Insect Flight and MAVs

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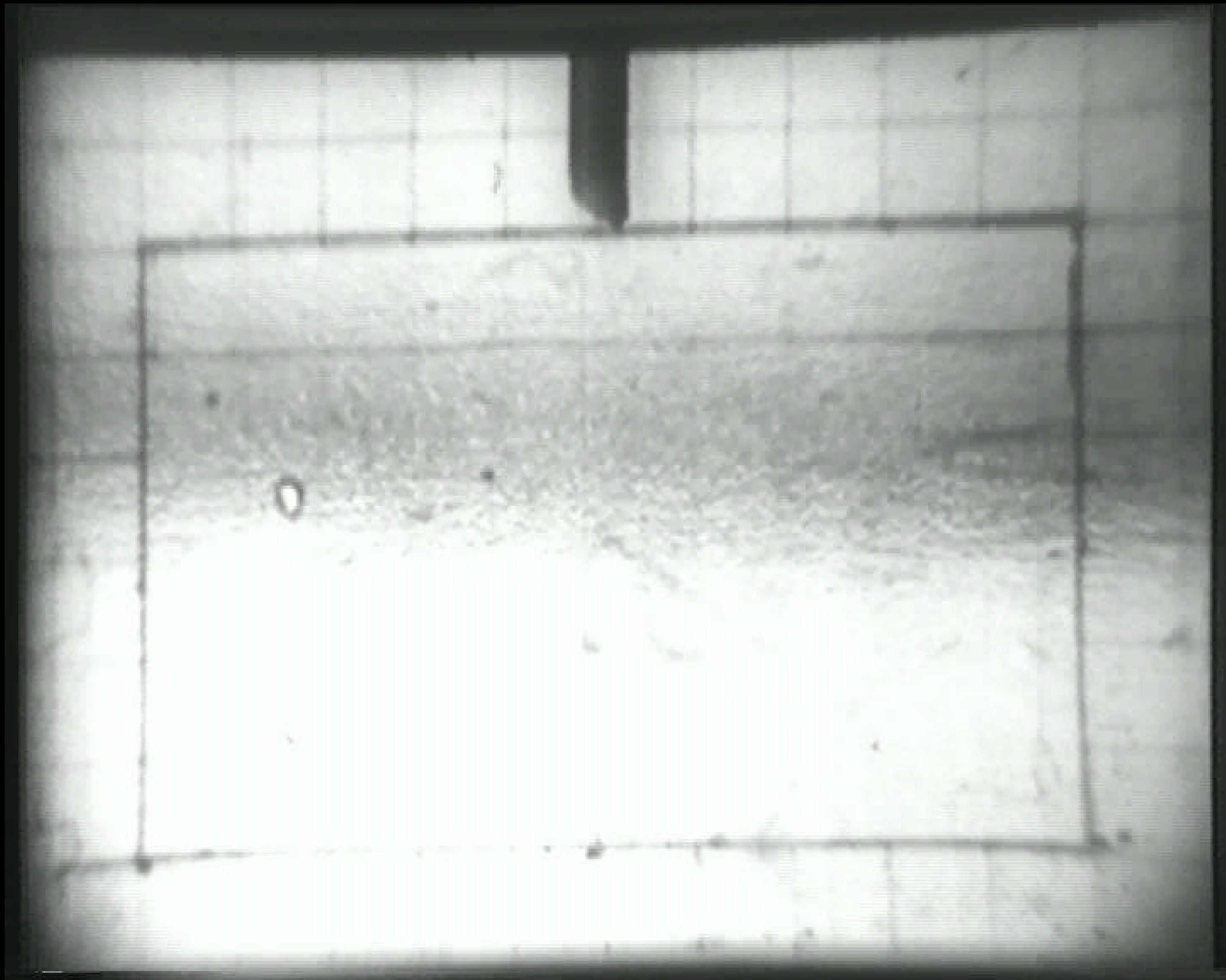
Flapping Wing MAVs

- Insects ARE highly successful autonomous MAVs
- They are specialized for flight at this size range, where conventional wings in steady motion perform badly
- Flapping wings can generate 2-3X more lift - the extra lift capacity is highly desirable for MAVs
- ONLY a flapping design can exploit the high-lift/high-drag aerodynamic mechanisms found in insect flight
- After 350 million years of evolution, they have probably found good solutions for
  - Kinematics
  - Wing design
  - Control Systems



High-Lift Mechanisms in Insect Flight

- **Delayed, or Dynamic, Stall**

- **Rotational Mechanisms**

  •The ‘Fling’ et al. to create high circulation during the rotational phases of the wingbeat.

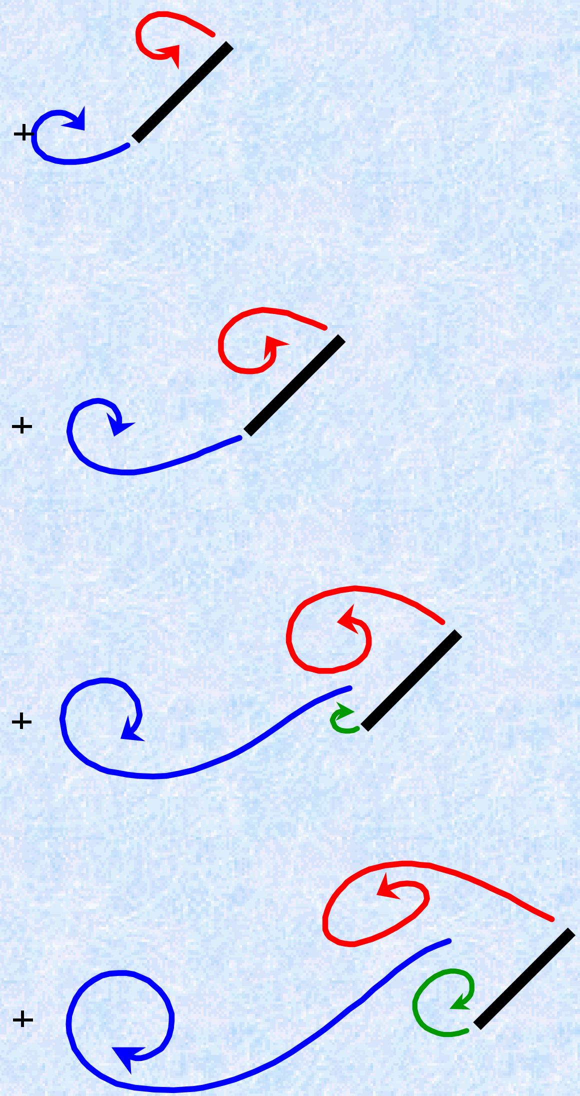
  •$d\alpha/dt$ at the 3/4 chord towards the end of the wingbeat (quasi-steady rotational model) to sustain or augment high circulation create by another mechanism.

Dynamic Stall –

a conventional, unsteady high-lift mechanism

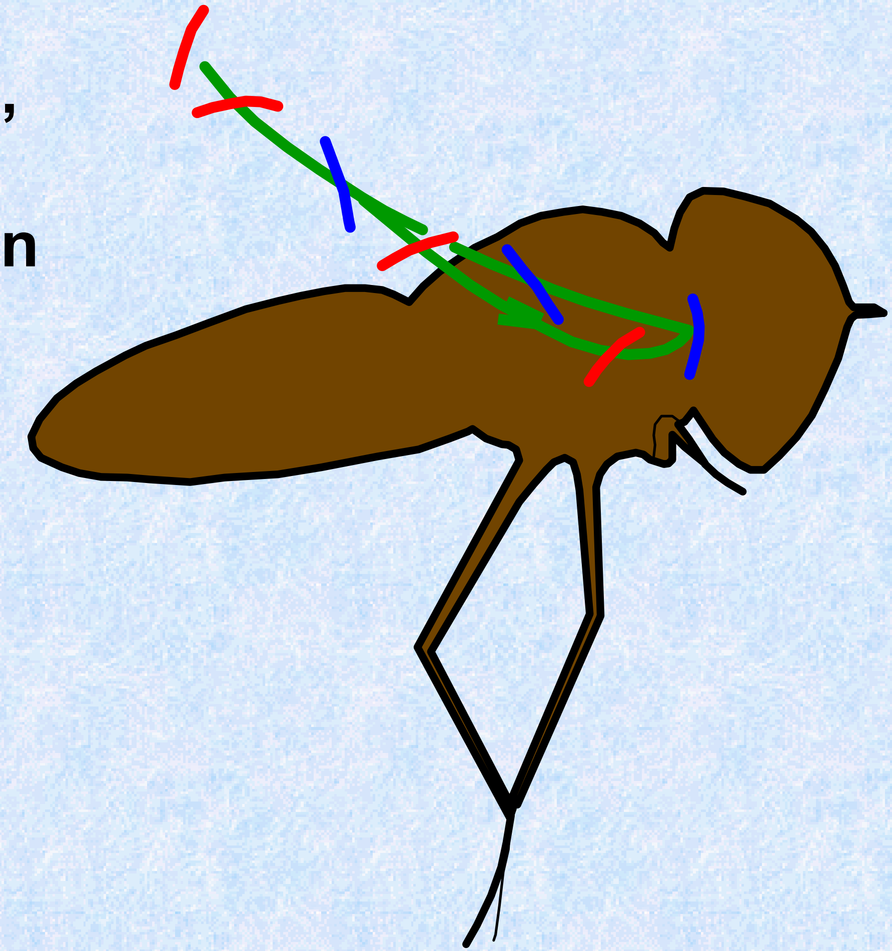
Extra lift is created by a leading-edge vortex when the wing is moved at high angle of attack.

