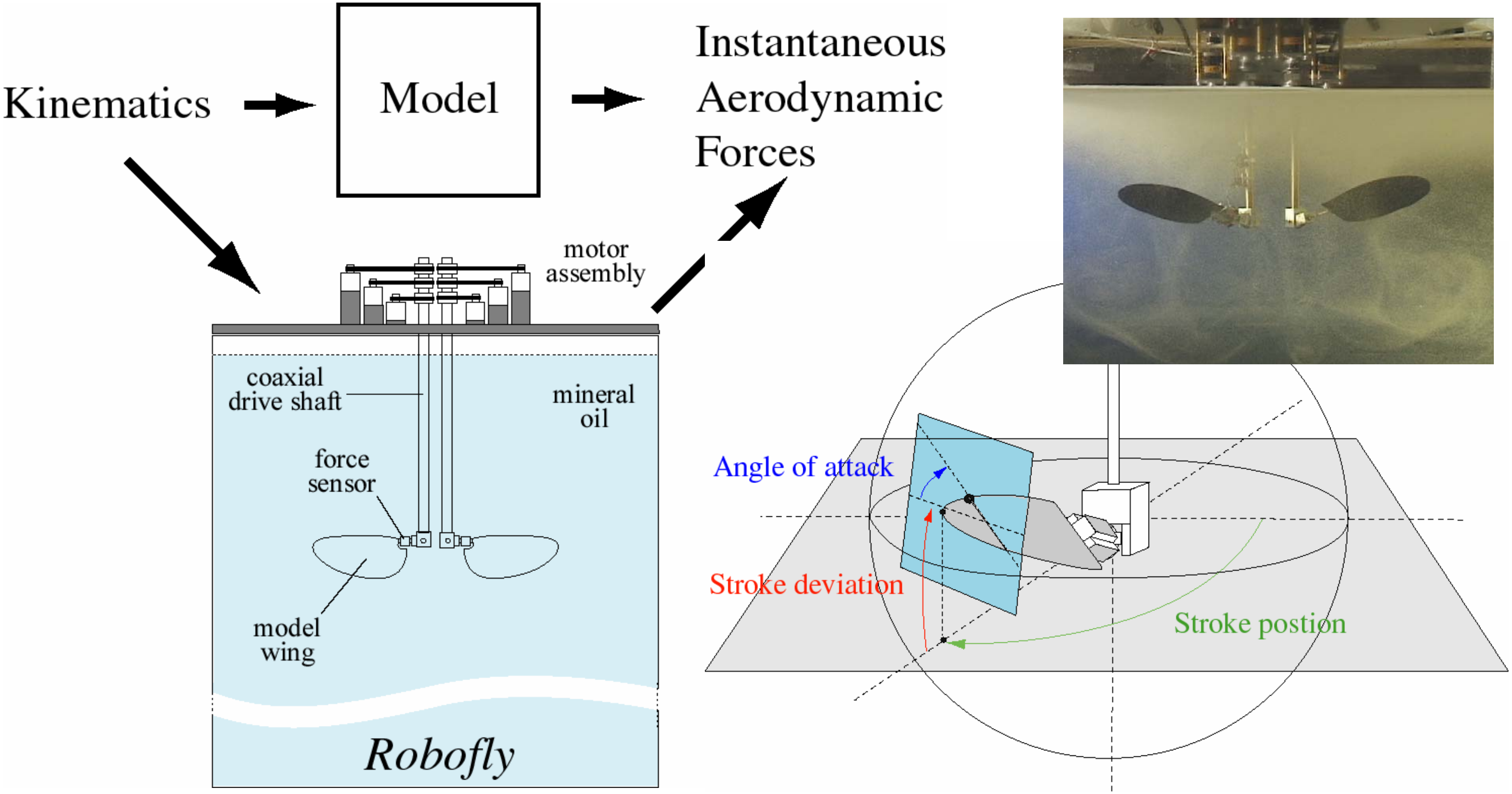
Dickinson's "Robo-fly"*



- Dynamical scaling: Reynolds number and reduced frequency parameter conserved
- Motors allow any arbitrary 3-D kinematic pattern
- Force sensors measure instantaneous forces on the wing

* Sanjay Sane, UW; Mark Willis,CWRU

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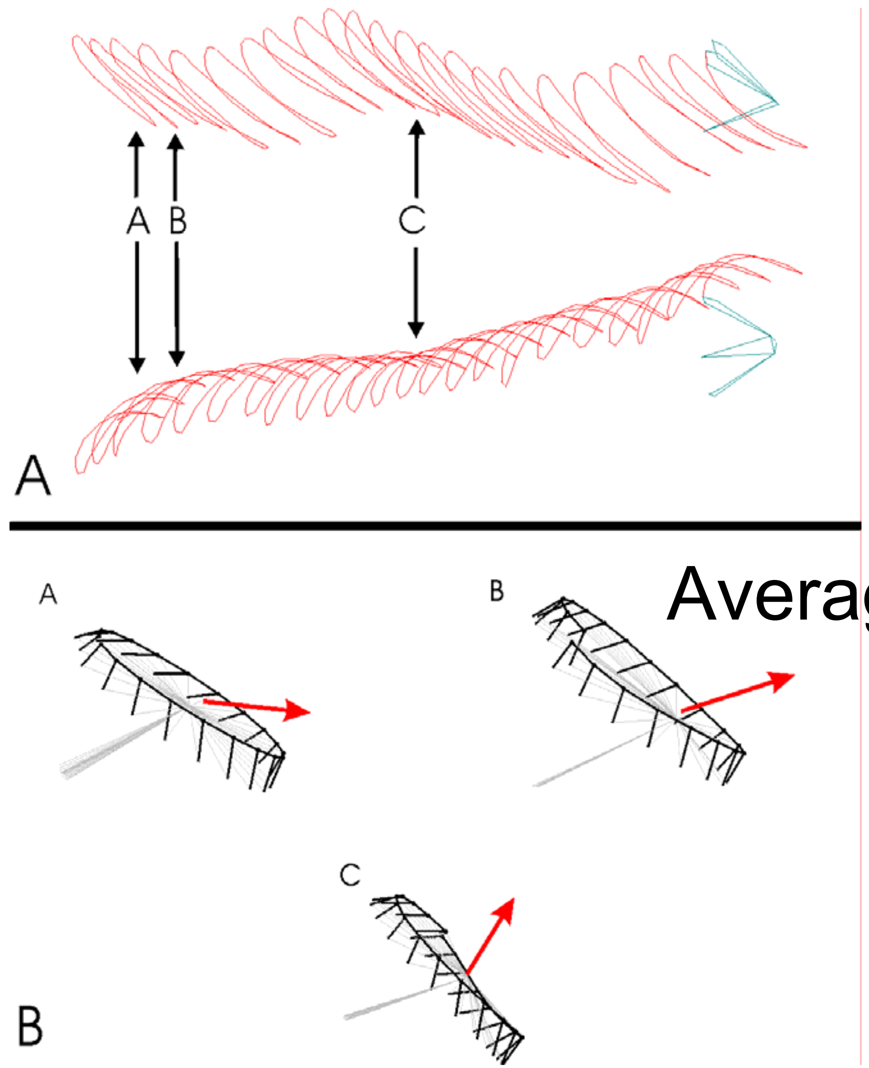
Trajectory of forward flight and net aerodynamics forces measured by Robofly



Average forces ~ mg

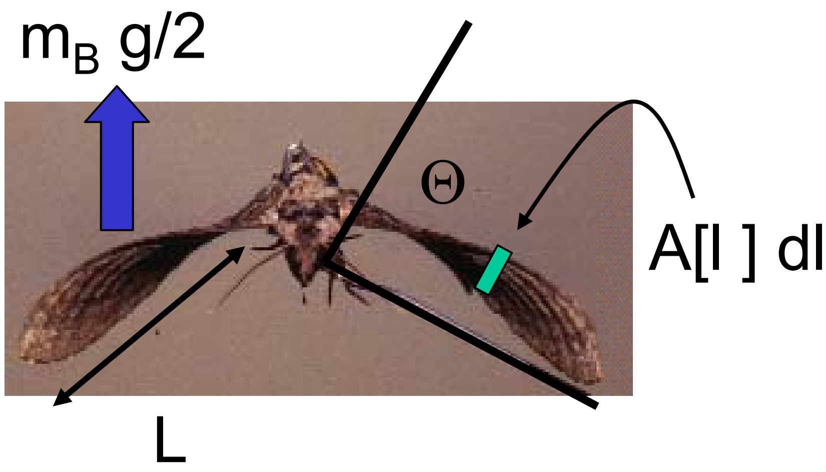
Copyright Tom Daniel, 2004 Sane, Johnstone, Dickinson and Willis

Such physical models work well for wings whose flexion is rather minimal.
It is difficult to scale elastic and fluid dynamic stresses simultaneously

Dalton, 1975

Many wings flex significantly

Brackenbury, 1992



Scale question:
How large are the aerodynamic moments relative to inertial/elastic moments?

$$M_{AERO} \sim m_B \, g \, L/4$$

$$M_{INERT} \sim \rho_{app} \int l^2 \, \Theta \, \omega^2 \sin(\omega t) \, A[l\,] \, dl$$

$$\sim m_{app} L^2 \, \Theta \, \omega^2 /3$$

$$M_{RAT} = M_{INERT} / M_{AERO}$$

$$\sim (m_{app}/m_B) \, L \, \Theta \, \omega^2 / g$$

~ 5.0 *Manduca*

~ 50.0 *Drosophila*

See as well Ennos ‘89, Zanker and Götz ‘90

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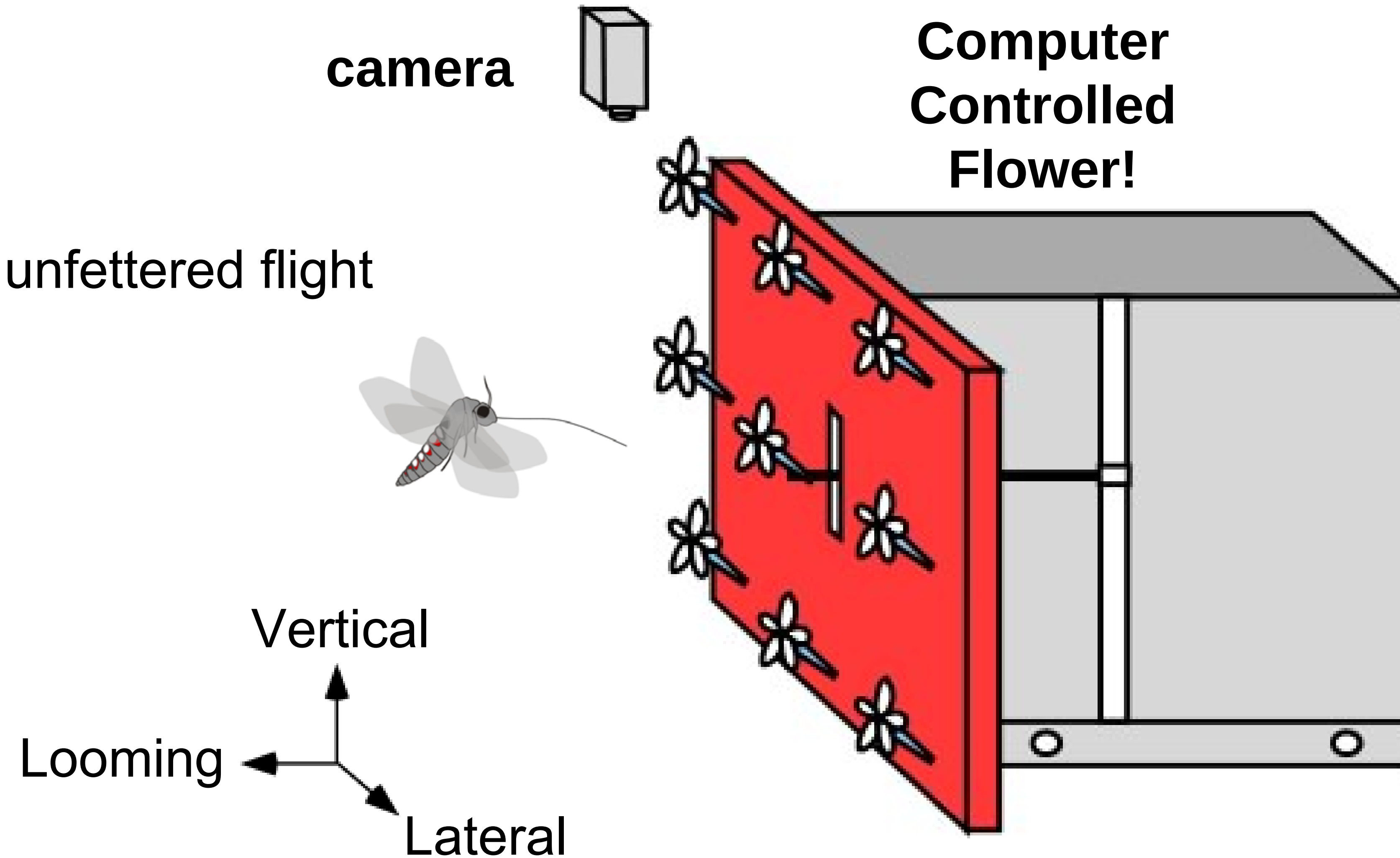
Need high-speed videography of flapping wings during maneuvers.

