Ph.D. Course on *Vorticity, Vortical Flows and Vortex-Induced Vibrations*
Technical University of Denmark, Copenhagen, Denmark
vortex.compute.dtu.dk
August 26-30, 2019

Closing Remarks

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Reading Material

- Bhat, S., Zhao, J., Sheridan, J., Hourigan, K. & Thompson, M.C., Uncoupling the effects of aspect ratio, Reynolds number and Rossby number on a rotating insect-wing planform, Journal of Fluid Mechanics, 859, 921-948, 2019.
- Bhat, S., Zhao, J., Sheridan, J., Hourigan, K. & Thompson, M.C. 2019 *Journal of Fluid Mechanics, 868, 369-384.*
- Cummins C*. et al*. 2018 A separated vortex ring underlies the flight of the dandelion *Nature 562, 414-418*.
- Ellington C. P. *et al*. 1996 Leading-edge vortices in insect flight. *Nature 384, 626-630*
- Sane S. P. 2003 The aerodynamics of insect flight*. Journal of Experimental Biology 206, 4191-4208*
- Wilkin P. J. *et al.* 1993 Comparison of the Aerodynamic Forces on a Flying Sphingid Moth with Those Predicted by Quasi-steady Theory. *Physiological Zoology 66, 1015-1044*.
- Willmott A. P. *et al.* 1997 Flow visualisation and unsteady aerodynamics in the flight of the hawkmoth, Manduca sexta*. Phil. Trans. R. Soc. Lond. B, 352, 303-316*

Lecture Objectives

Learn:

An overview of what has been presented

An outline other directions for study of vorticity & vortices

Some case studies in biomimetic flight involving vortices and optimisation of wing design

Outline of Lecture

- **Overview of the Course**
  - **Vorticity Generation**
  - **Vortex Filaments and Instabilities**
  - **Swirling Flows**
  - **Vortex Dynamics**
  - **Bluff Body Flows**
  - **Flow-induced Vibrations**
  - **Wind Turbines**
- **Other Directions**
  - **Multidiscipline Approaches**
  - **Biomimetic**
  - **Optimisation methods**
  - **Computational Techniques**
  - **Experimental Methods**
  - **Artificial Intelligence – Deep Learning**

General course objectives

Vorticity is a measure of the spinning motion of a fluid. Understanding the sources, dynamics and structure of vorticity, in particular the interaction of vortices, is of key importance in fluid mechanics. It is the purpose of the course to give the students an overview of recent research in this field.

Learning objectives

A student who has met the objectives of the course will be able to:

- understand the mathematical definition and the physical meaning of vorticity
- understand how vorticity is generated and be able to analyze the vorticity flux near boundaries and interfaces
- understand the dynamics of vortex filaments, be able to perform a simple stability analysis
- understand the concept of vortex breakdown and indentify it in various engineering situations
- understand the generation of vortices in the wake of bluff bodies and be able to identify different types of vortex wakes
- perform a basic analysis of the topology of two-dimensional flow, based on dynamical systems theory and experimental or computational data
- understand how vortices interact with solid bodies, how vibrations are induced and how to model this interaction mathematically
- understand the generation of vortices behind wind turbines, and how this is modelled

Aims of the Course

Participants will:

- **Gain an introduction to various (but not all!) aspects of vorticity and vortices**
- **Learn of recent research in vortex dynamics, bluff body flows, flow induced vibrations, wind turbines, vortex breakdown**
- **Practise some techniques of coding (Python/Anaconda), flow analysis (PIV, Stability) and hands-on simple construction and experiments in anemometry, flow-induced vibration, and turbines.**

LEADING-EDGE VORTICES IN INSECT FLIGHT

Charles P. Ellington, Coen van den Berg, Alexander P. Willmott & Adrian L. R. Thomas