But the LEV is unstable, and the wing stalls after 3-4 chords of travel.



Hovering with an Inclined Stroke Plane

Hoverflies, dragonflies, small birds and bats rely on dynamic stall on the downstroke (red) for weight support



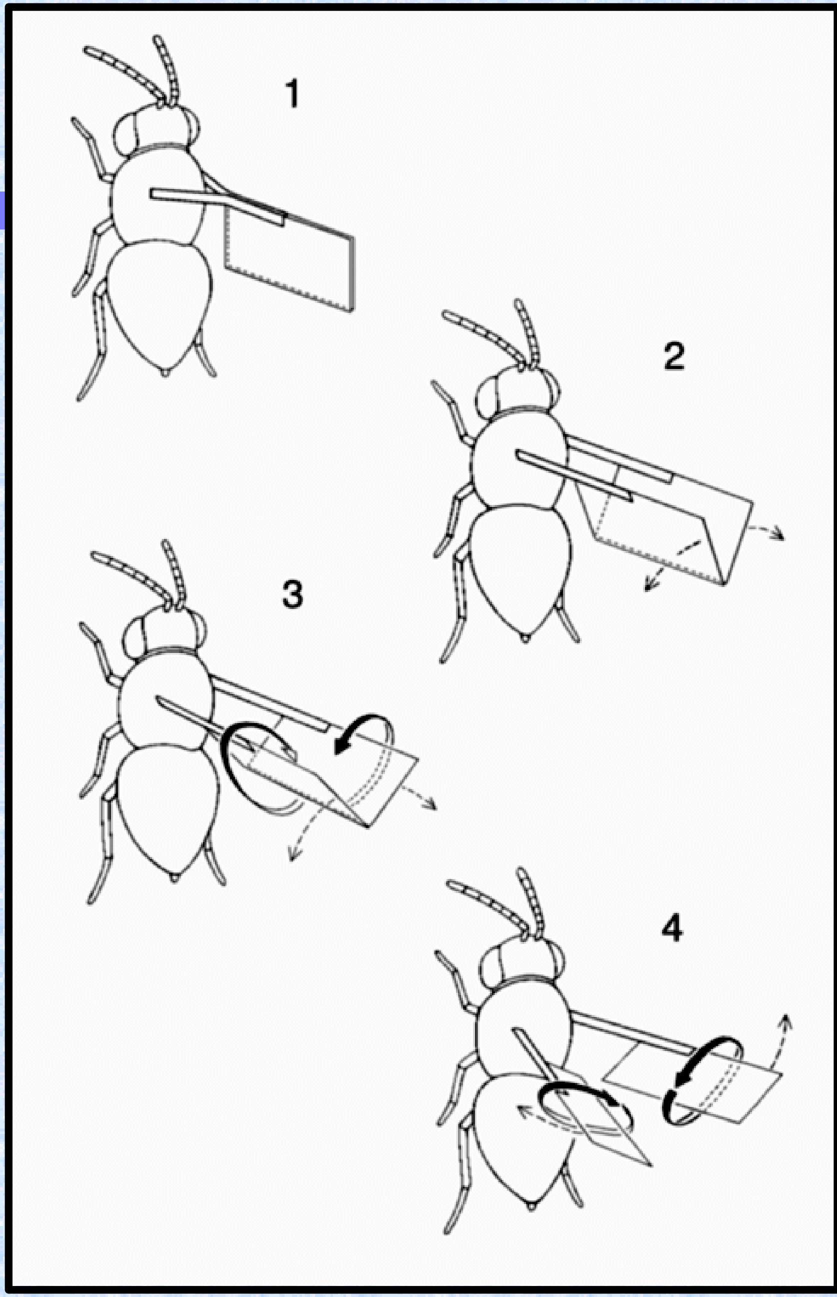
Episyrphus balteatus

Fling Mechanism

Generates high lift for tiny insects, once thought to ‘swim’ through the air. Also found in some moths, butterflies, etc.

Mechanical wear and tear of the wings limits its usefulness.

(Weis-Fogh, 1973)

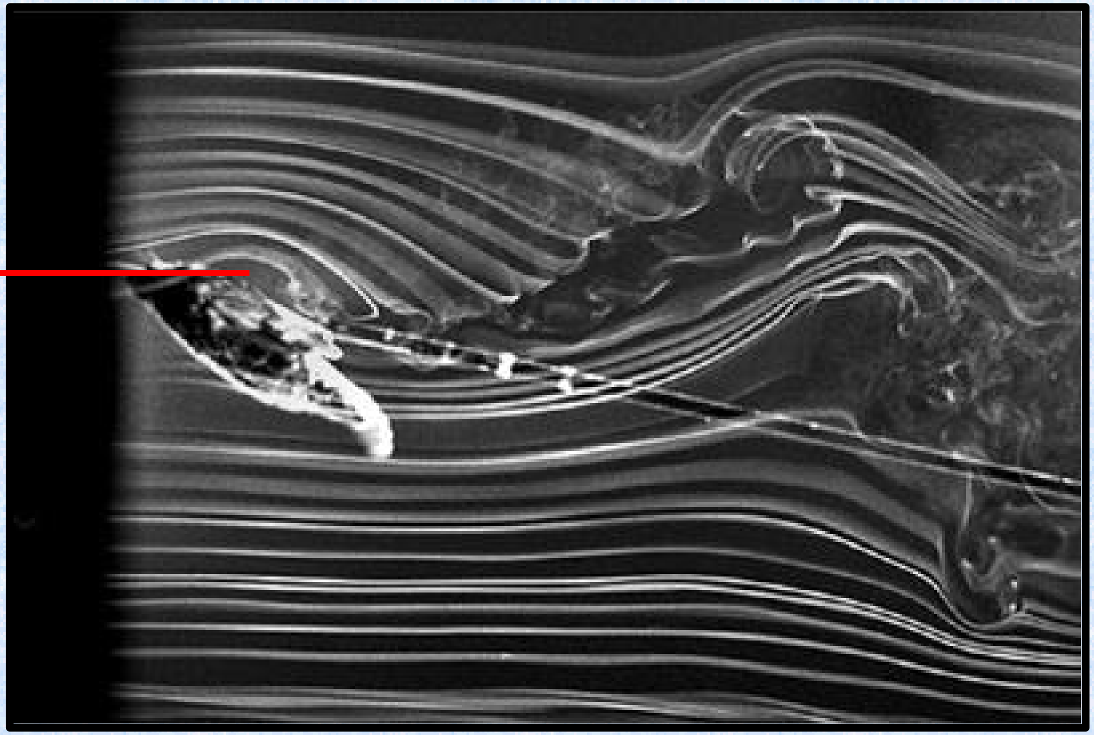


How Do Most Insects Fly?