"Robo-Bush"



Carlos Moreno

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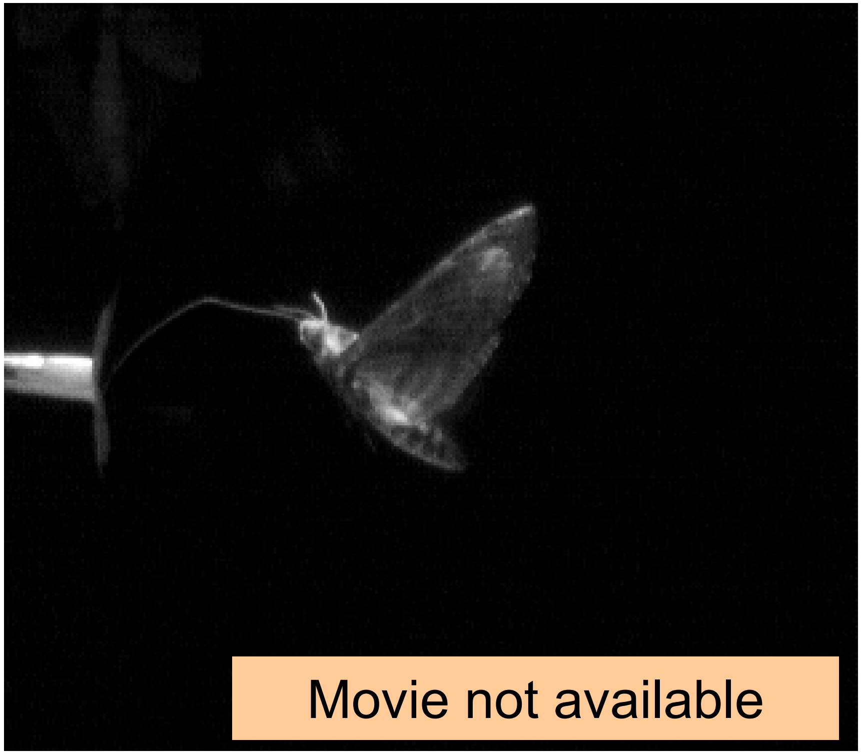

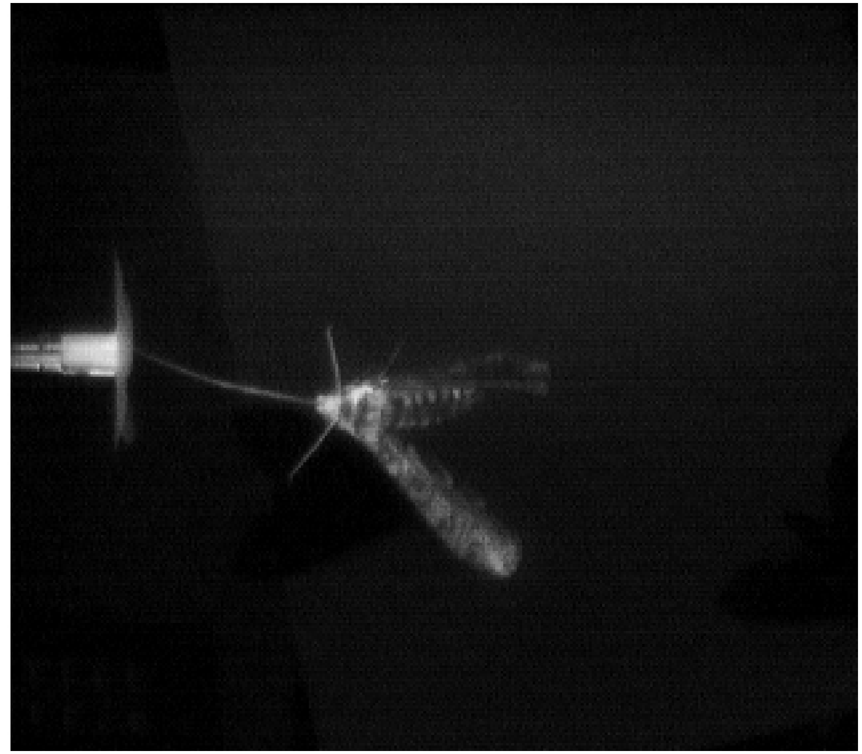

•To what extent are these motions determined by fluid dynamic events?
•What are the mechanical properties of these wings?

Michael Tu and Katarzyna Kodizcezswka

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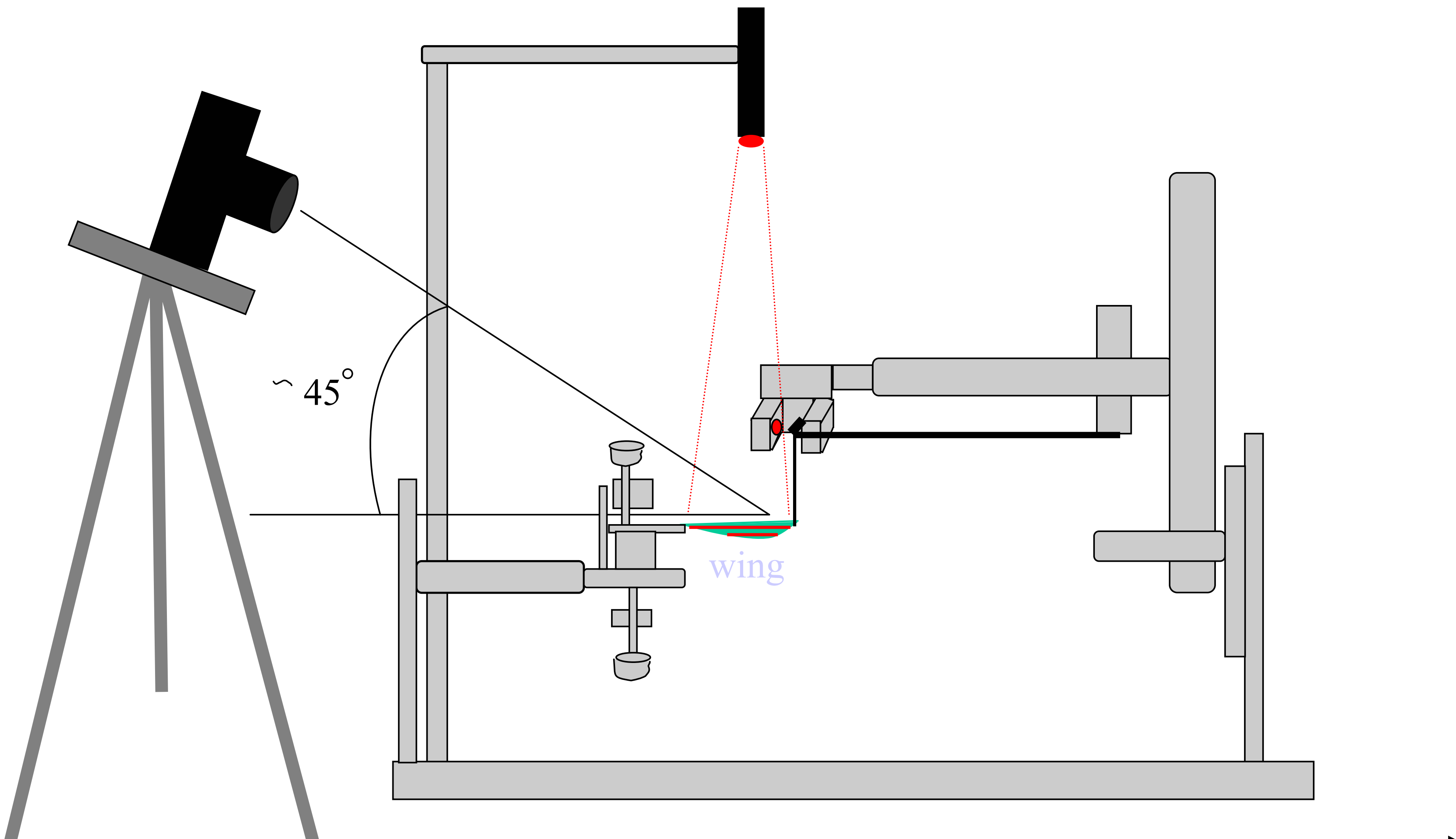
Measuring displacement continuously along a wing



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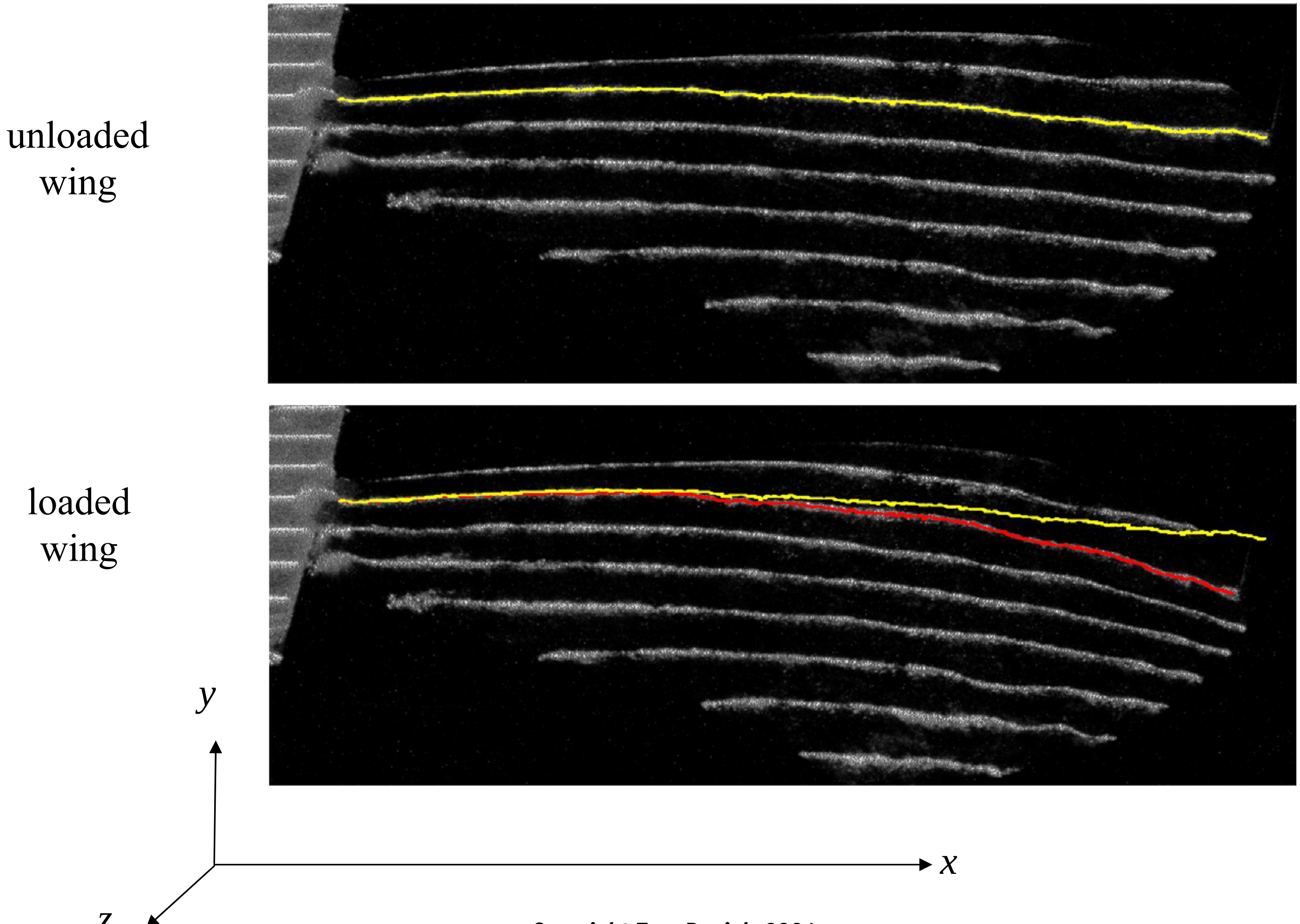
Combes and Daniel, 2004

Changes in the y-direction of the picture correspond to bending in the z-direction of the wing