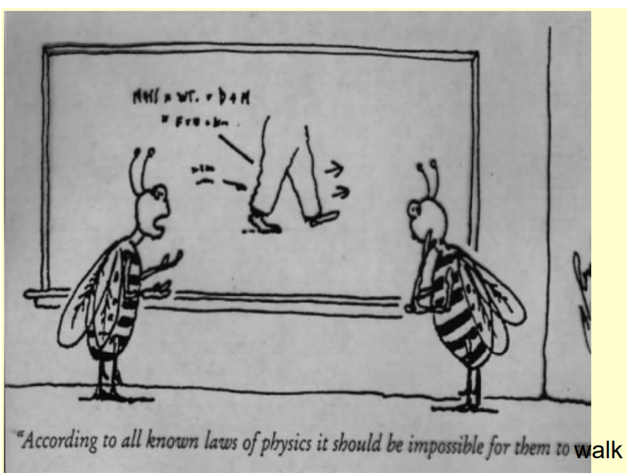
Nature 384, 626–630 (1996)

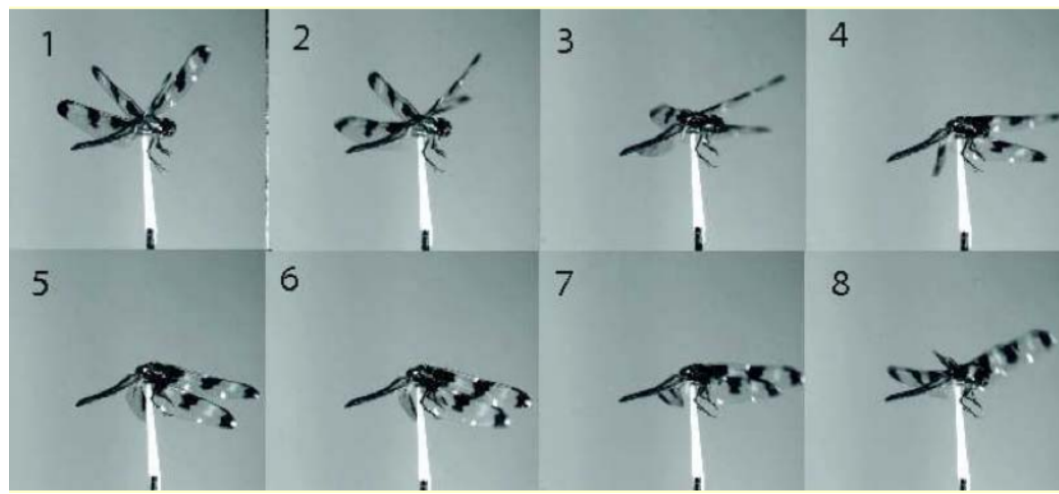
Introduction and Background

- **"Insects cannot fly"**
  - Flapping Flight vs. Steady Motion
  - Lift Force Disagrees with Conventional Aerodynamic Theory
    - Consider Translation and Rotation with quasi-steady wing element theory
  - Where is the Extra Lift?

$$\text{Lift Force} = 0.5 \times \rho \times \sum_{r=0}^{r=R} \times U_{\mathrm{w}}^{2}(r) \times S(r) \times C_{\mathrm{L}}(r),$$

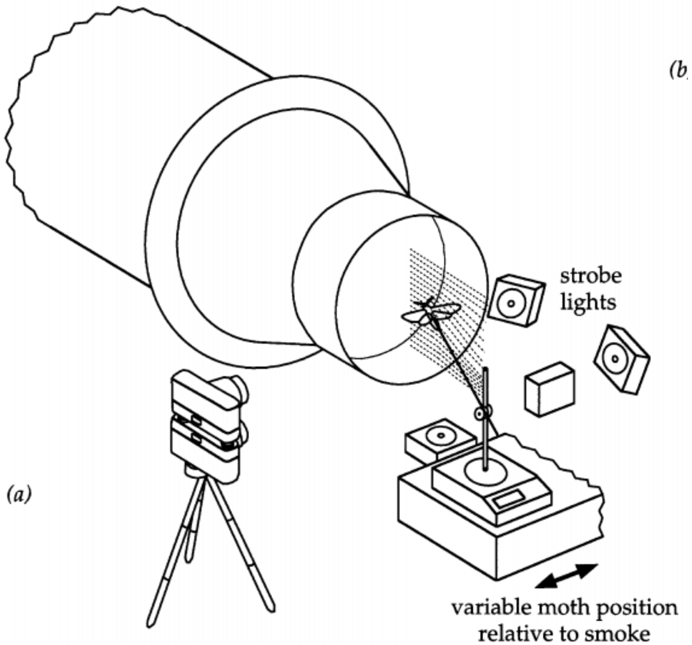
$$\text{Drag Force} = 0.5 \times \rho \times \sum_{r=0}^{r=R} \times U_{\mathrm{w}}^{2}(r) \times S(r) \times C_{\mathrm{D}}(r),$$