Hawkmoth *Manduca sexta*

Smoke Flow Visualization

Small LEV

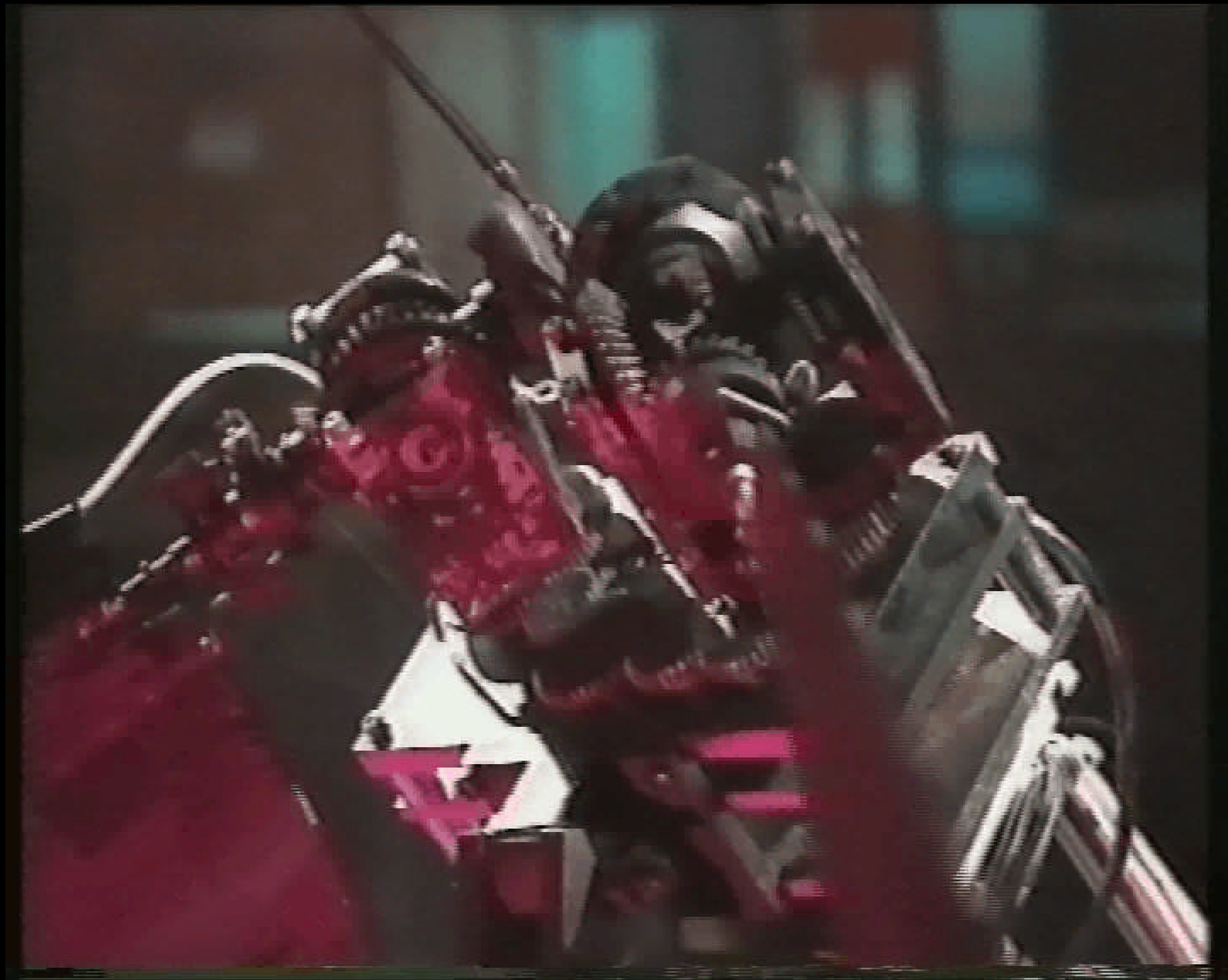


(with Sandy Willmott and Adrian Thomas)

The Flapper: x 10 Mechanical Model

(with Coen van den Berg)