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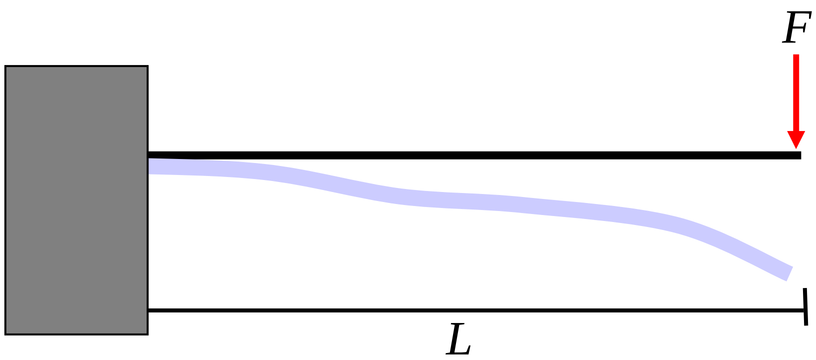
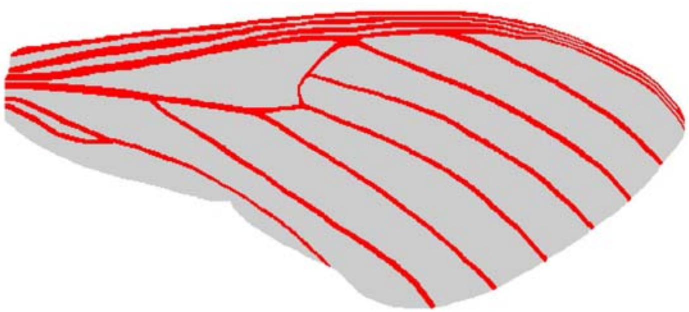
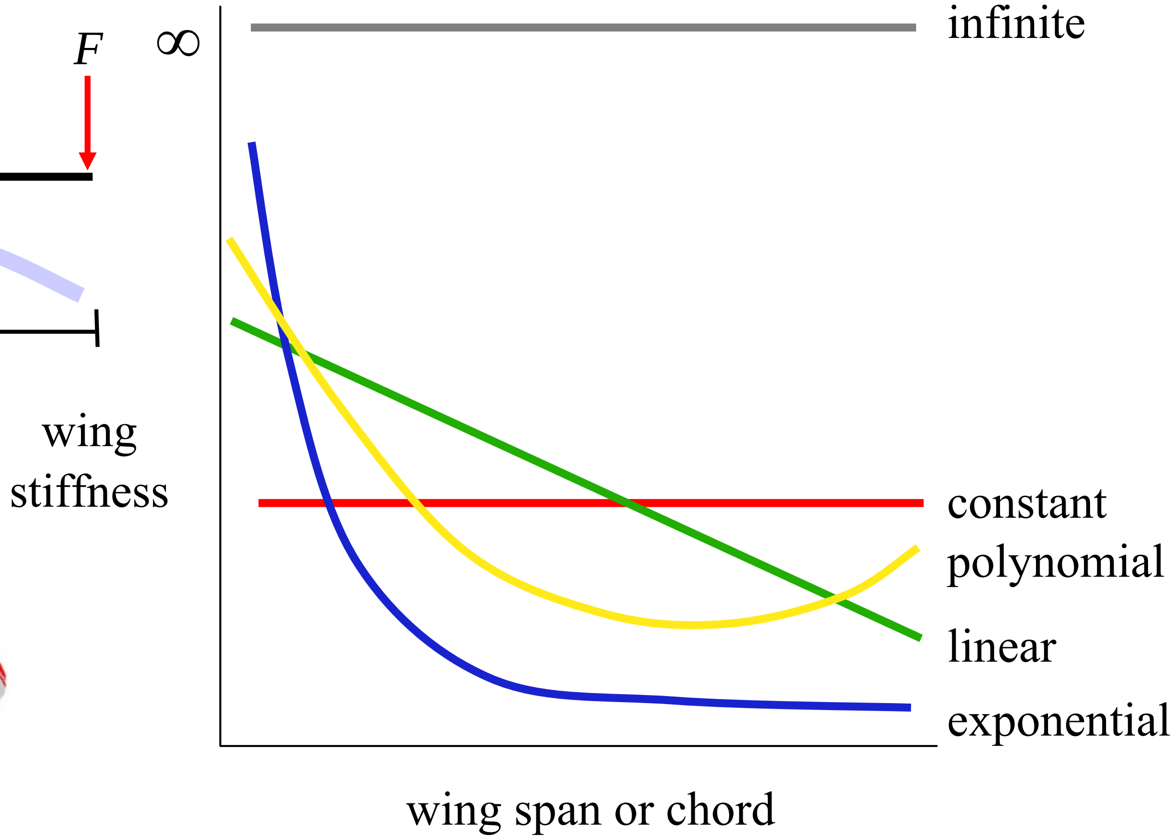
Possible patterns of spatial variation in wing stiffness

heterogeneous beam







Combes and Daniel 2004

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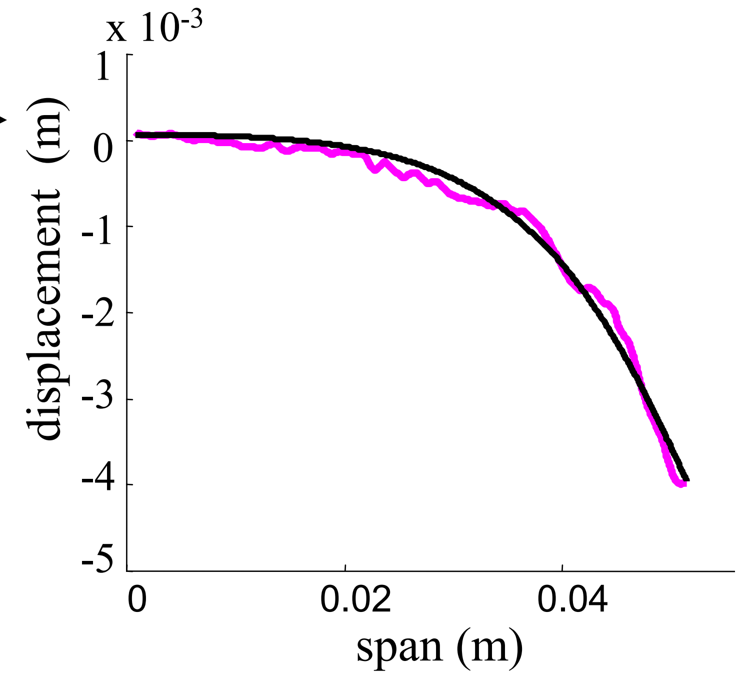
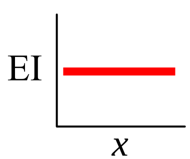
Solve for the EI distribution that best fits the measured wing displacement

$$EI(x) = \frac{F(L-x)}{d^2\delta / dx^2}$$

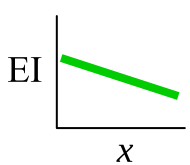
$$\delta(x) = \iint \frac{F(L-x)}{EI(x)} d^2x$$

→ simplex minimization →

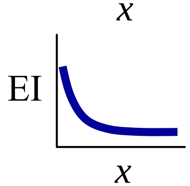




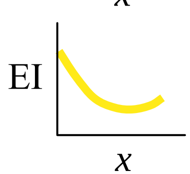
constant $[EI(x) = k]$



linear $[EI(x) = m\,x + b]$



exponential $[EI(x) = c^{*}\exp^{ax}]$



polynomial $[EI(x) = px^2+qx+r]$

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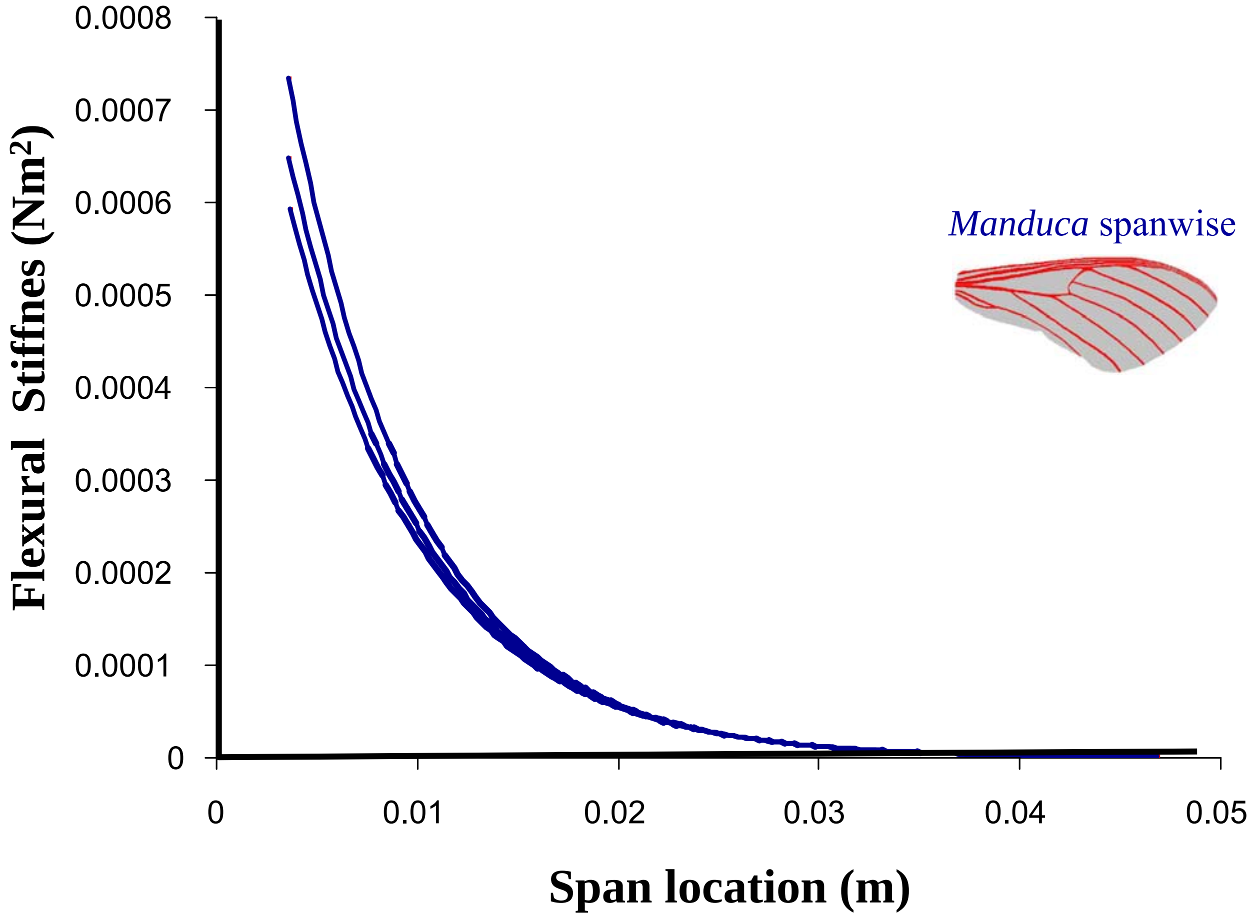
Spanwise wing stiffness flexural stiffness declines exponentially in span and chord directions



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Wings flex.
With measured
mechanical, geometric,
and kinematic
characters…
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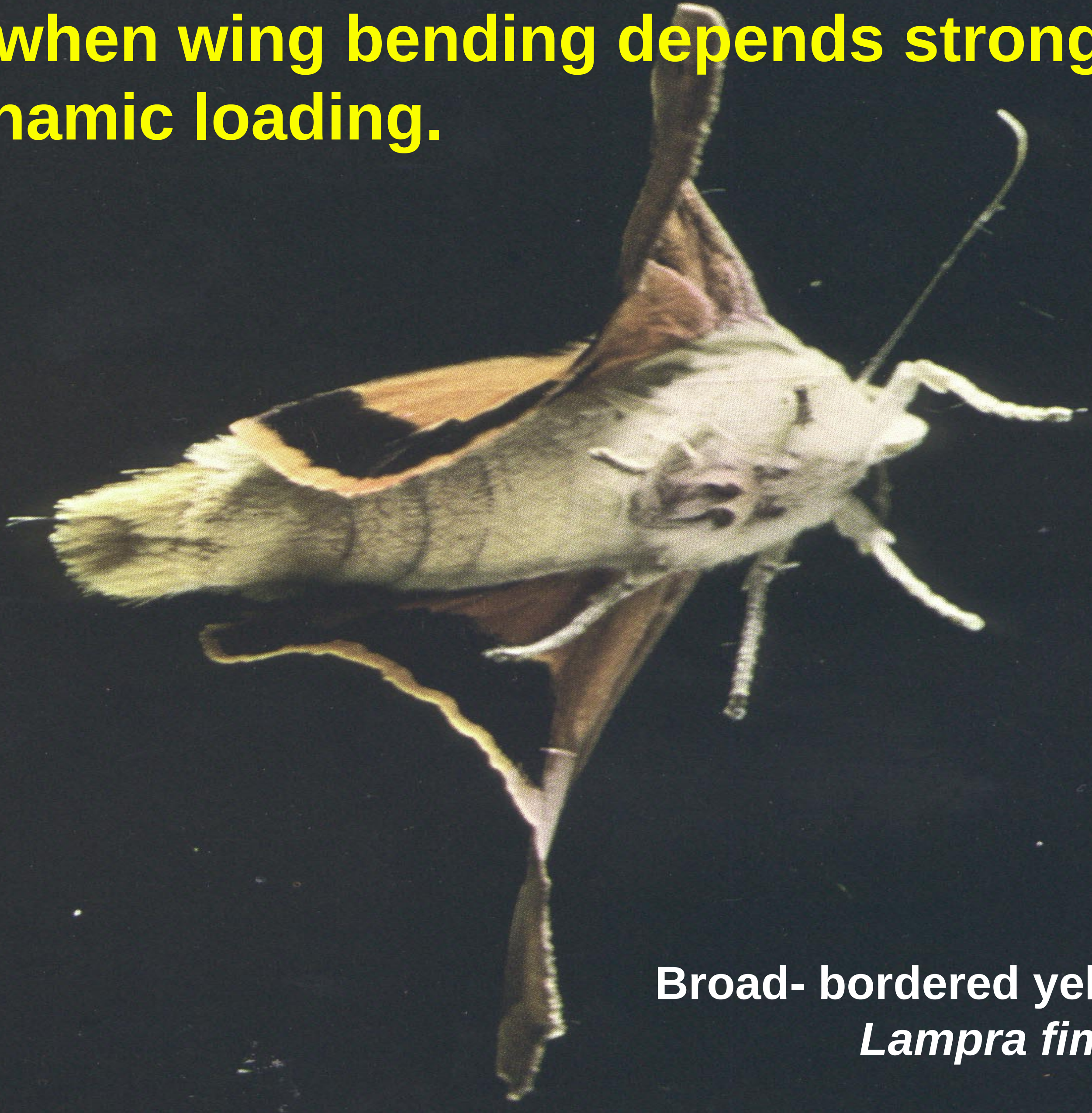
…. use FEM to compute motions. From that compute aerodynamic forces

Movie not available

Aerodynamic force calculations from FEM are illegal when wing bending depends strongly on aerodynamic loading.