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

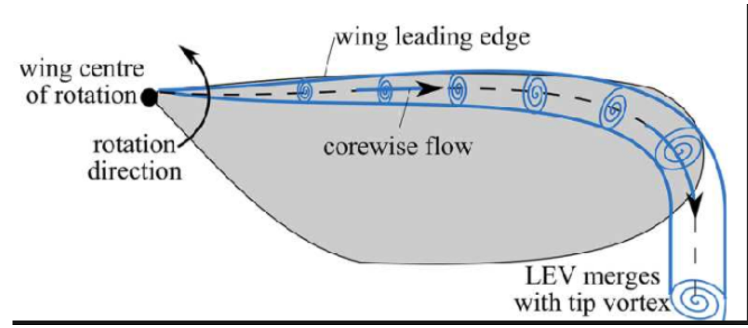


Experimental Treatment

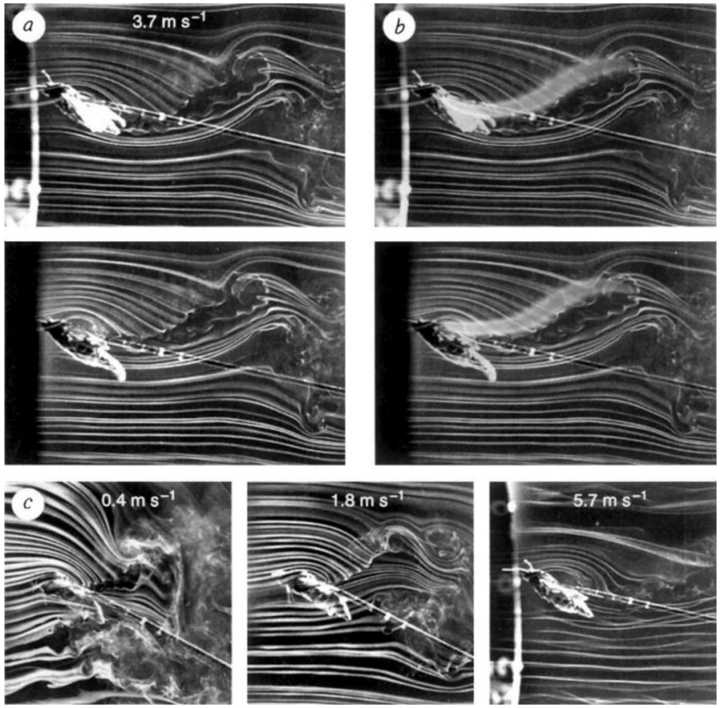
- **Visualisation of airflow**
  - Hawkmoth Wings
  - “Hovering” Mechanical Model
- **Visualisation Techniques**
  - Planar/Sheet Illumination?
    - Flow normal to planes difficult to detect
  - Stereophotography of smoke around wings
    - Two Offset Cameras to capture 3-D effects



Results



- **Intense leading-edge vortex on downstroke**
  - Explains High-Lift Forces
  - Flow separates at leading edge and re-attaches to upper surface
    - Breaks away and rolls up into a tip-vortex at wing ends