The Flapper

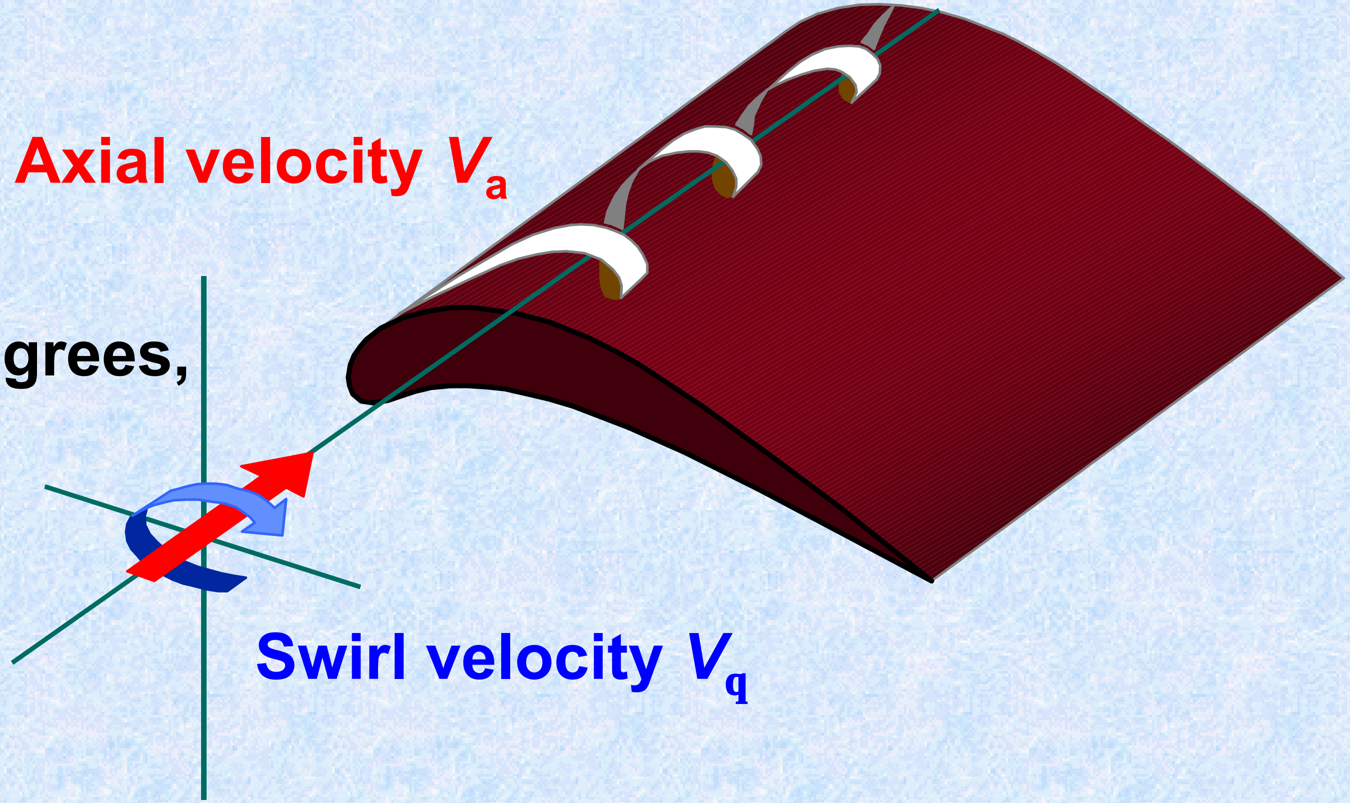


Mid-Downstroke

End of Downstroke

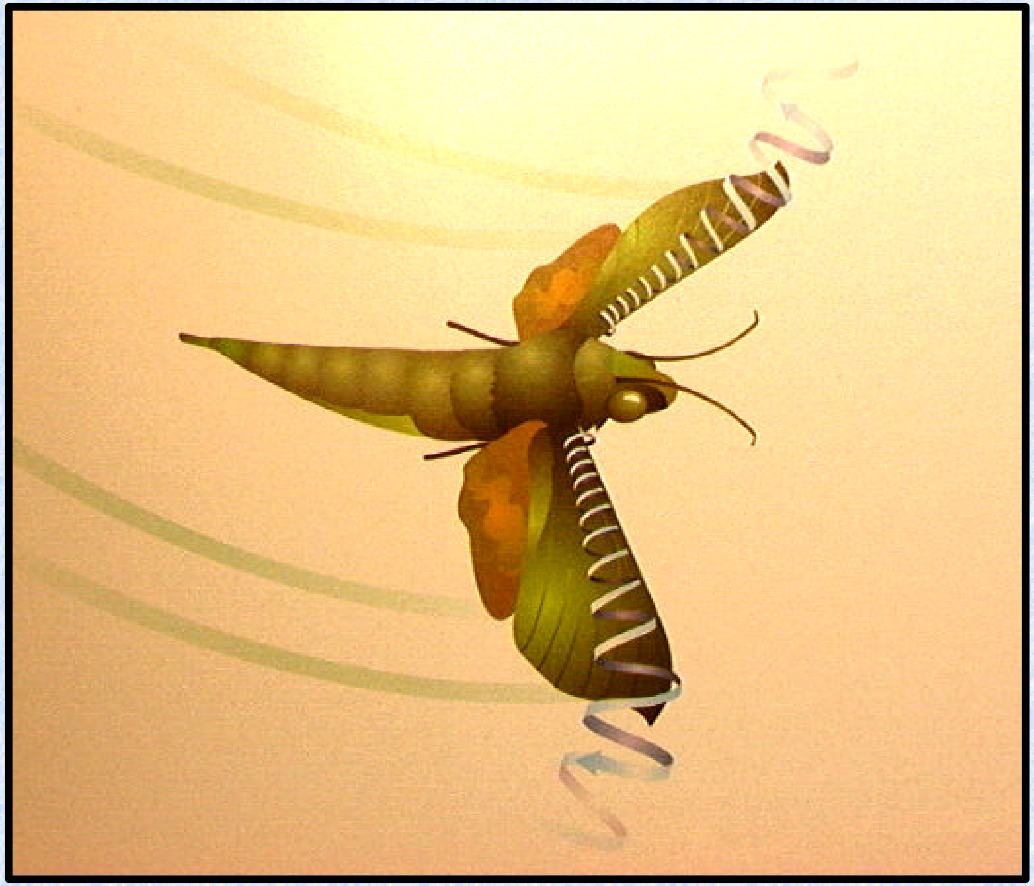
Velocity Components of Spiral LEV

Helix angle is 46 degrees,
so $V_q \gg V_a$

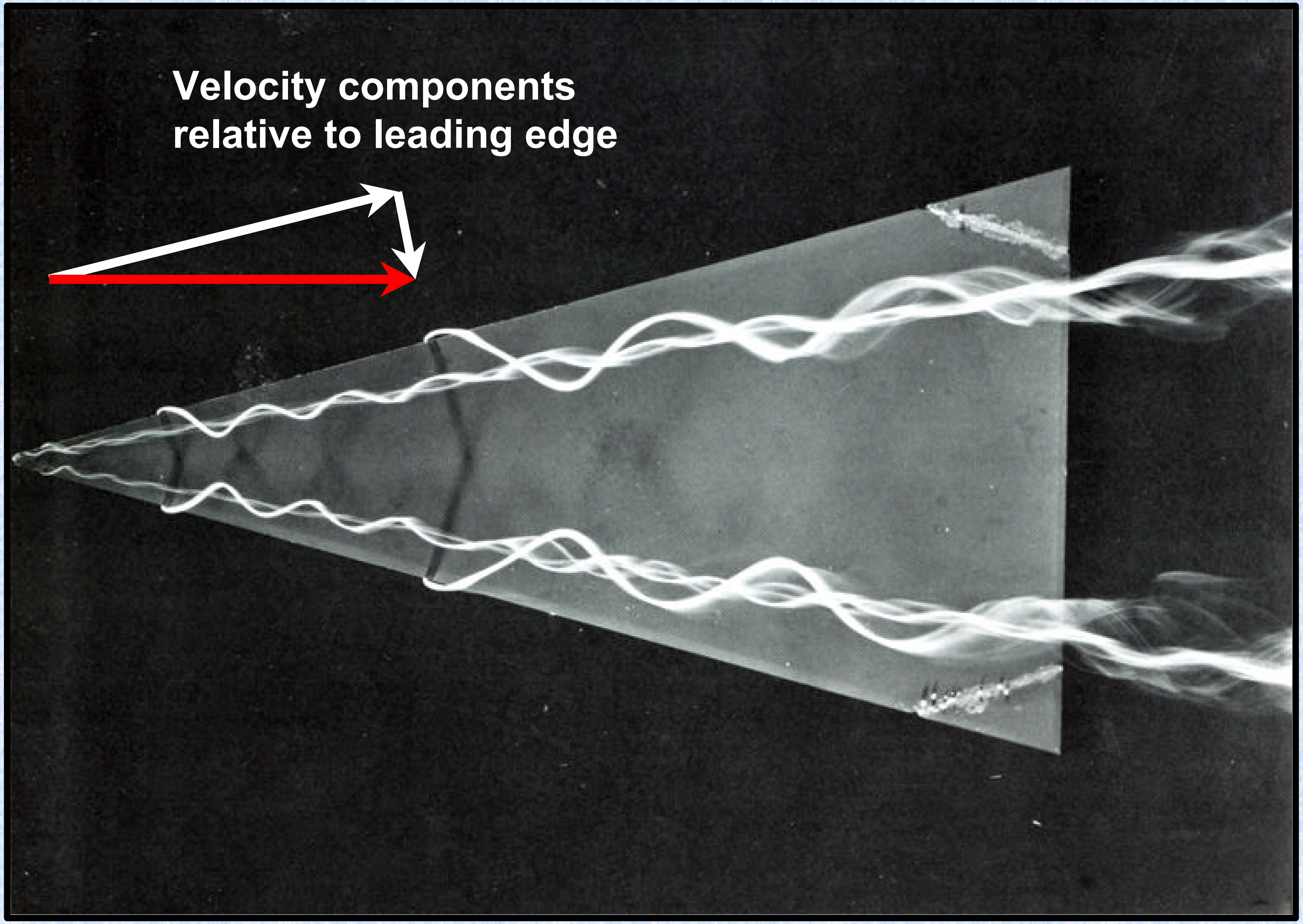


Dynamic Stall with a Spiral LEV

- Spanwise flow stops early separation of the LEV
- The resulting Spiral LEV accounts for most of the lift
- L/D ratio is still awful, typically less than 2
- It has not been reported for rotors and propellers



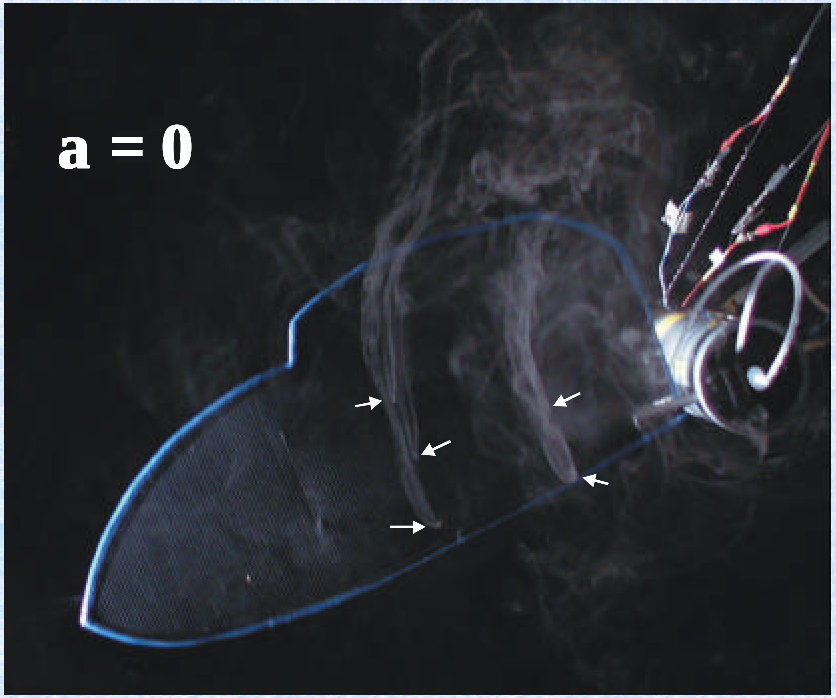
Delta Wing Analogy

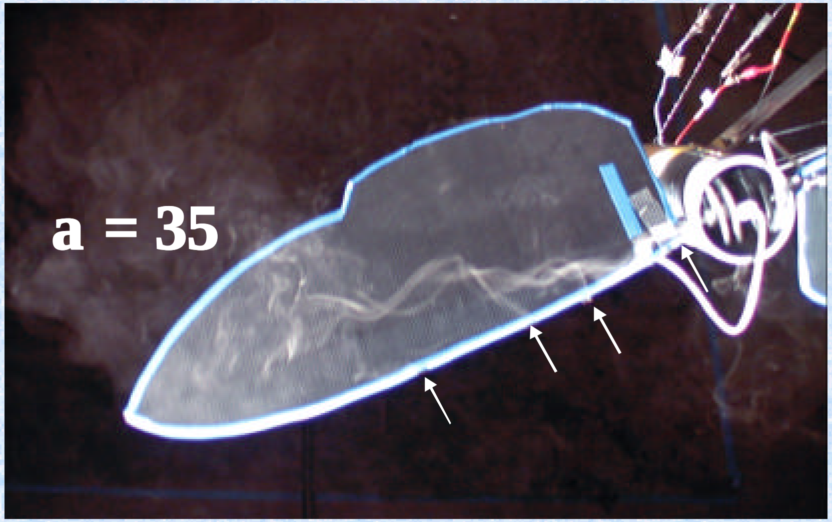


Propeller Experiments

- Propellers provide an analogy for ‘translation’ during the flapping phase of the cycle.
- Flow visualization is easy
- Thrust and torque measurements for force coefficients