Broad- bordered yellow Underwing
Lampra fimbriata

(Dalton, 1975)

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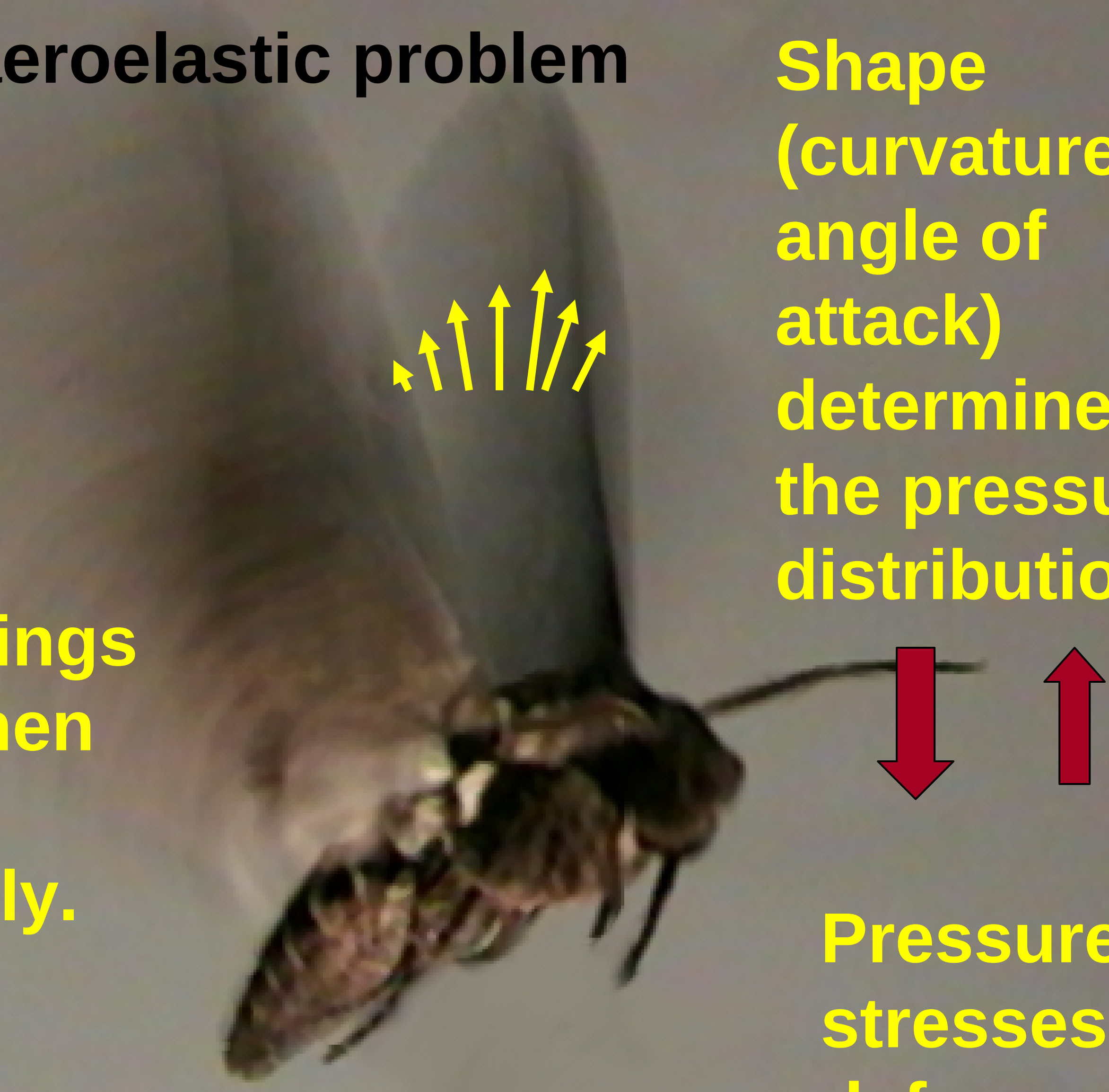
The basic aeroelastic problem



Shape (curvature, angle of attack) determines the pressure distribution.

Flexible wings deform when moved dynamically.

Pressure stresses deform flexible wings.

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A scale argument for a thin flexing wing

Movie not available

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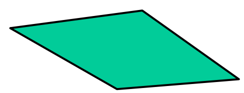
A scale argument for a thin flexing wing

Movie not available



Imbue with

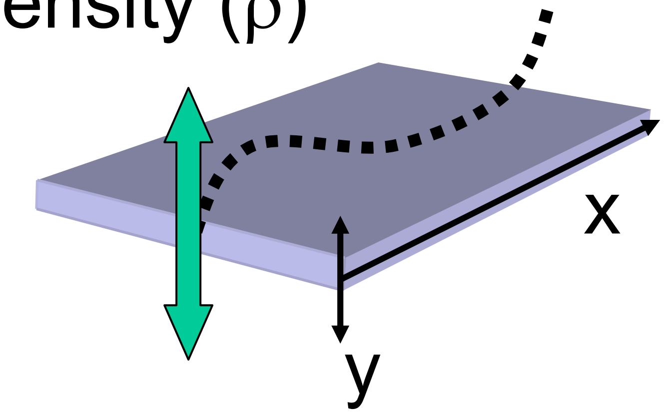
Stiffness (E)

thickness (t)

width (w)

EI (flexural stiffness)

density (ρ)



Impel with

A sin(ω t)

What deformations -- y(x,t) arise?

What bending moments follow from this y(x,t)?

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A different tact :

Solve this wave equation

$\partial y^2 / \partial t^2 = -(EI/\rho A)\, \partial y^4 / \partial x^4$

with the right boundary conditions

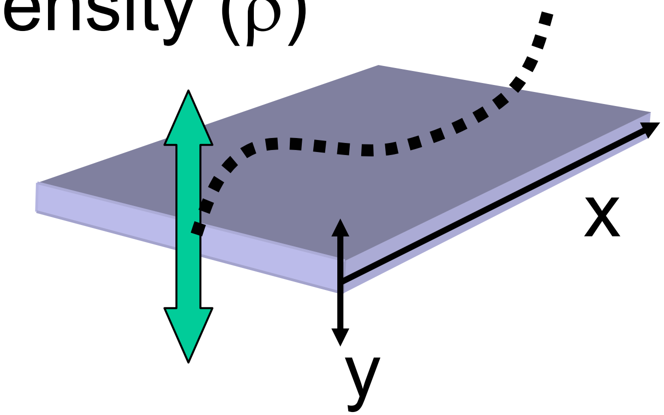
$\Downarrow$

y(x,t)

$\Downarrow$

Moment = EI $\partial y^2 / \partial x^2$

Imbue with
Stiffness (E)
thickness (t)
width (w)
EI (flexural stiffness)
density (ρ)



Impel with
A sin(ω t)

What deformations -- y(x,t) arise?

What bending moments follow from this y(x,t)?

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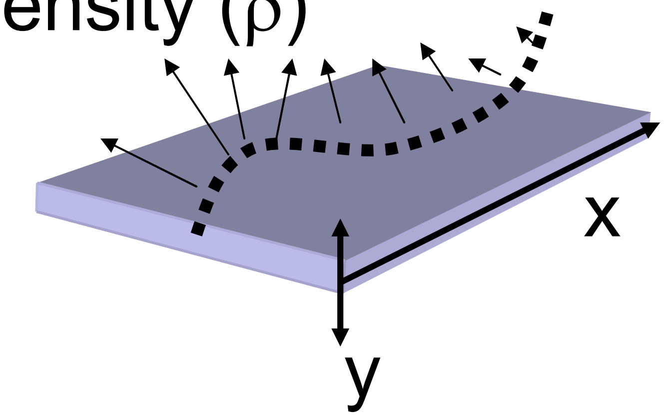
A different tact :

Imbue with
Stiffness (E)
thickness (t)
width (w)
EI (flexural stiffness)
density (ρ)

Inviscid blade-element analysis (from Wu,1971)



y(x,t)

p(x,t) -> $M_{fluid}(x,t)$

-> $\iint M_{fluid}(x,t)$ -> M_{fluid} -> $M_{elastic}$

Manduca : L = 0.03,w = 0.01, $\omega = 2 \pi 25$

Wu 1971 set this up

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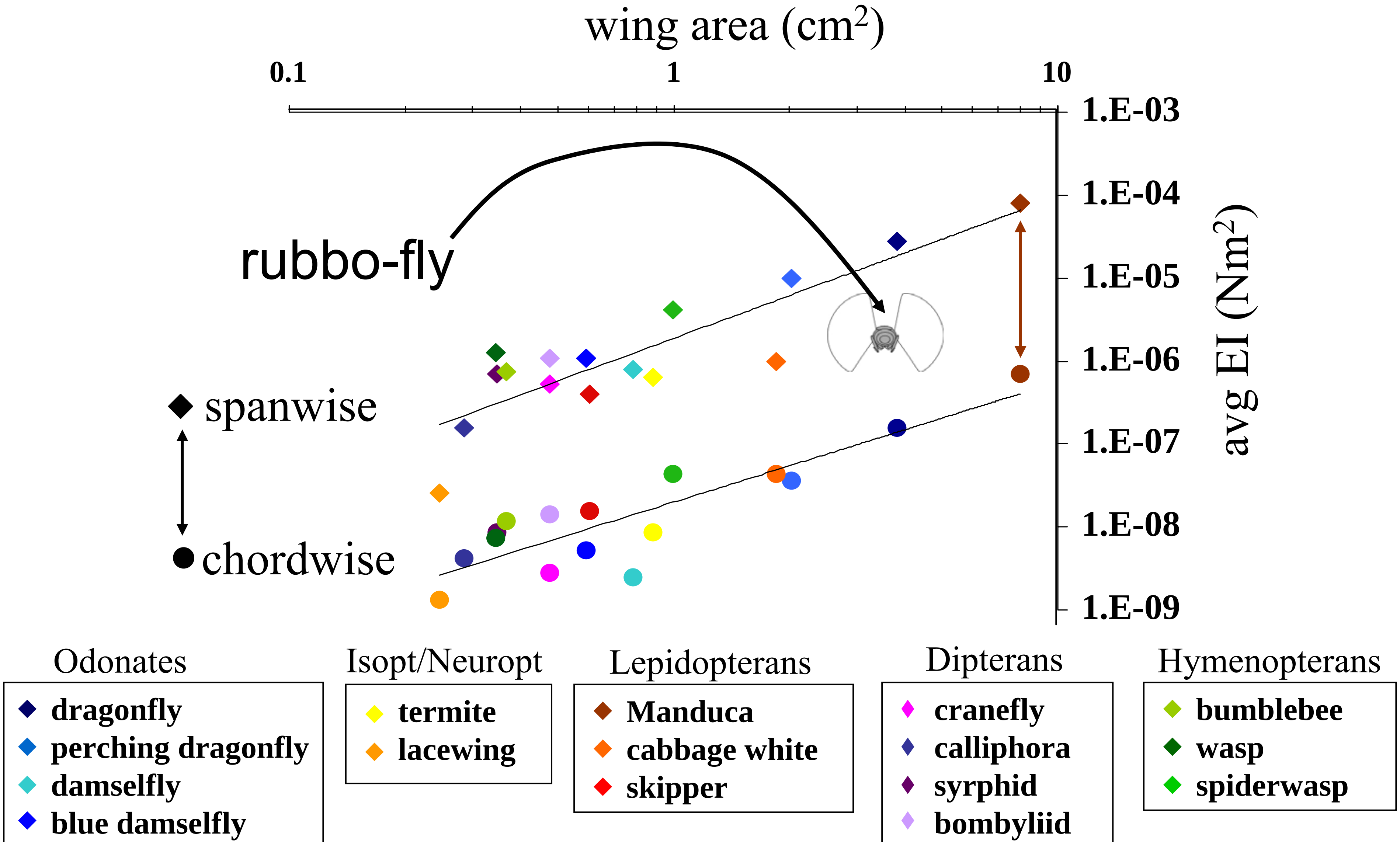
Flexural stiffness data of Combes



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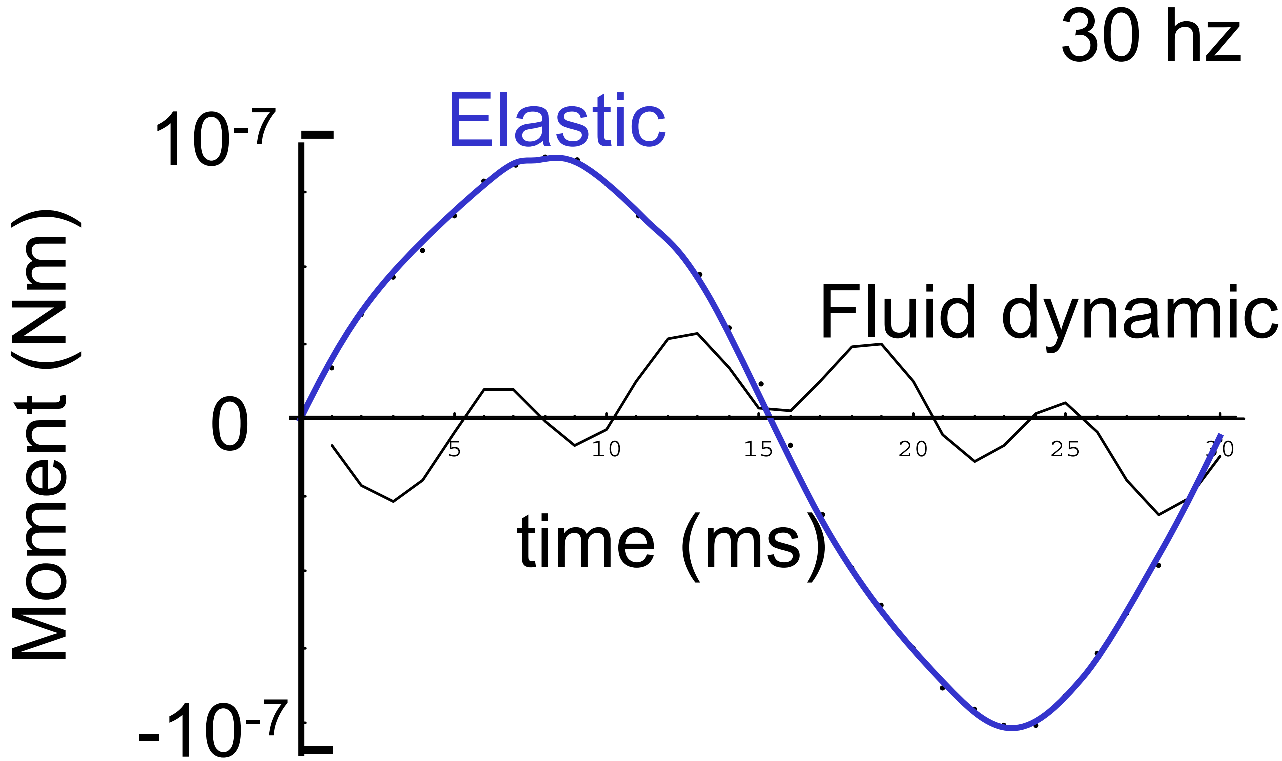
Dynamic bending moments are dominated by elastic/inertial phenomena