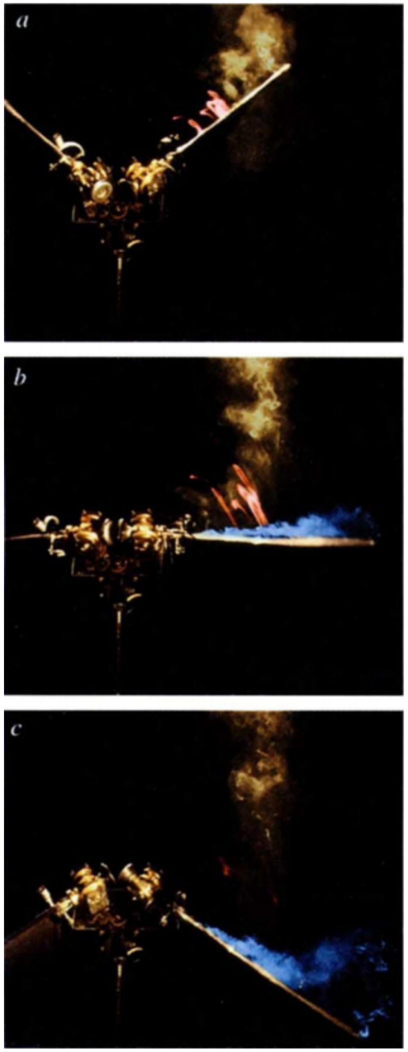


- **What is the mechanism responsible for creation?**
  - Mechanisms typically translation or rotation (AoA change)

- **Dynamic/Delayed Stall**
  - Translational phase high AoA with large LEV before stall
  - LEV created during the downstroke?
- **Rotational Mechanisms**
  - LEV created as wing flips over for subsequent half stroke?

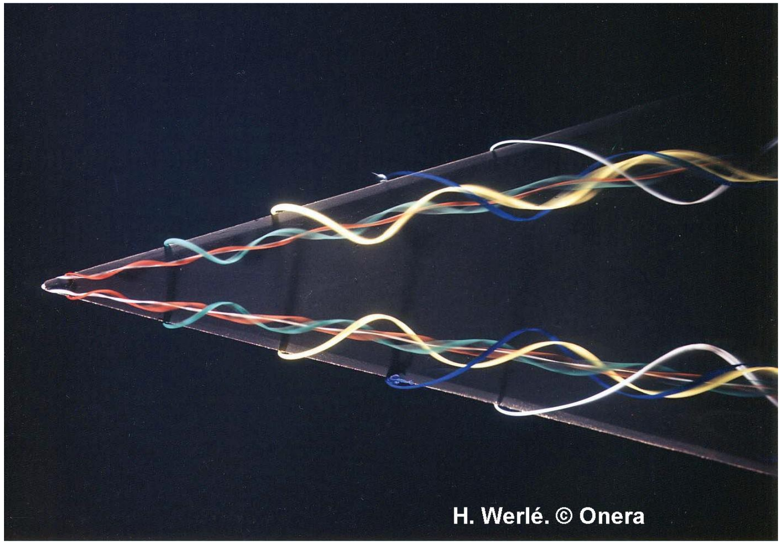
Results

- **3-D Large scale mechanical model**
- **Release of smoke from LE of wing directly into LEV**
- **Clear identification of dynamic stall as high-lift mechanism**
- **Downstroke**
  - (a) LEV formed after pronation
  - (b) Vortex left behind and not captured by the wing
  - (b) New LEV formed (blue) due to translational motion
  - (b) Grows Larger towards wingtip
  - (c) Conical Spiral breaks down, separates and merges with tip-vortex
- **Circulation Increases during downstroke**
  - Consistent with dynamic stall & not rotation
- **Mean lift force 1.5x weight of Manduca!**



Results

- **Similarities to high-lift devices / delta wings**
  - Spanwise flow component necessary for stability
  - Axial flow induced by active control or parallel flow component
- **Mechanism for generation of vortices different but physics the same**
  - Pressure gradient along insect wing
  - Centrifugal acceleration in boundary layer
  - Induced velocity field of spiral vortex lines