Spiral LEV on Laminar Propellers

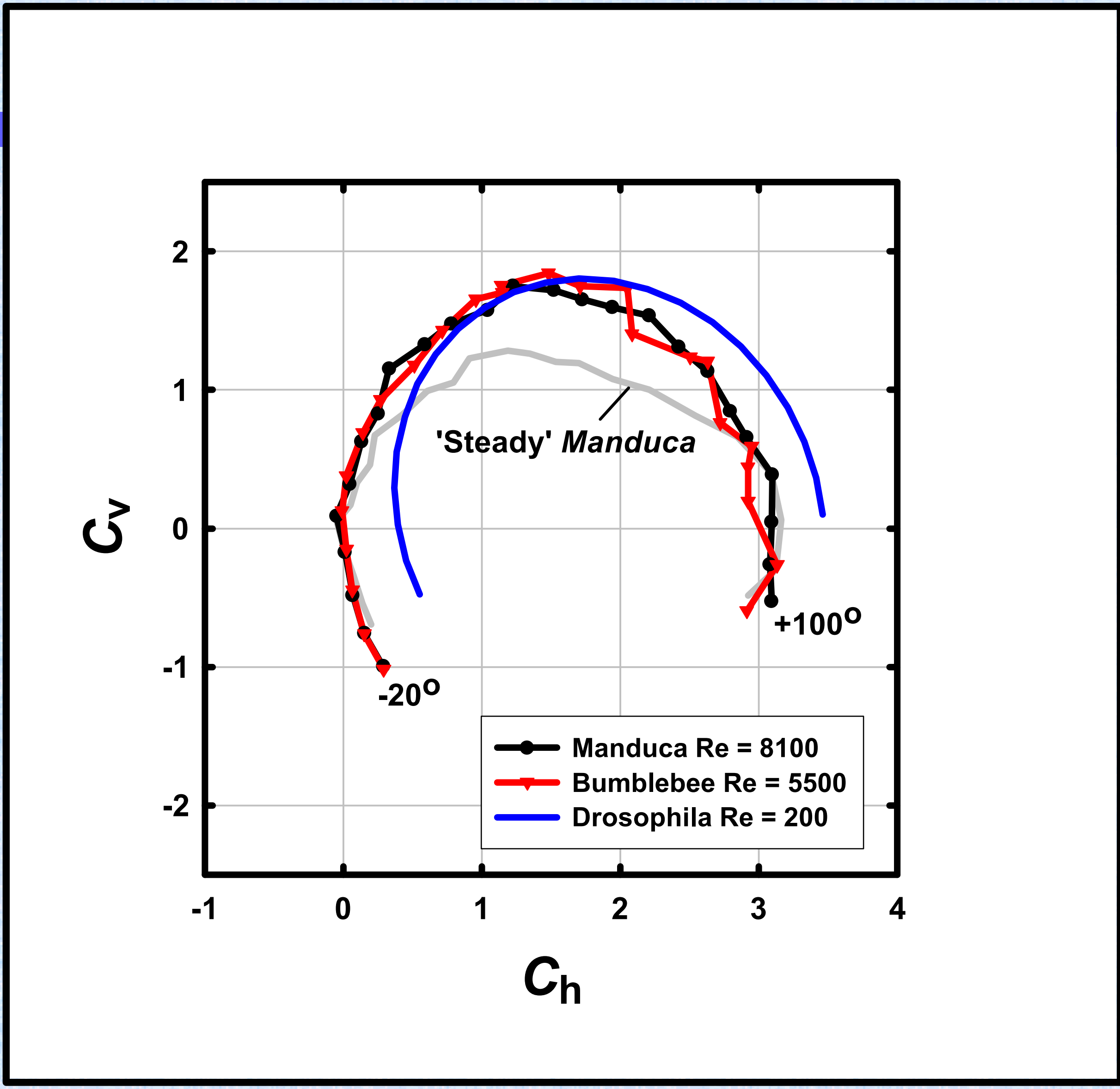




A quasi-steady rotary wing phenomenon, not an unsteady mechanism

(with Jim Usherwood)

‘Early’ Polar for a Range of Species



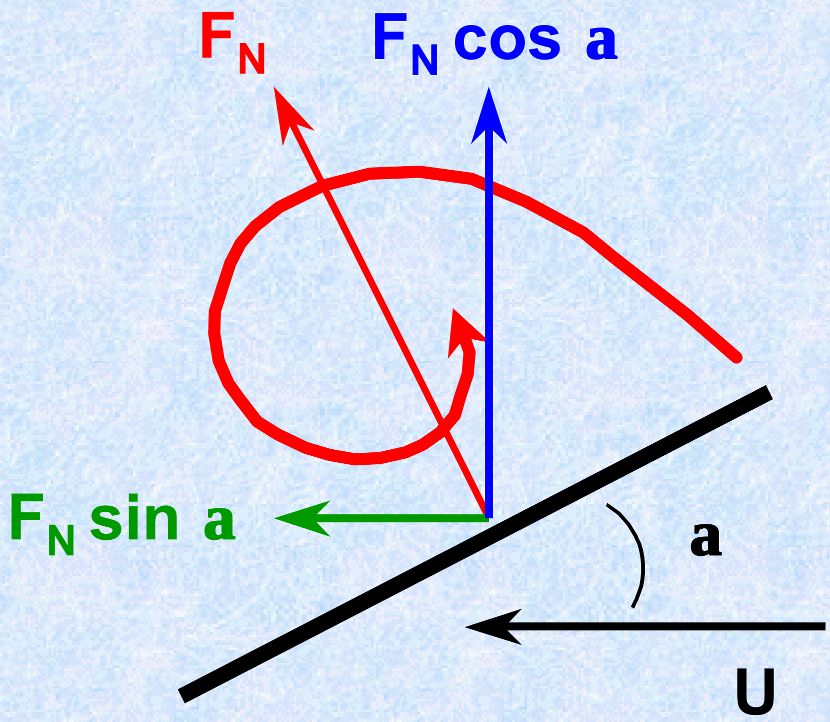
Extra Drag as well as Extra Lift

Leading-edge separation causes loss of leading-edge suction.

The normal force resulting from low pressure in the LEV creates extra lift.

But it also has a large drag component, giving a poor lift-to-drag ratio.

L/D » cot a < 2



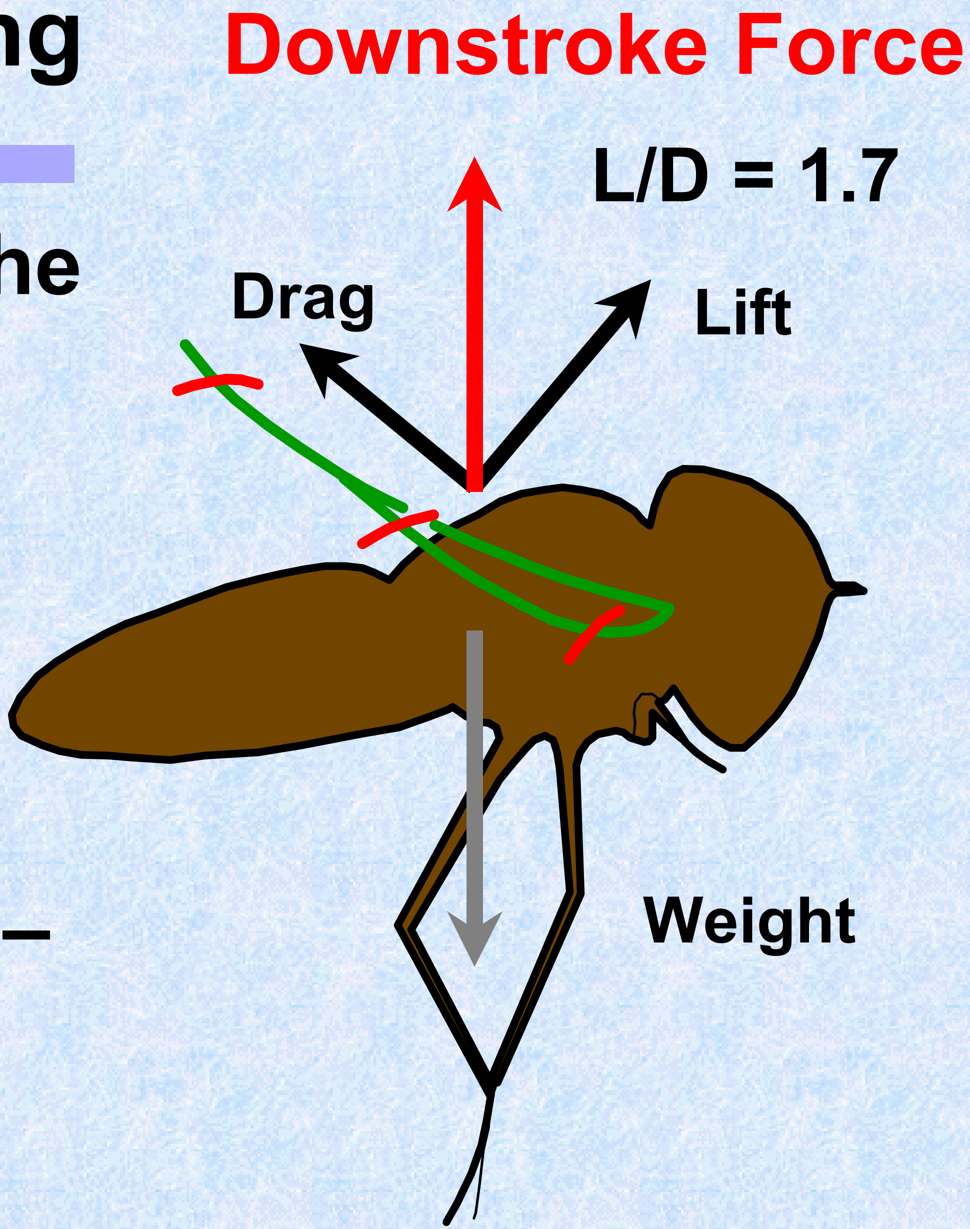
Conclusions for Laminar Propellers

- Delayed Stall can be delayed indefinitely
- Polars are remarkably similar for different cambers, twists, aspect ratios, etc.
- Leading-edge separation causes loss of leading-edge suction, and the normal force dominates.
- Lift-to-Drag ratio is primarily determined by the angle of attack, and is less than 2.
- High drag is a necessary adjunct to high lift.
- The wing motion must be adjusted to exploit the high <u>resultant</u> force, and not the high lift per se.