EI = 6 10^{-6} Length = 0.03, width = 0.01

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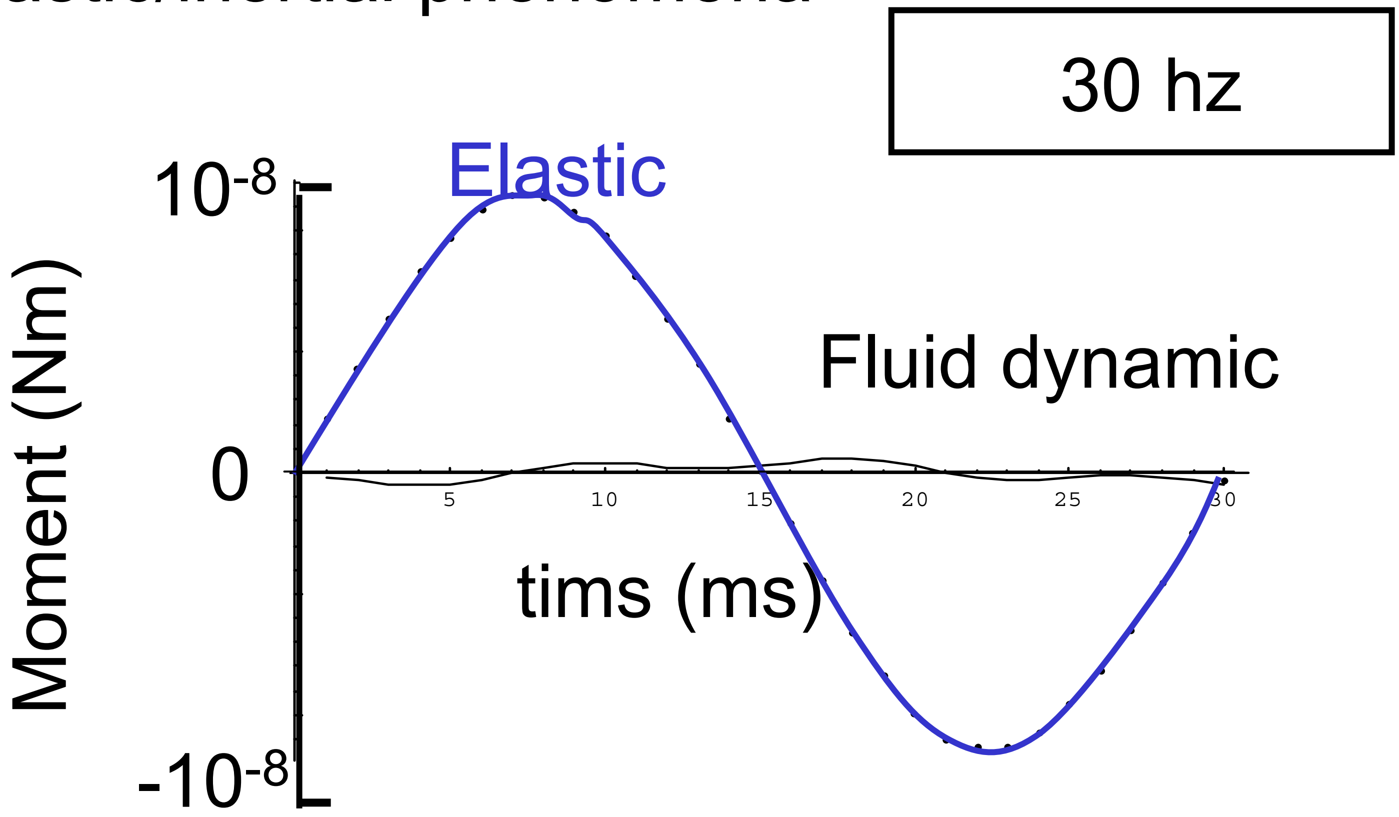
Dynamic bending moments are dominated by elastic/inertial phenomena



EI = 6 10^{-6} Length = 0.02, width = 0.01

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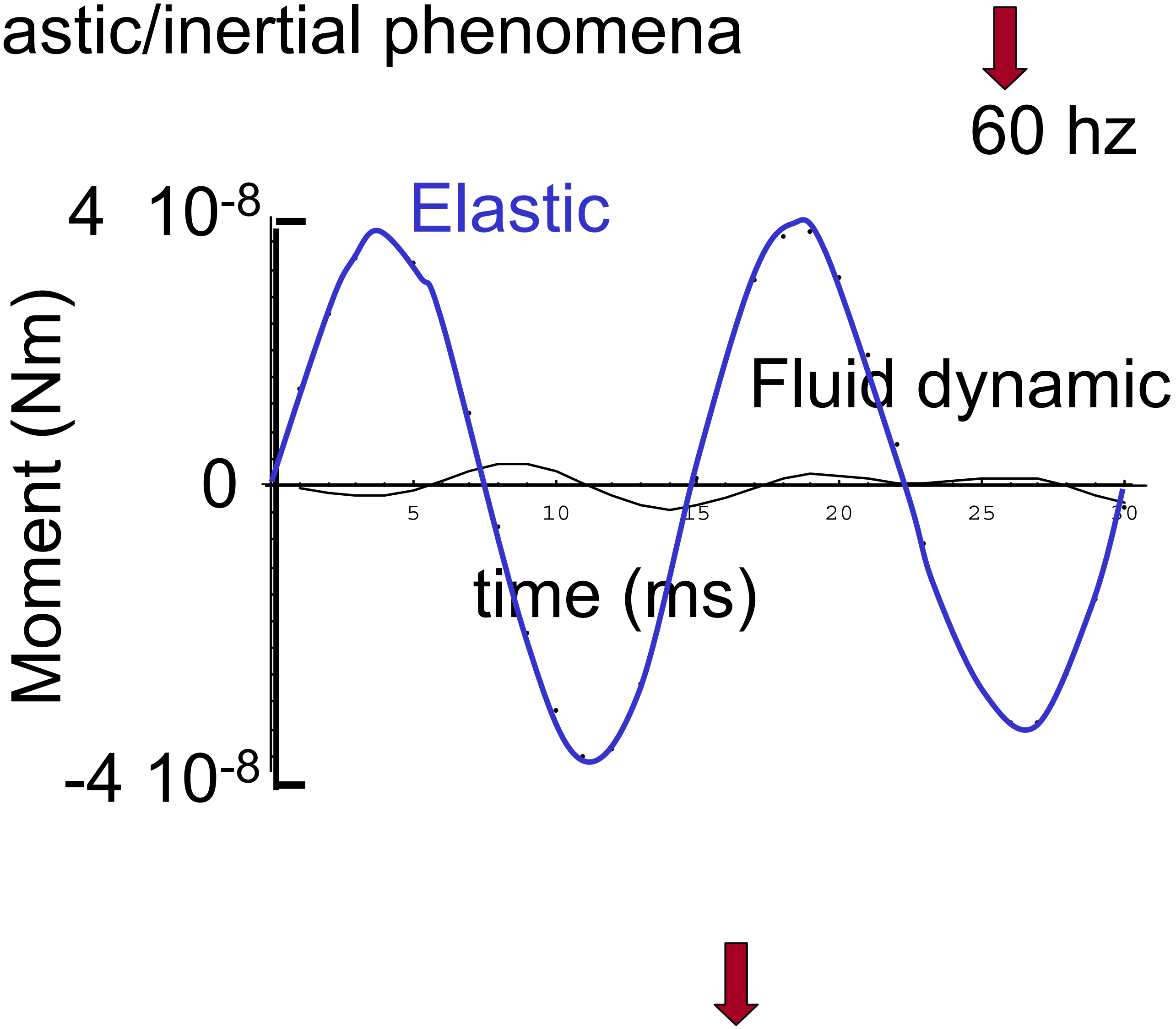
Dynamic bending moments are dominated by elastic/inertial phenomena



EI = 6 10^{-6} Length = 0.02, width = 0.01

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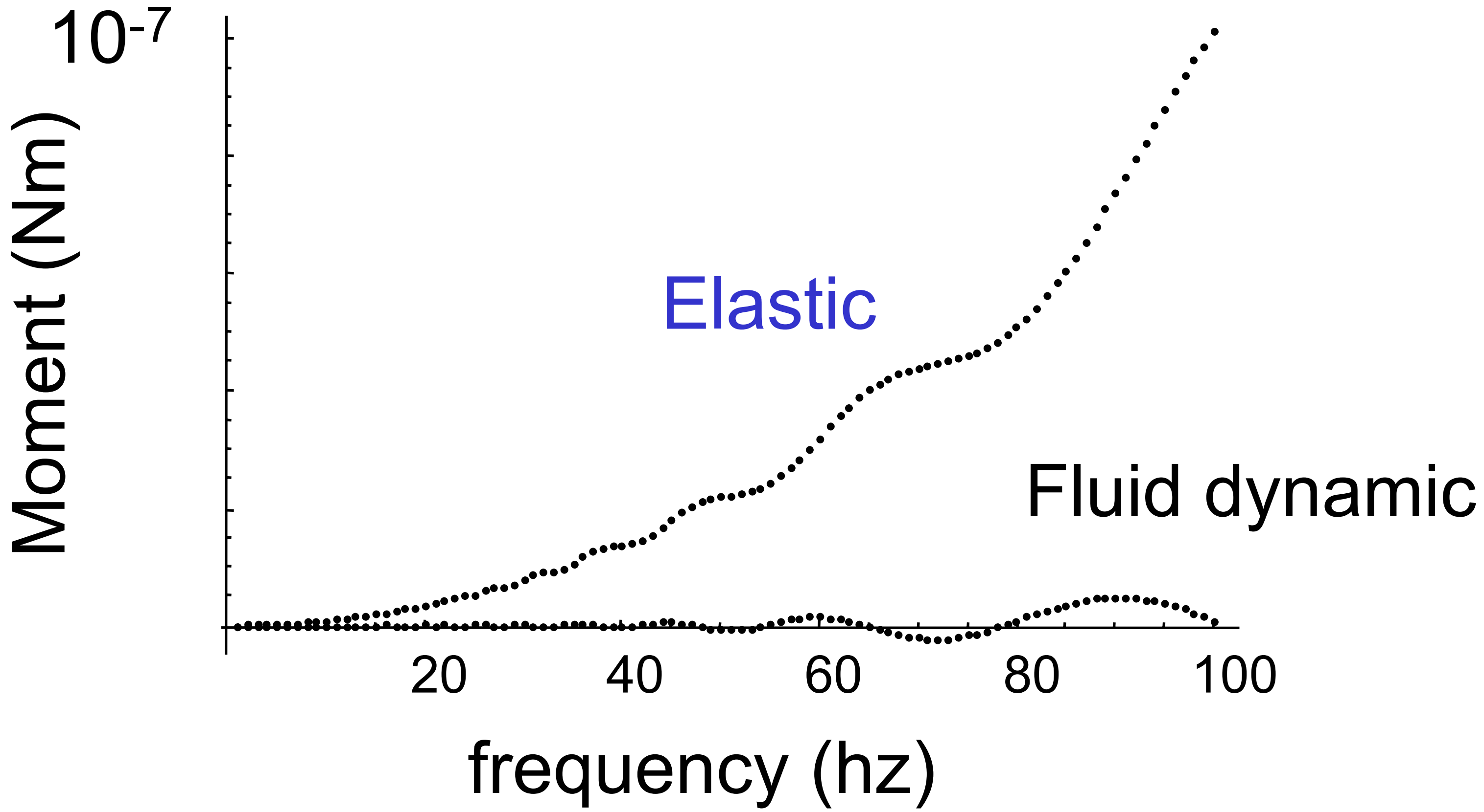
Inertia is generally large