A SEPARATED VORTEX RING UNDERLIES THE FLIGHT OF THE DANDELION

Cathal Cummins, Madeleine Seale, Alice Macente, Daniele Certini, Enrico Mastropaolo, Ignazio Maria Viola & Naomi Nakayama

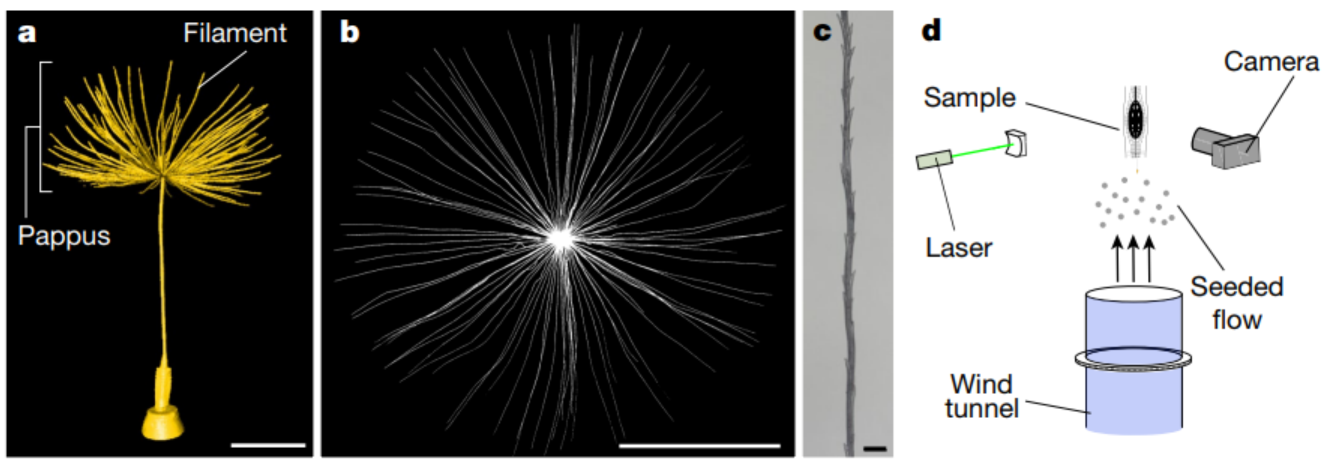
Nature **562**, 414–418 (2018)

Introduction and Background

- **Lifting and Spreading of Seeds (Common Dandelion)**
  - **How are the seeds kept aloft over such large (2m-150km) distances?**
    - **“Pappus” consists of ~100 filaments attached to central point**
    - **Parachute? Why not a wing-like membrane?**

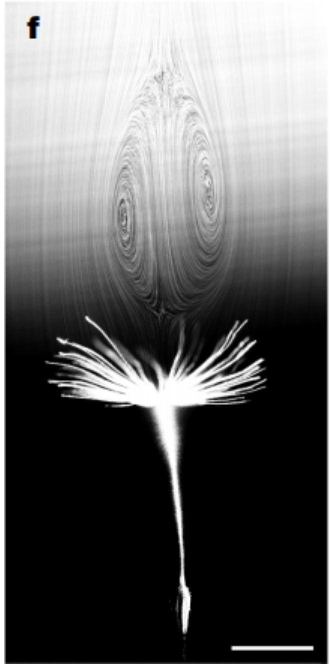
Experimental Treatment

- Vertical Wind Tunnel
  - Seed hovers at fixed height
  - Long Exposure photography
- Morphology
  - X-Ray computed microtomography
  - Light Microscopy
- Flow Visualisation
  - PIV
- Solid/Porous Disk