Inclined Hovering

Lift <u>and</u> Drag on the downstroke support the weight

No wasted power – it all goes into weight support



Hovering Flapping Flight – a MAV Design Study

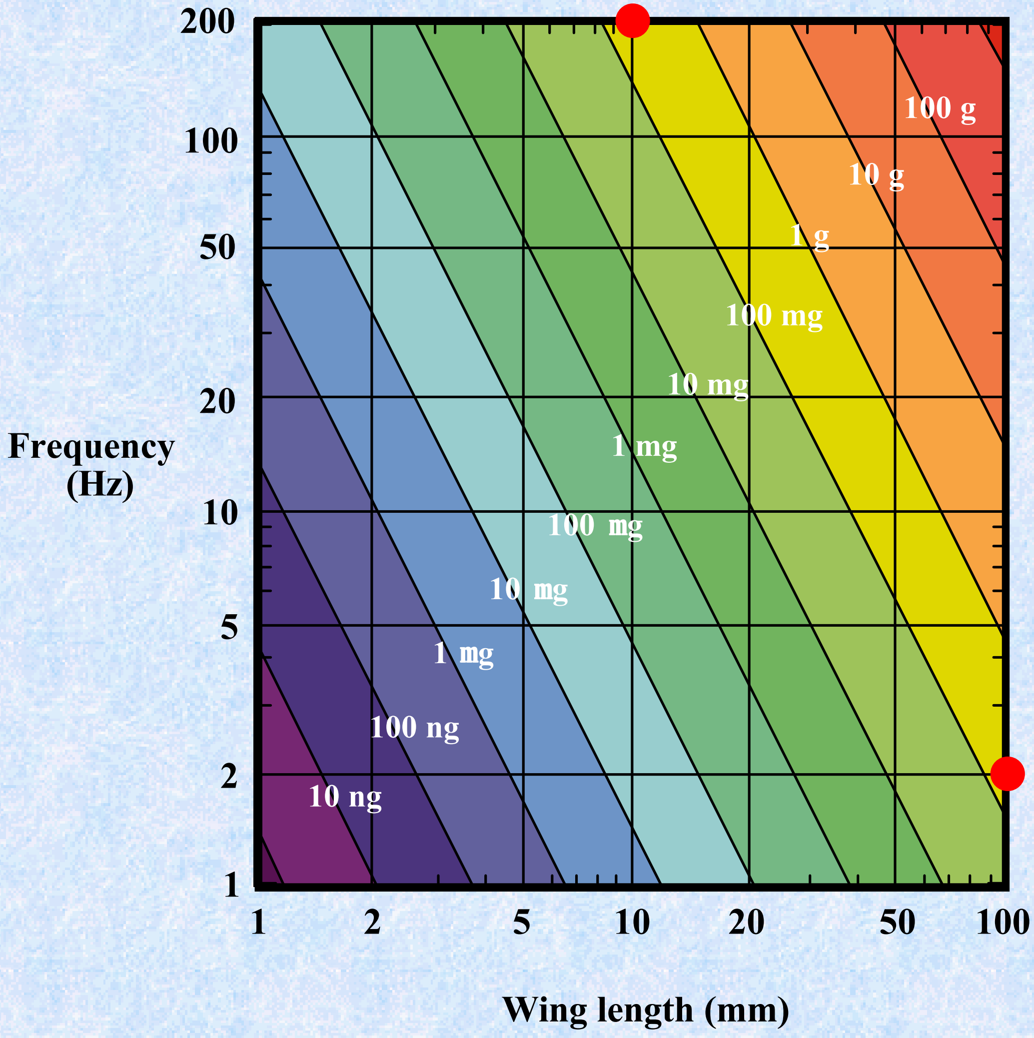
- Simple design equations
- A practical experimental testbed
- Pendulum stability
- Maximum lift coefficients
- Maximum power

Assumed Values

- Simple harmonic motion for the wings
- Flapping amplitude is 120 degrees
- Aspect ratio = 7
- Centroid of wing area at 0.5 R
- $C_L = 2$
- $C_L/C_{D,pro} = \cot(a) = 1.7$

Mass Supported

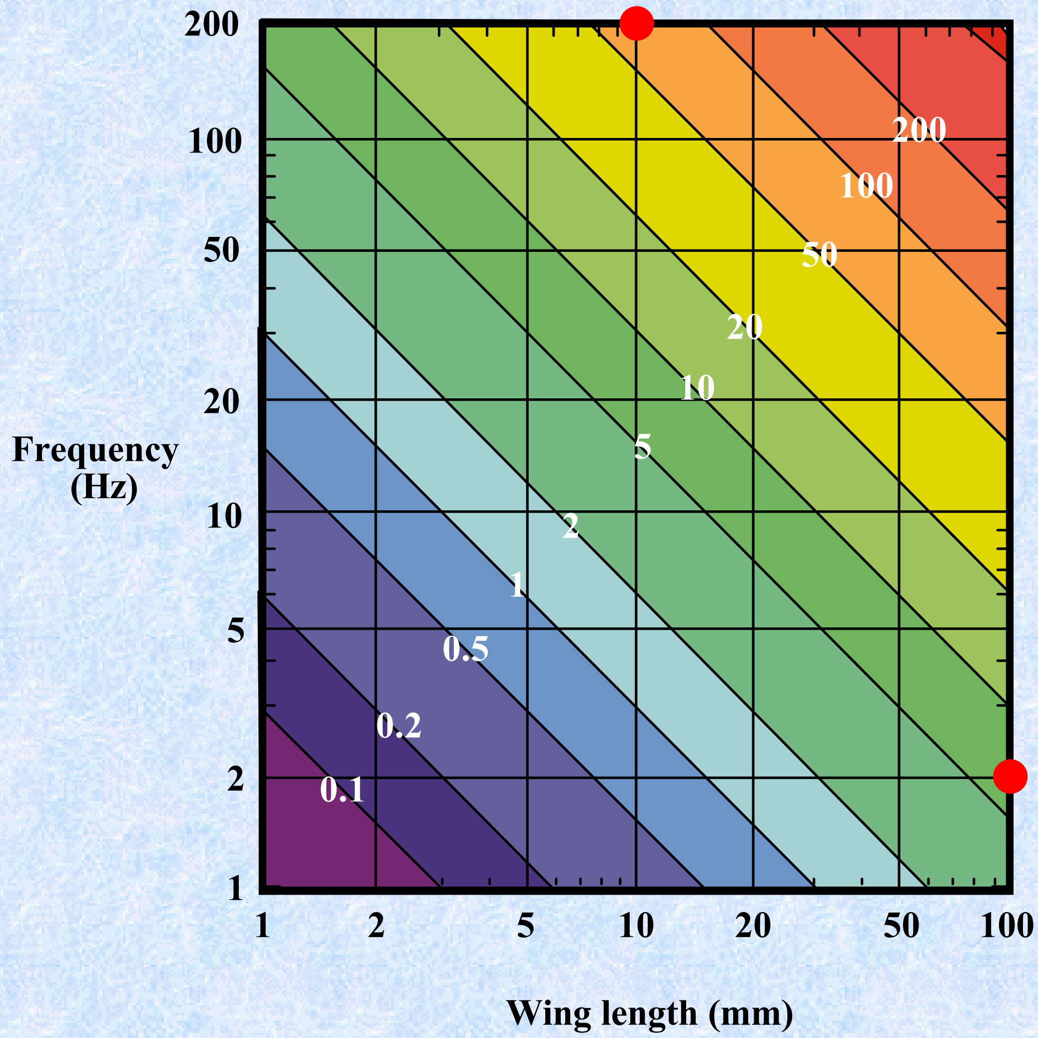
$$m = 0.387\,\frac{F^2 n^2 R^4 C_L}{AR}$$