$EI = 6\ 10^{-6}$

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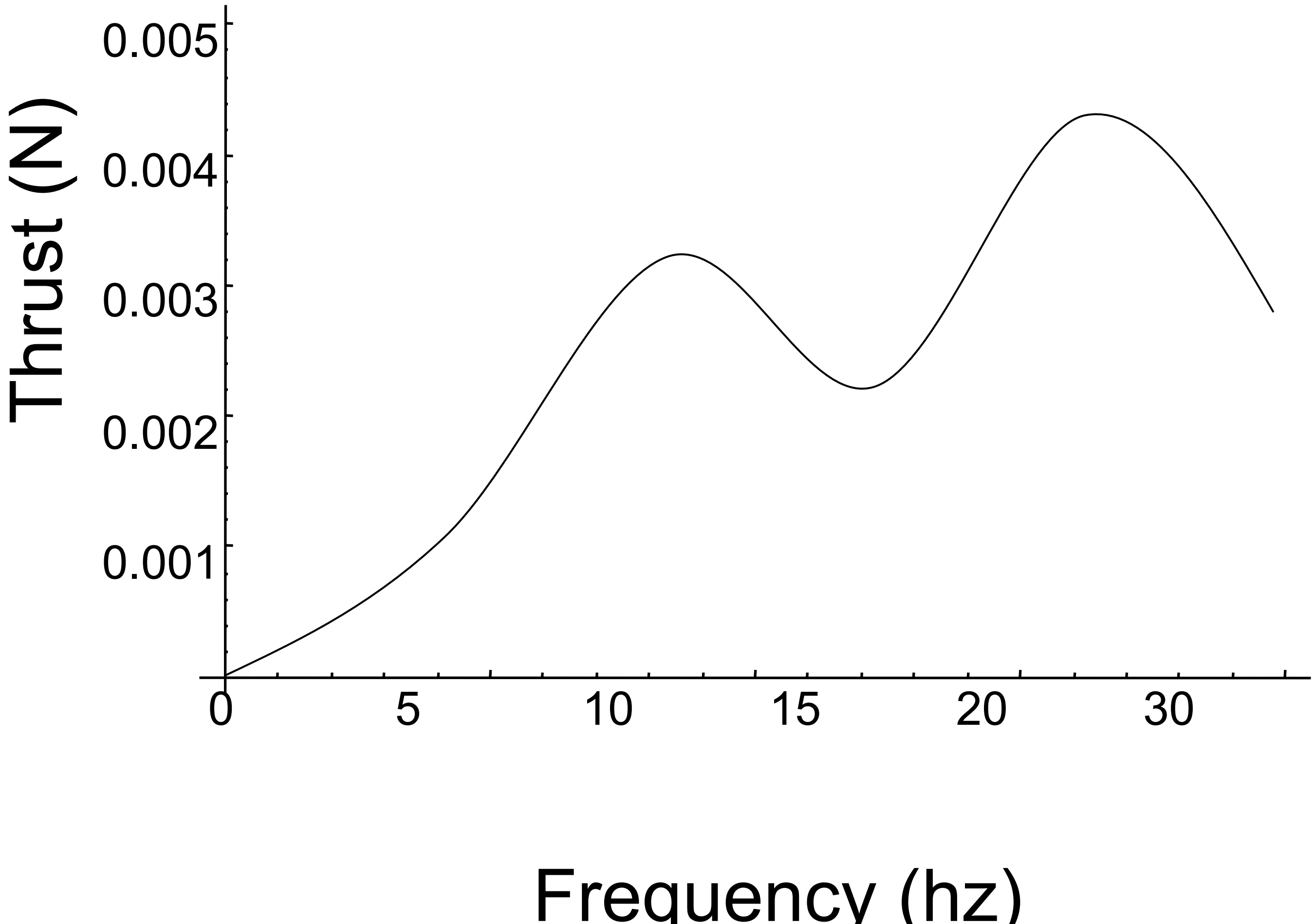
Thrust depends on emergent deformations (non-monotonically).



EI = 6 10^{-6} Length = 0.03, width = 0.01

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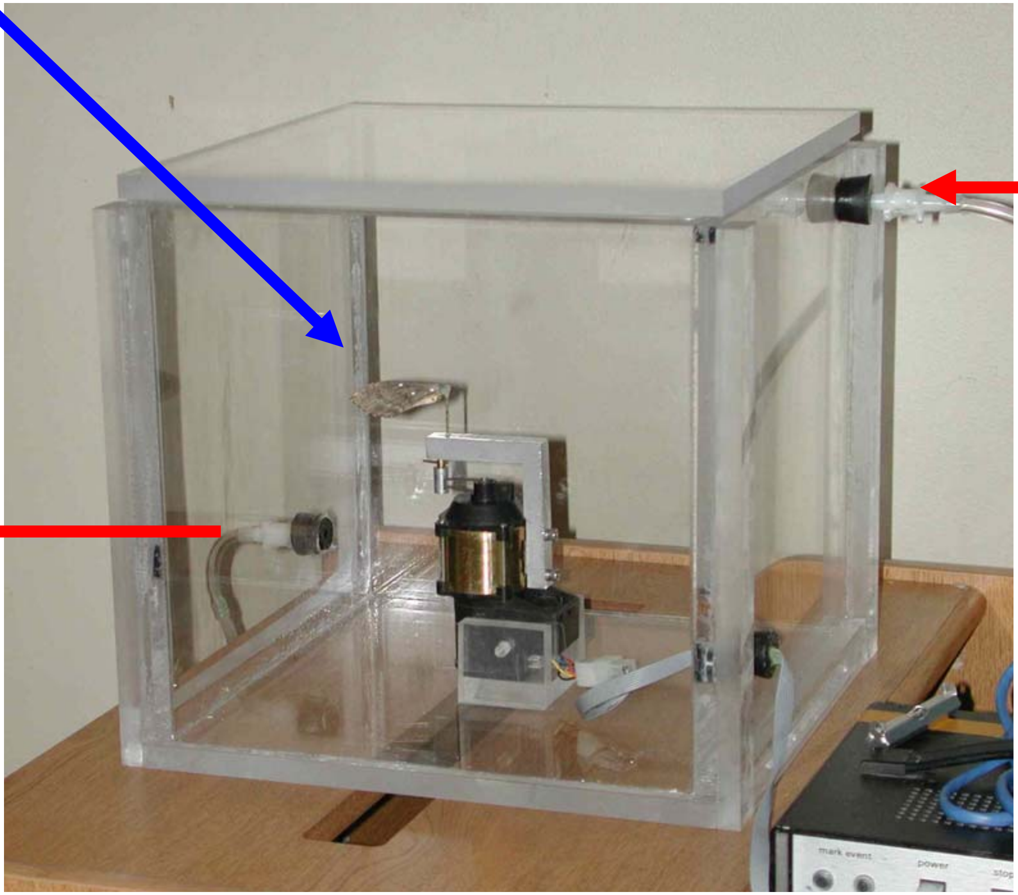
Can we trust the theoretical results?

Set density to as low as possible to eliminate fluid dynamic loading and query wing shape.

fresh *Manduca* wing on motor



add Helium (~20% air density)

remove 50% of air volume

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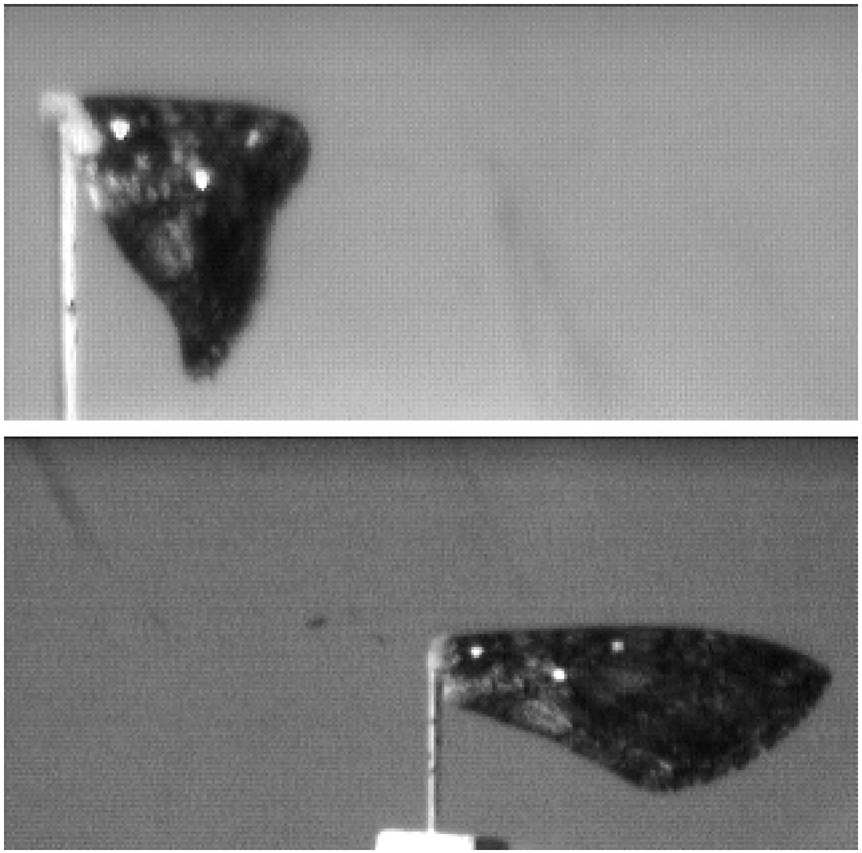
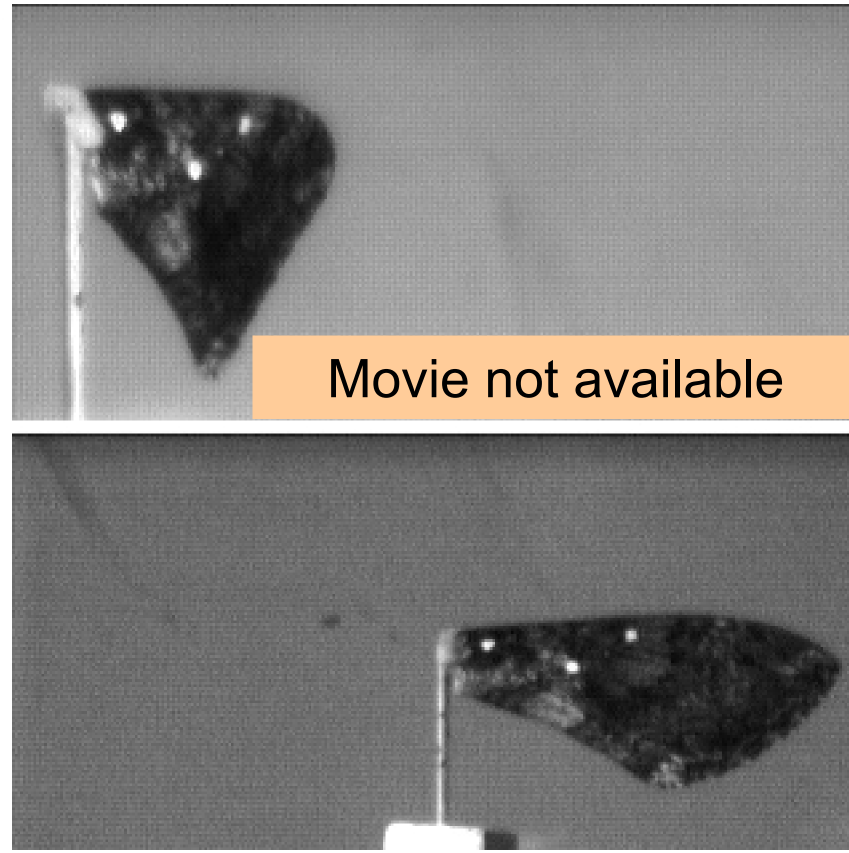
normal air density



10% air density



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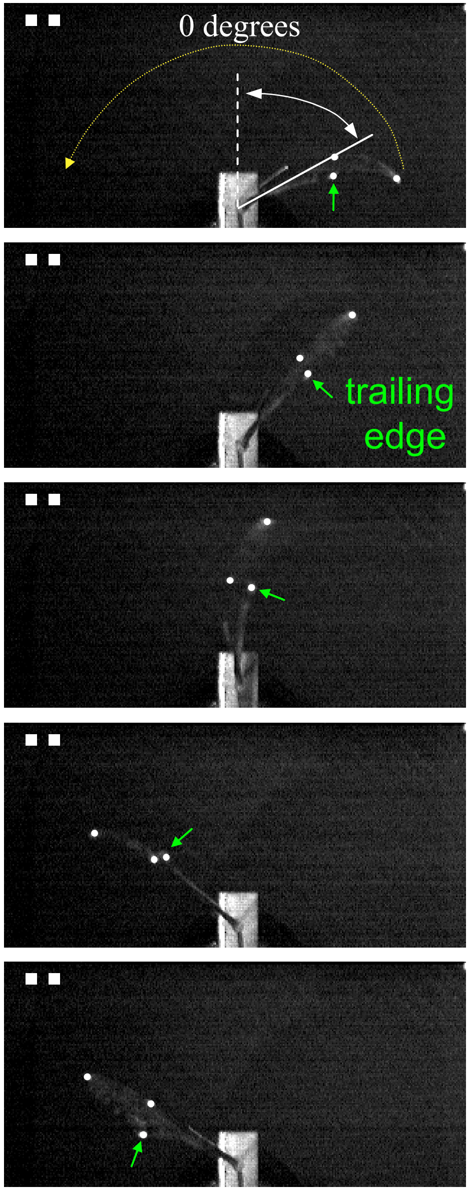
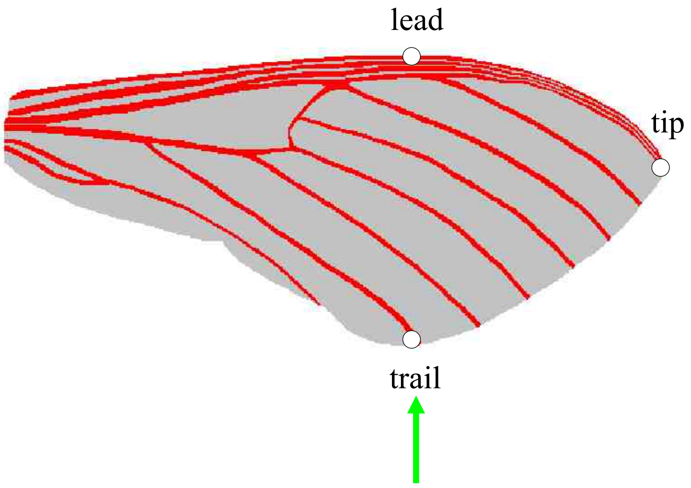
Quantify wing bending at the wing tip, leading edge, and trailing edge