Results

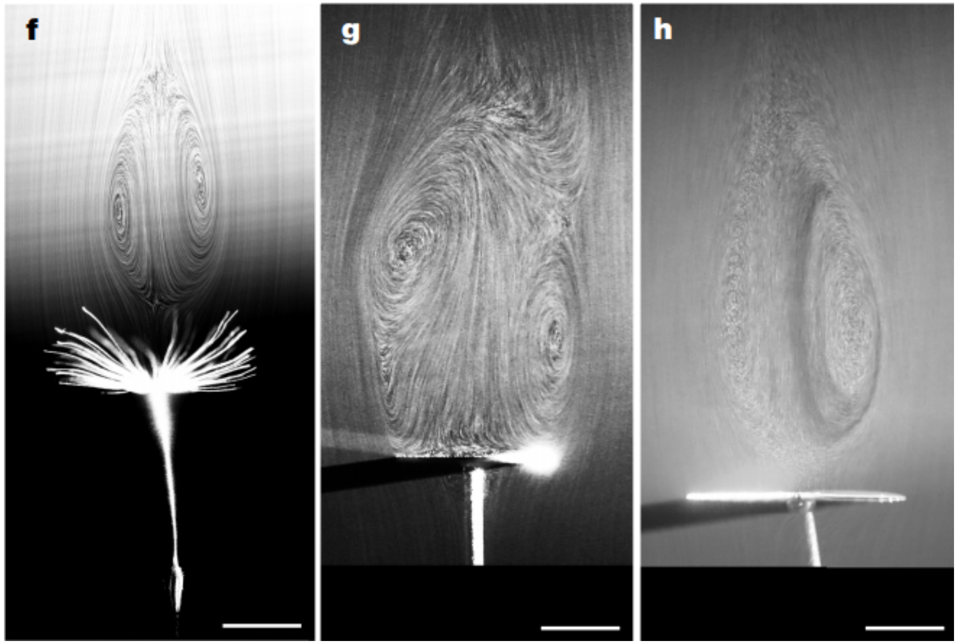
- Stable Separated Vortex Ring
  - Remains a fixed distance downstream
  - Bluff bodies generate vortex rings but are either attached or shed and advect downstream
  - Considered theoretically but too unstable to occur in nature
- Neighbouring filaments interact strongly because of thick boundary layers
  - Considerable reduction in airflow (decreasing permeability)
  - High drag coefficient
  - 4x amount of drag per unit area compared to a solid disk!



Results

- **Pappus acts as if it is a flat circular disk with equivalent porosity**

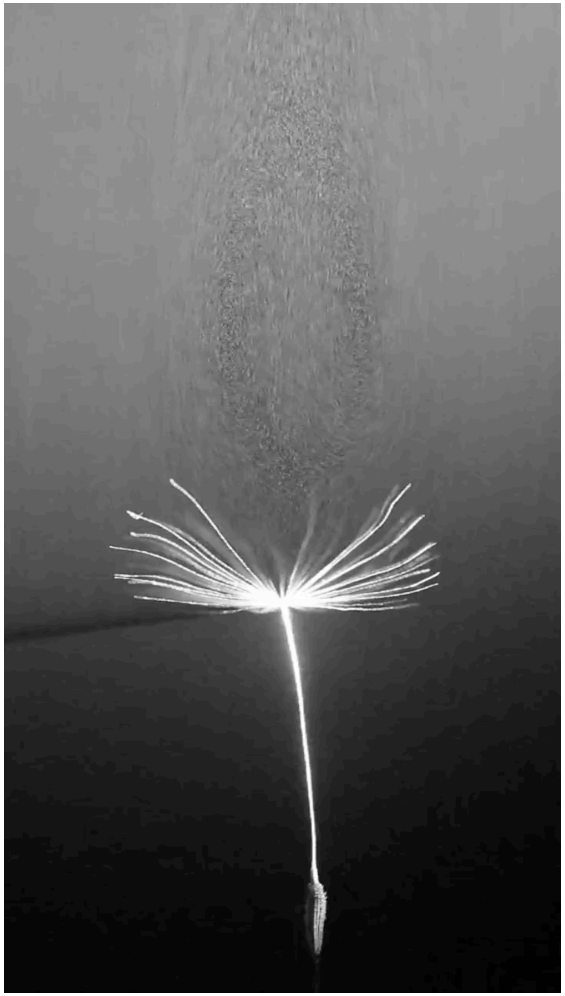
- **For a given porosity there is a critical Re at which Vortex Ring breaks down into shedding**
  - **All dandelion samples fly below Re_c**