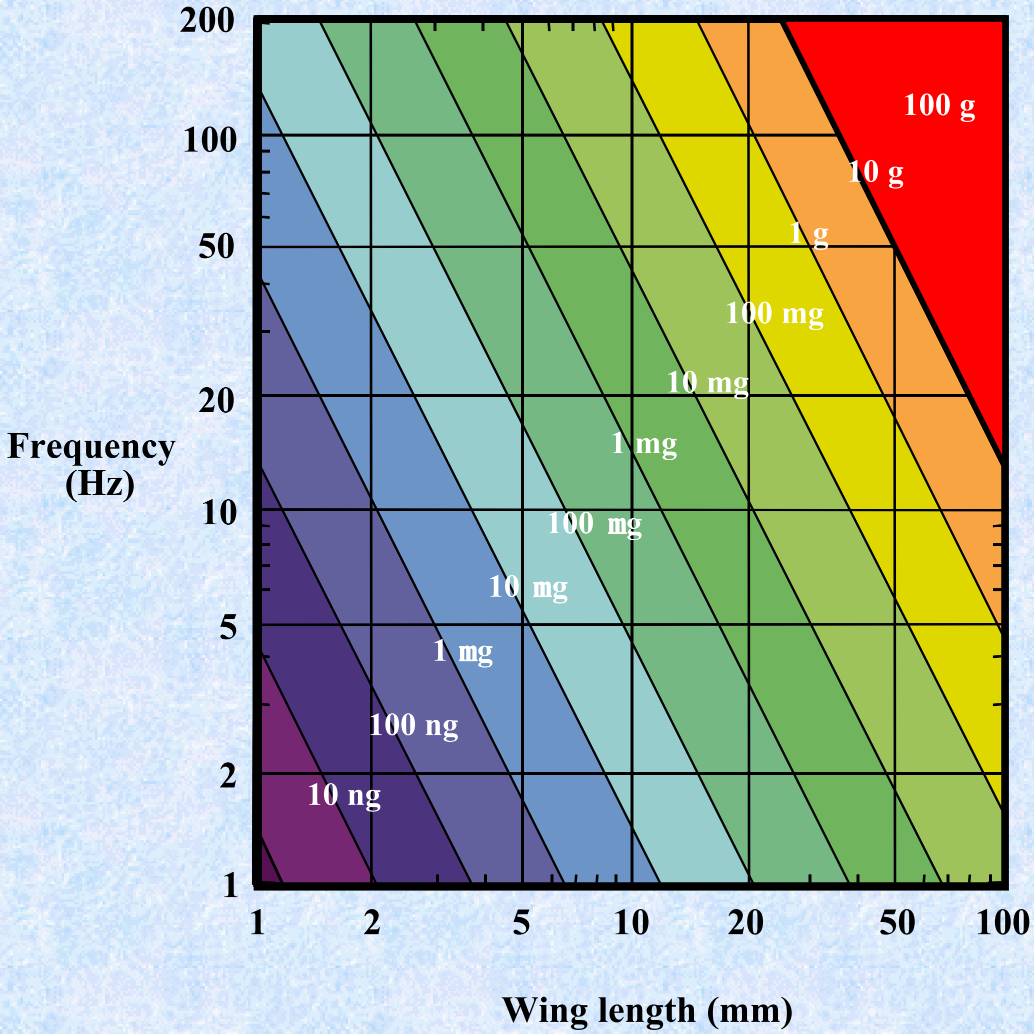
Aerodynamic Power (mW/g)

$$P^{*}_{ind} = 14.0\ n R \left(\frac{F\ C_L}{AR} \right)^{\frac{1}{2}}$$

$$P^{*}_{pro} = 18.2\ F\ n R \frac{C_{D,pro}}{C_L}$$



Mass Supported

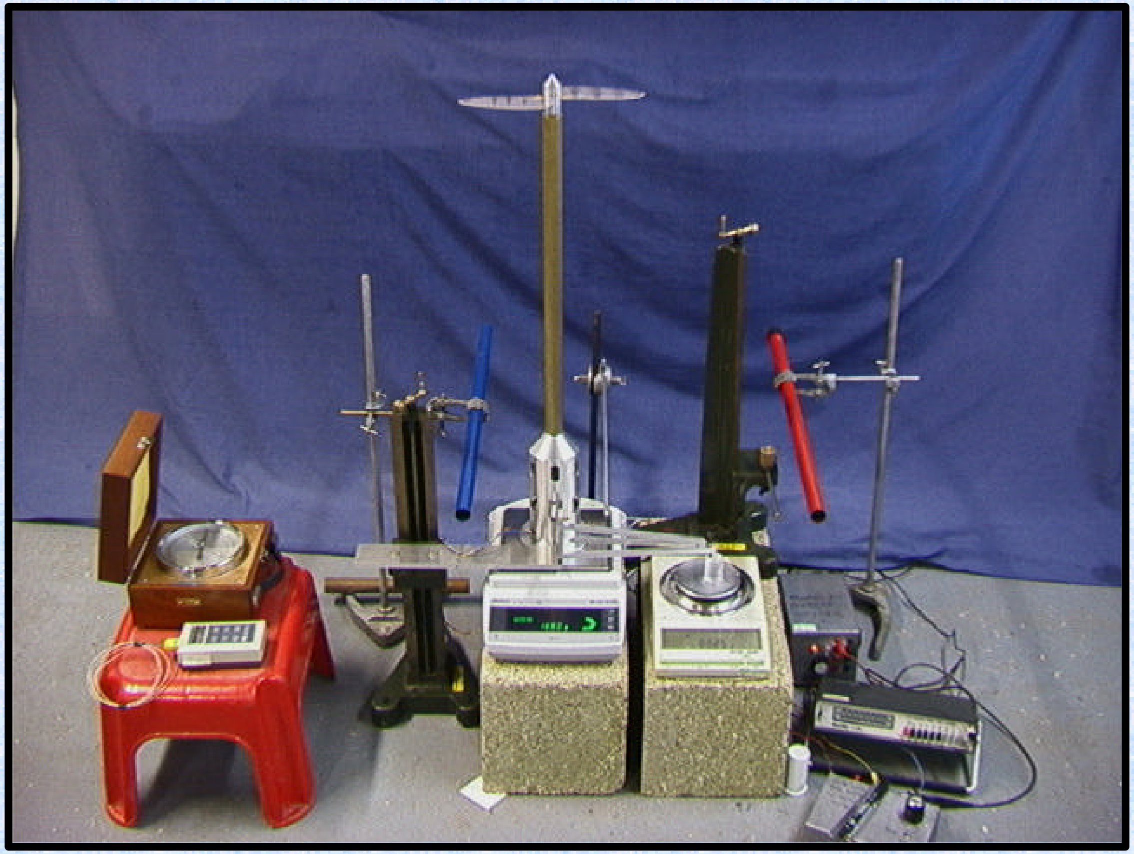


Turbulent Shear Layers at Re » 10000

Design Conclusions

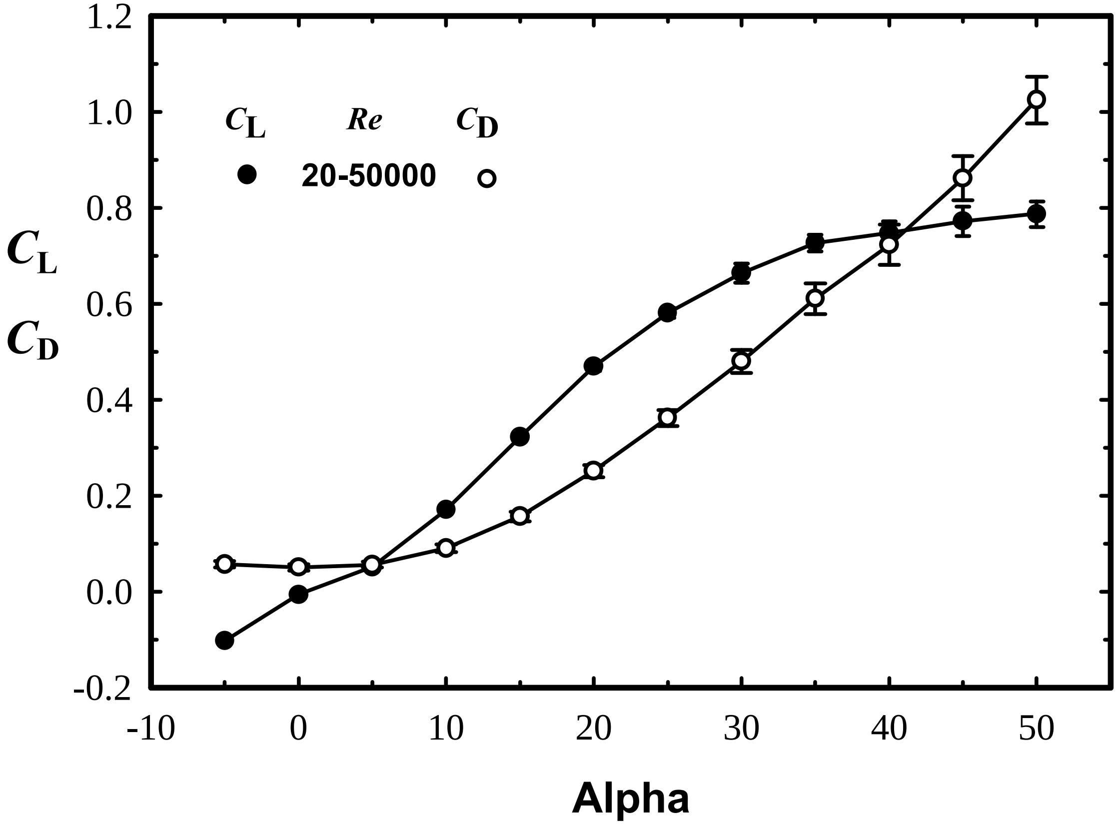
- Longer wings are better - much better
- The power requirements are achievable (just!)
- For reasonable mass support (e.g. about 50 g), Re is around 50,000
- Will the spiral LEV mechanism work at high Re?