26 Hz, normal air





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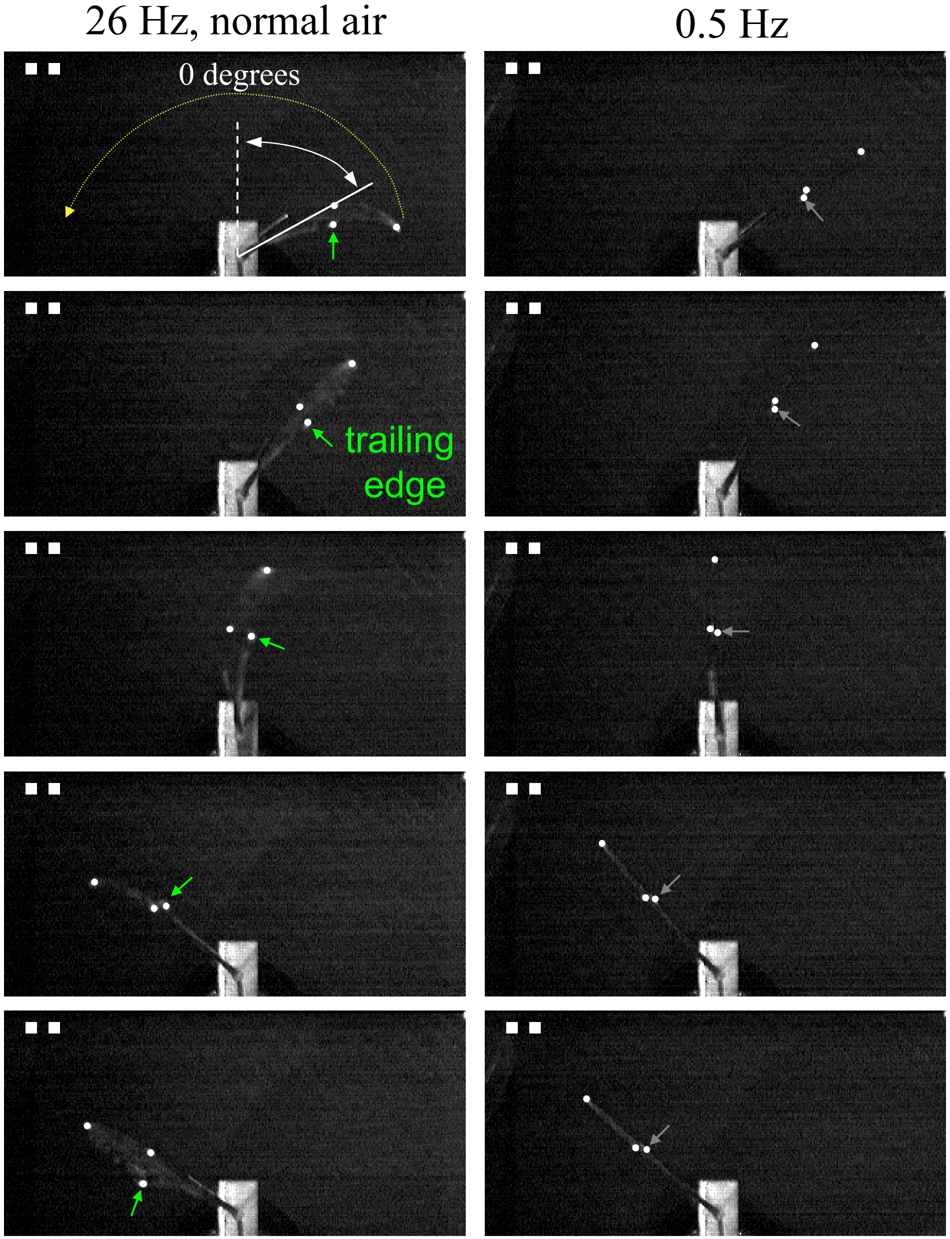
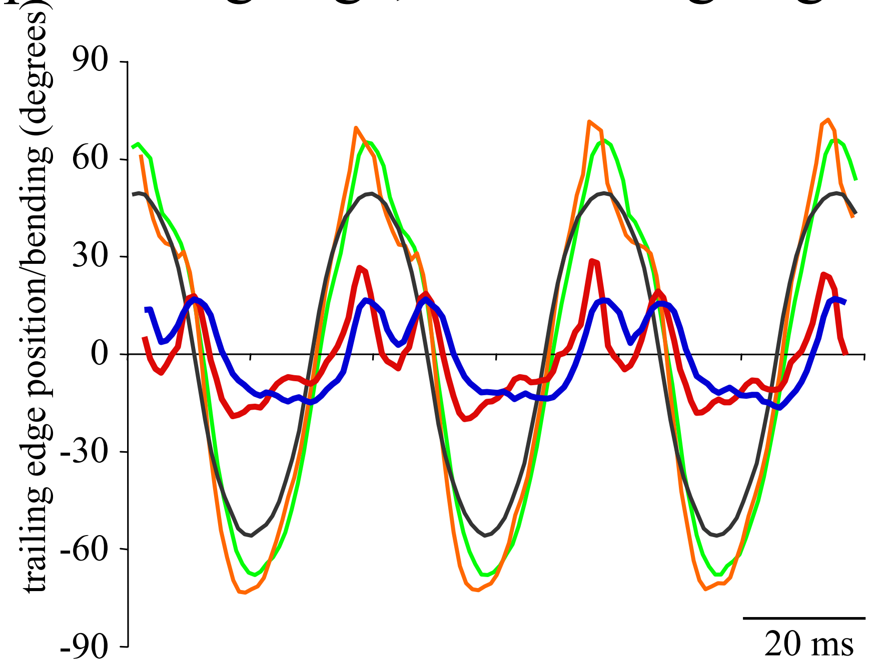
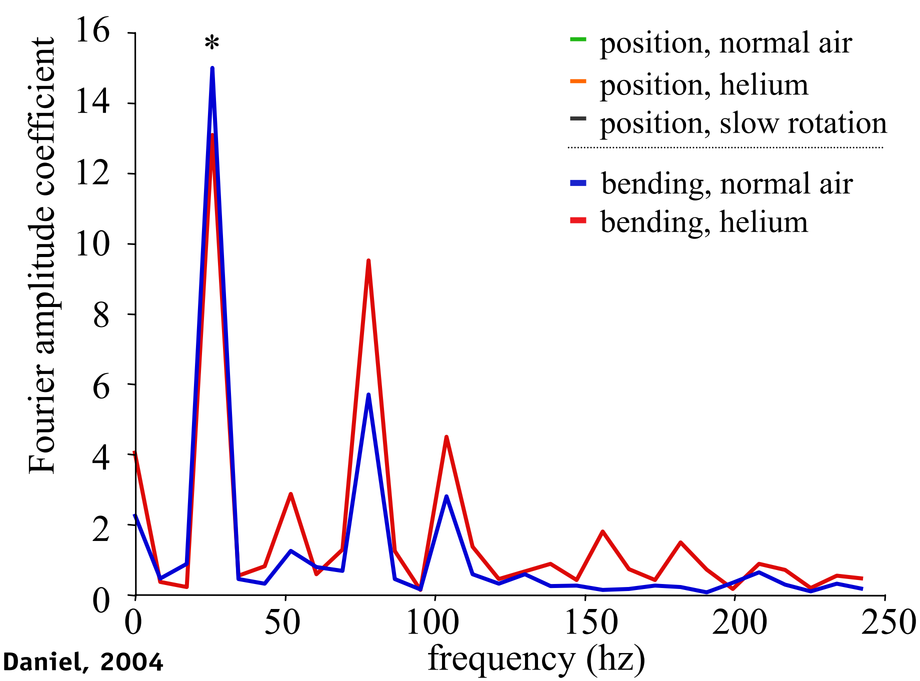
Quantify wing bending at the wing tip, leading edge, and trailing edge







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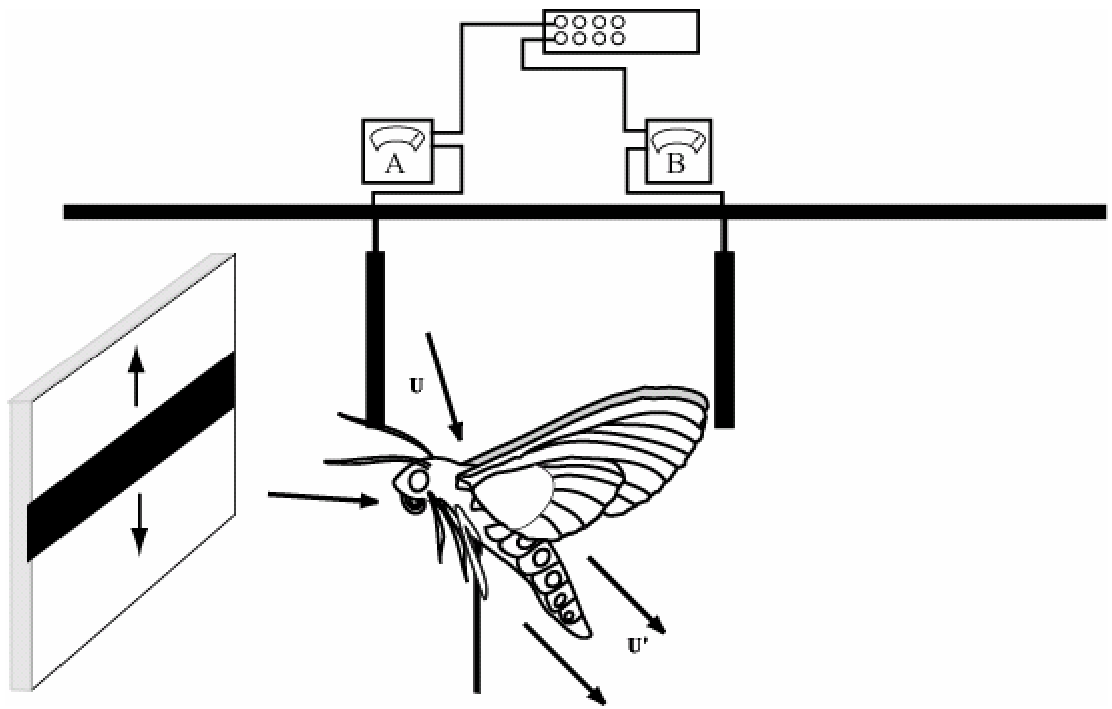
Evidence of bending on the air flow? Measure self-generated flows



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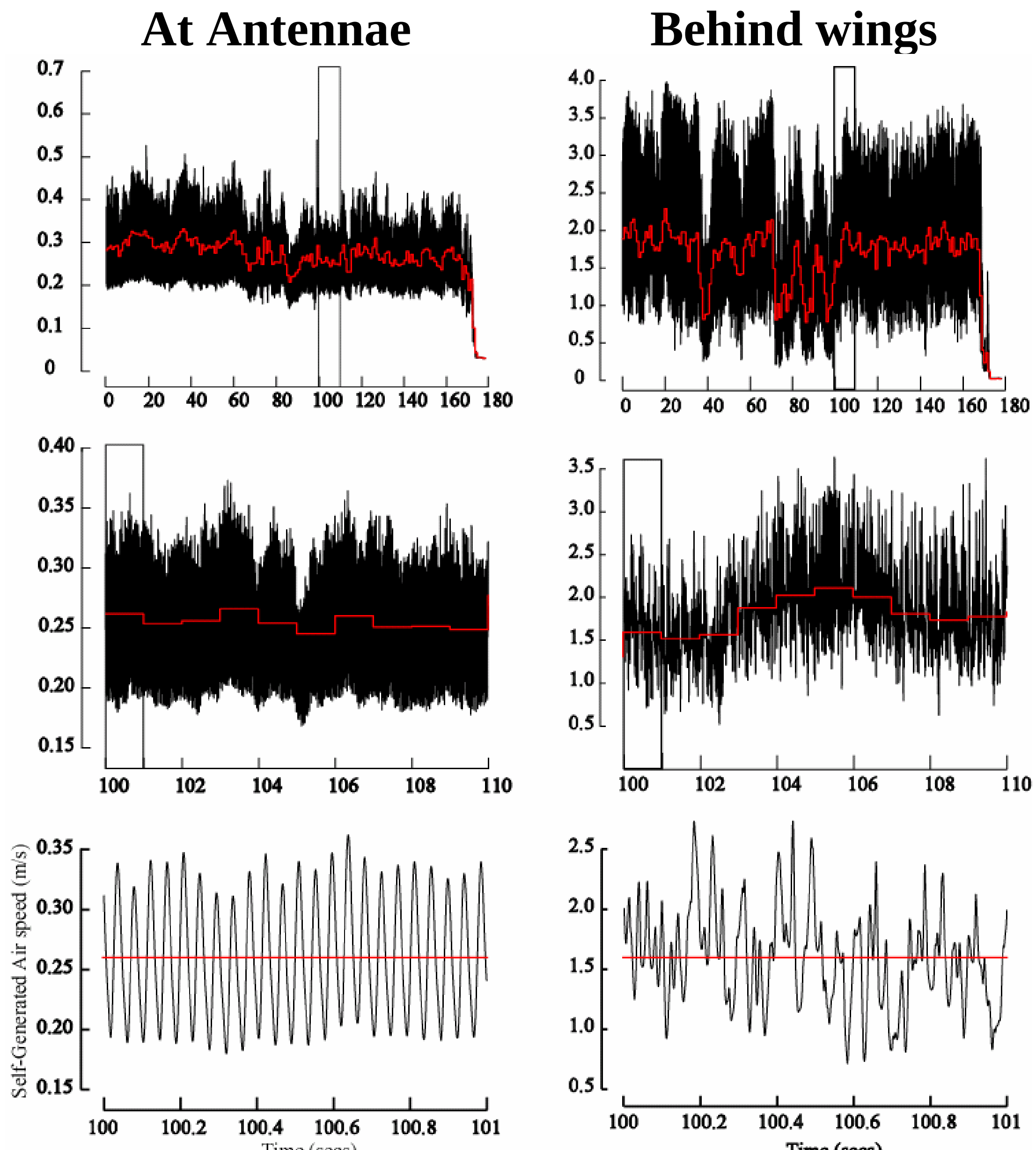
Raw data of self-generated airflow



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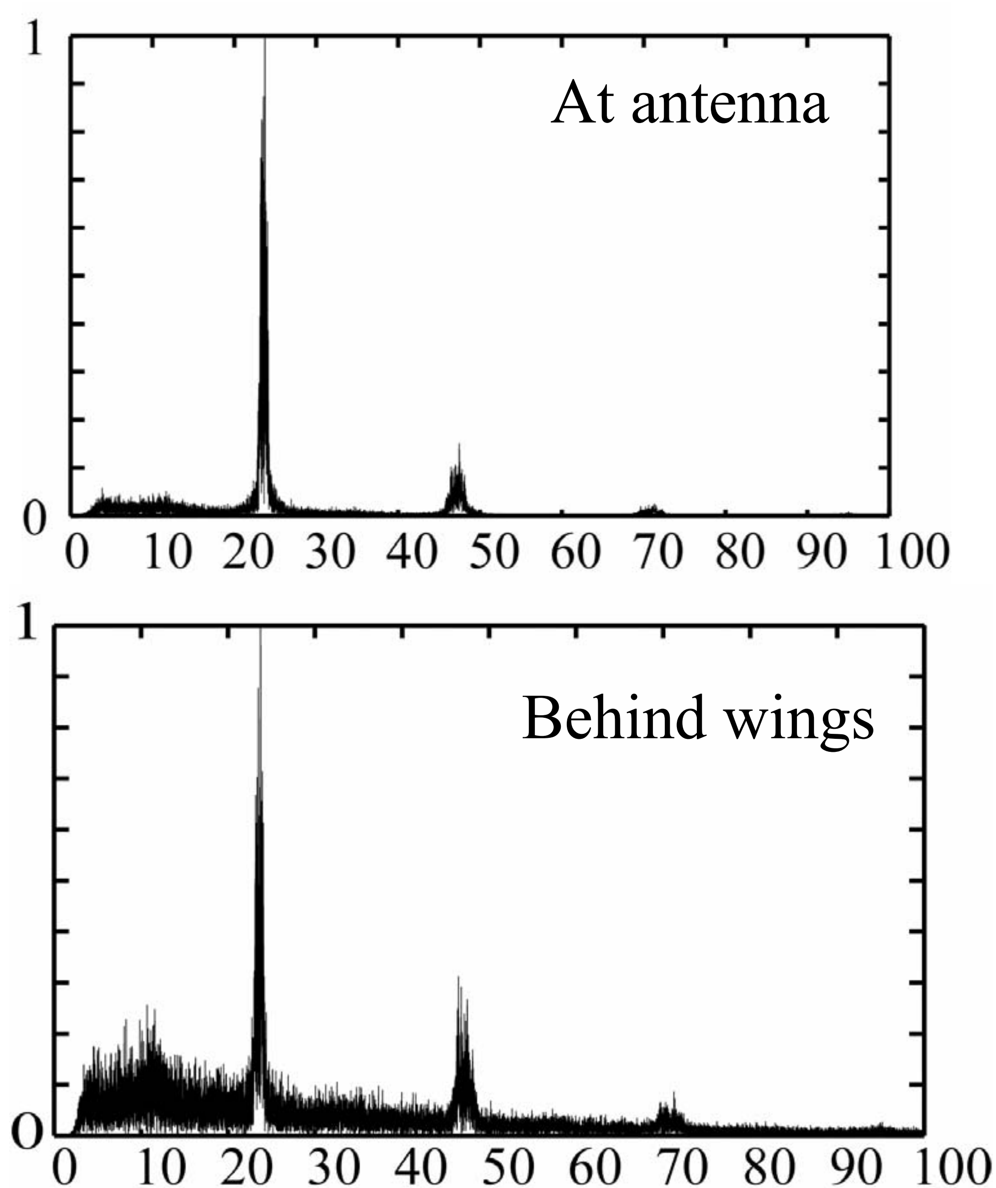
Spectra of recorded airflows



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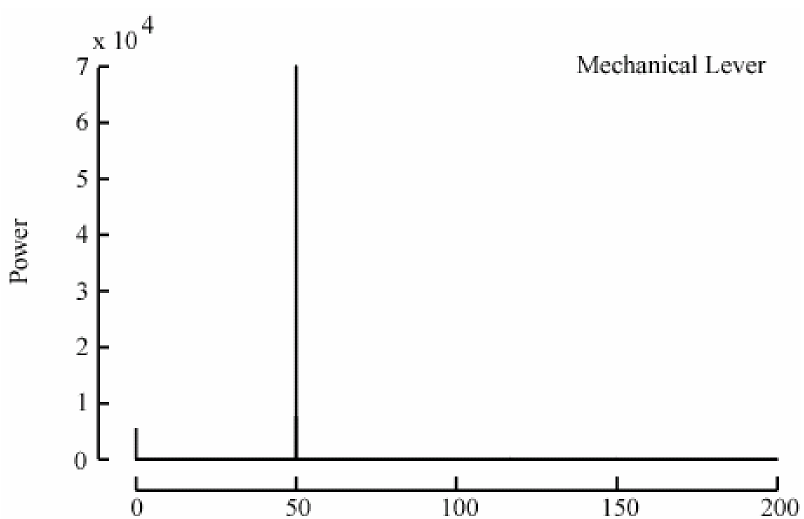
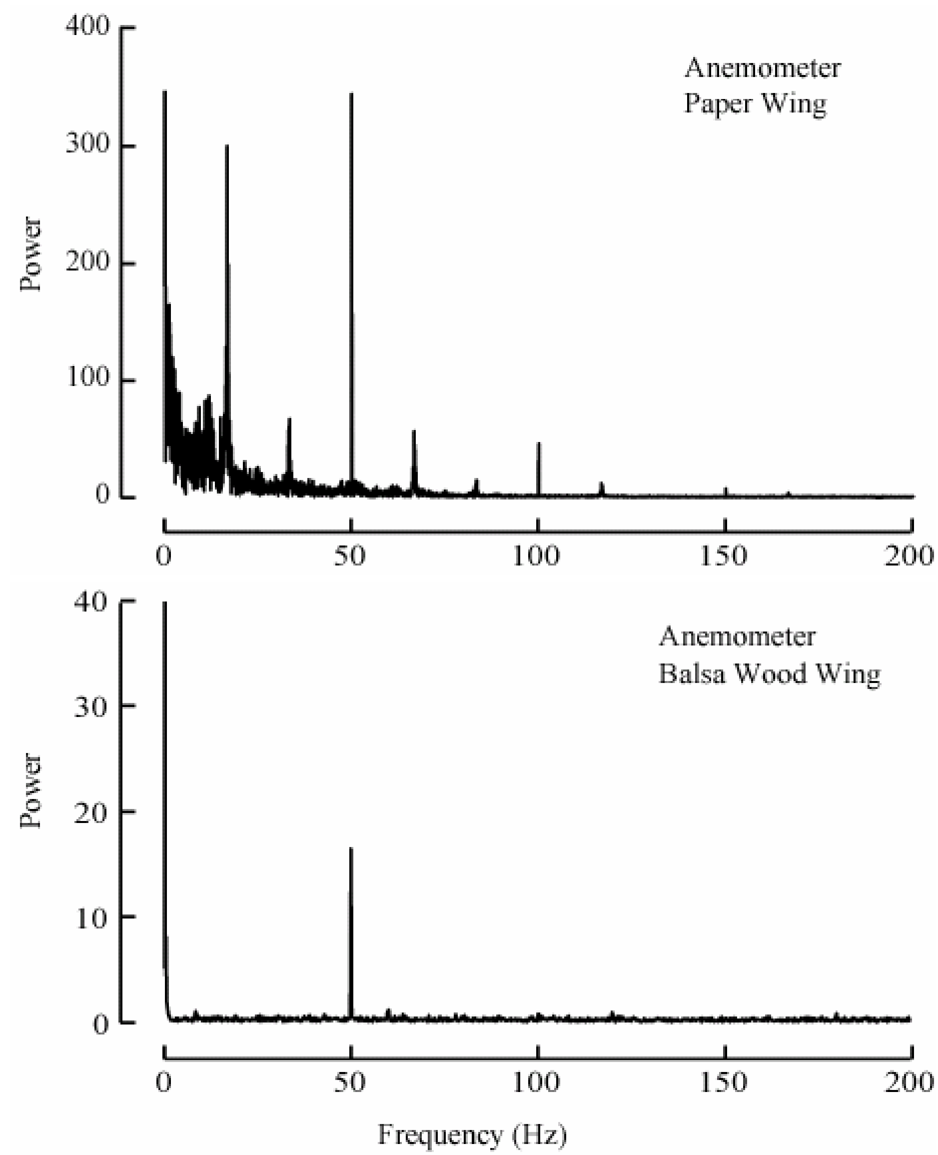
Aerodynamic signature of wing flexibility





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Summary

- Animal wings deform in response to both fluid dynamic loading and their own inertial mechanics.
- Simple scaling arguments suggest appendage inertia may dominate moments for “rigid” wings.
- Bending moments of wings are dominated by elastic/inertial mechanisms in air.
- There is a clear aerodynamic signature of bending wings.
- Thus we could use simple explicit methods for evaluating forces on flexible wings in air.

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CNS

SENSORY INPUT

MOTOR OUTPUT

FLIGHT MUSCLES

FORCE, STRAIN

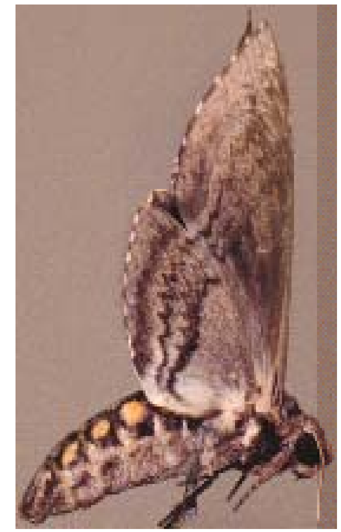
WING HINGE

WING MOTIONS

AERODYNAMICS

FORCES

Insect wings are equipped with a large number of strain sensors on their wings.



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Michael Dickinson, Nate Jacobson
Inspiration:
T.Y. Wu, Daniel Grunbaum

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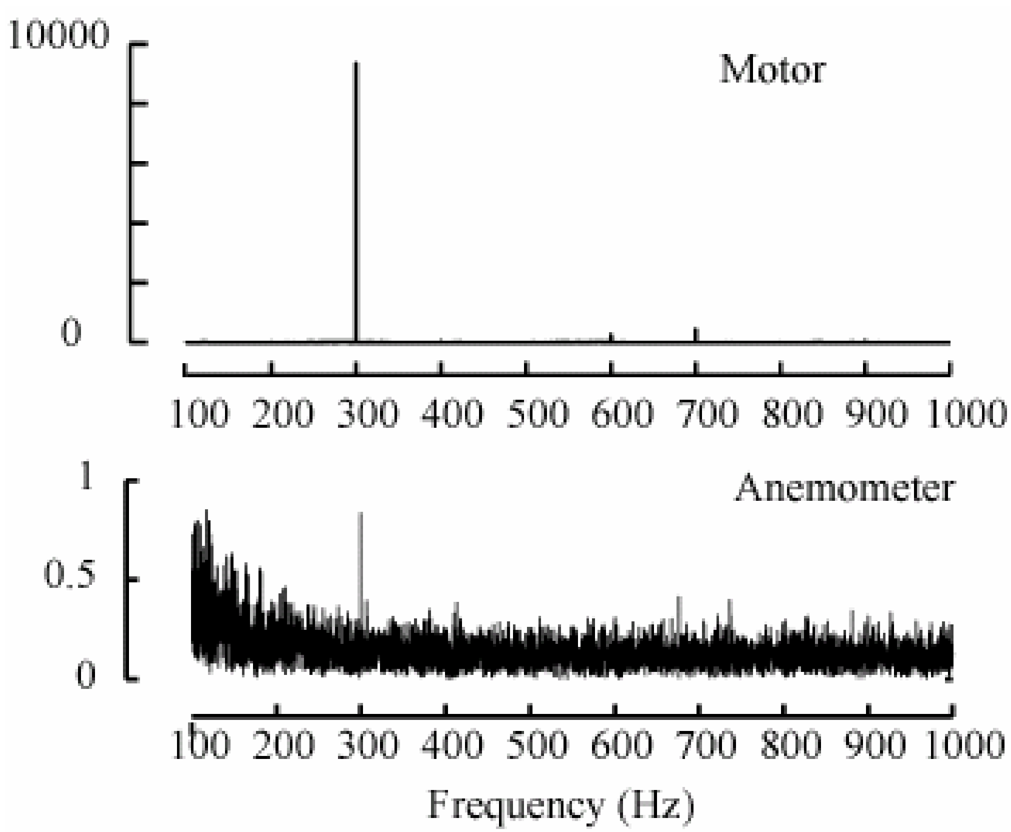
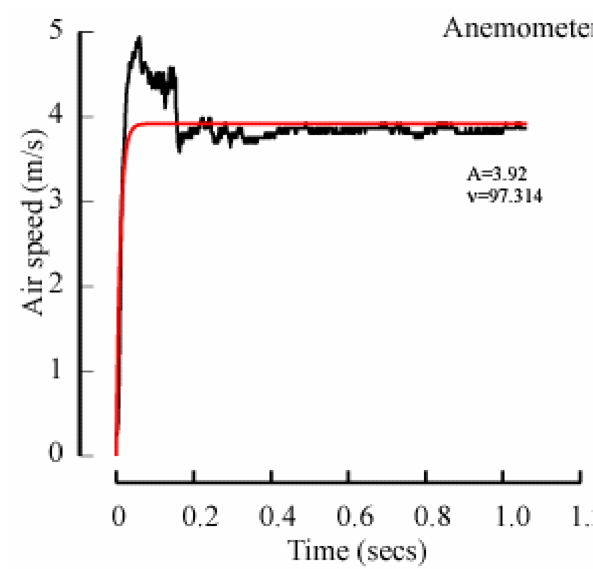
Anemometer Calibration





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