High-Re Propeller Rig



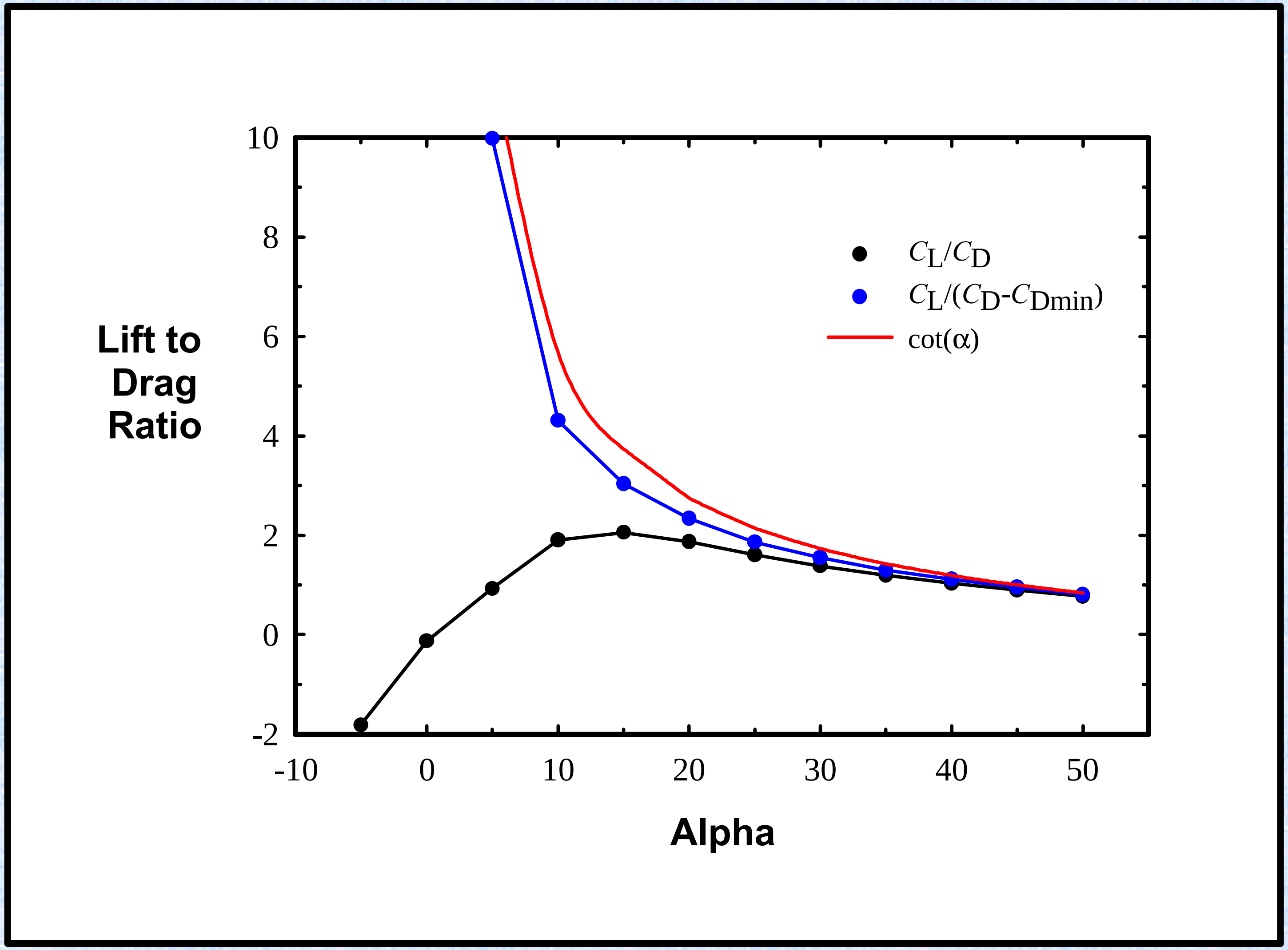
Will the spiral LEV mechanism work at high Re?

Means of All Wings, Re = 20,000-50,000



Error bars +/- 2 s.d.

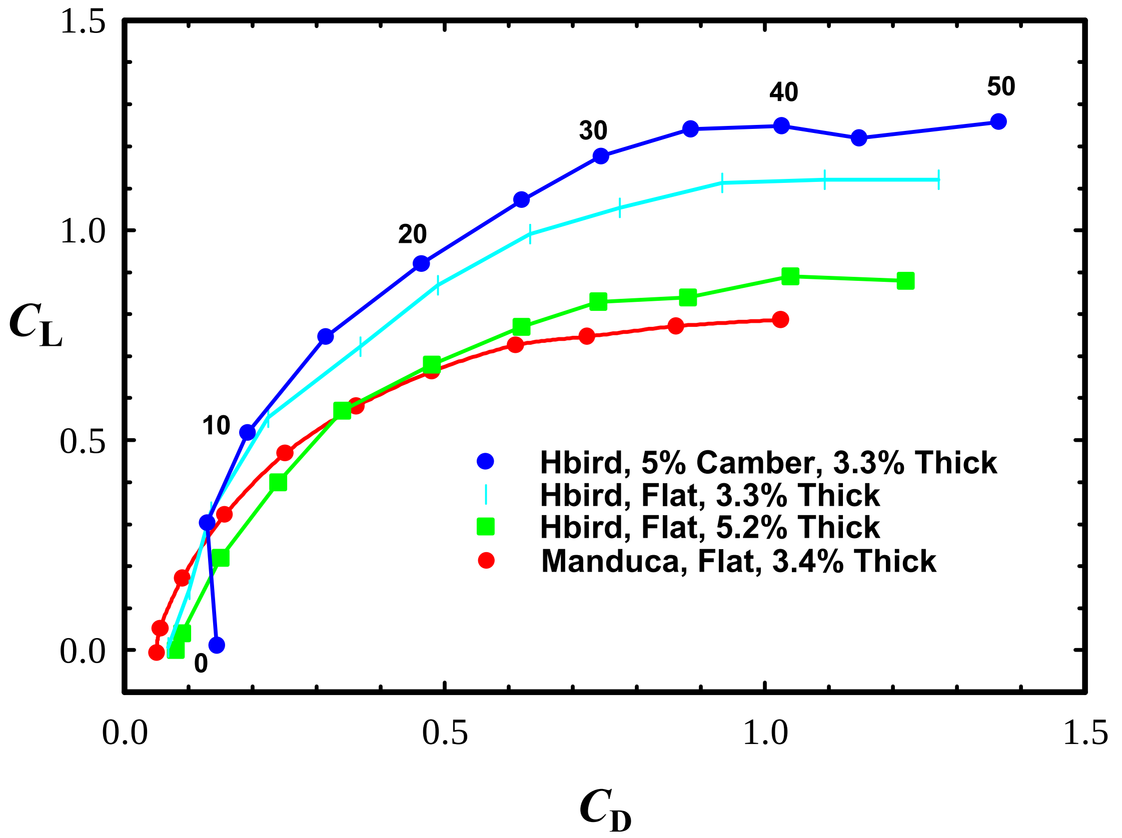
Lift-to-Drag Ratio



Conclusions for High-Re Propellers

- Leading-edge separation occurs: leading-edge suction is lost, and the normal force dominates
- The separated shear layer becomes turbulent at Re>10,000
- Spanwise flow is destroyed by turbulent mixing
- Results are consistent with periodic growth and shedding of an unstable LEV
- Conventional wings with attached flow give higher lift

Hummingbird Wing Models at *Re*=20,000



Hummingbird Wing and Models at *Re*=5000