Videos of Dandelion seeds

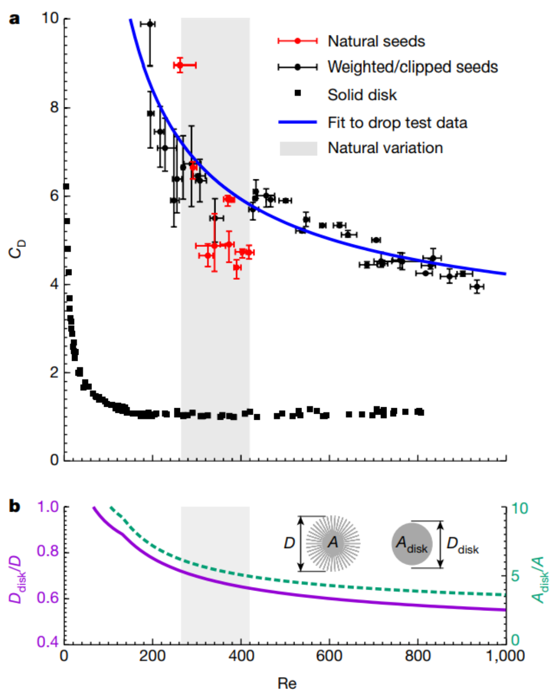
Freely floating

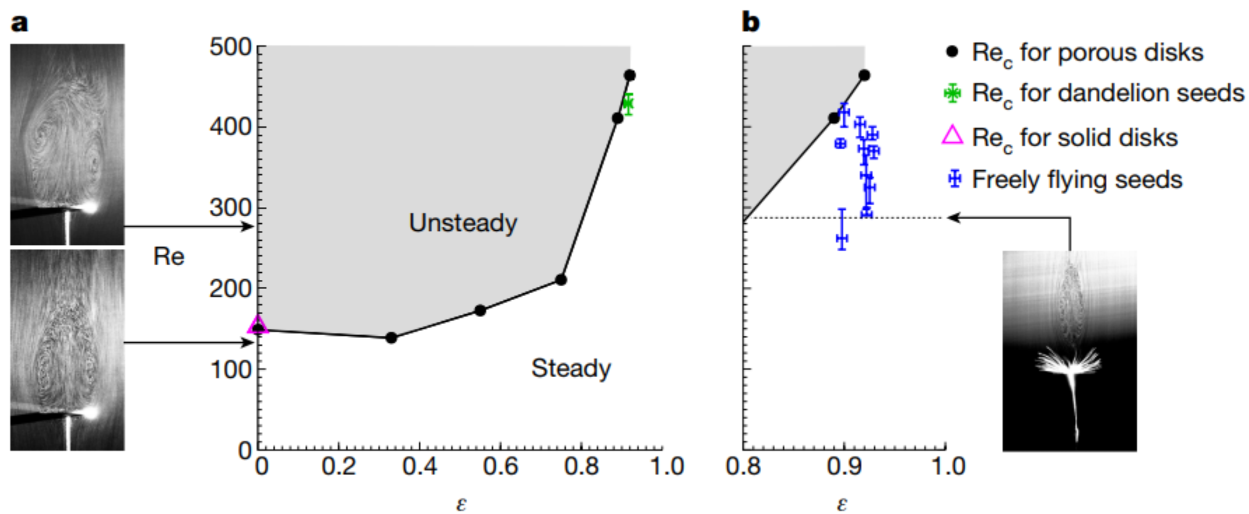
Fixed



Results

- **Tuning of pappus porosity to eliminate vortex shedding**
  - **Four-fold increase in the loading**
  - **Enhancement of the flight stability**

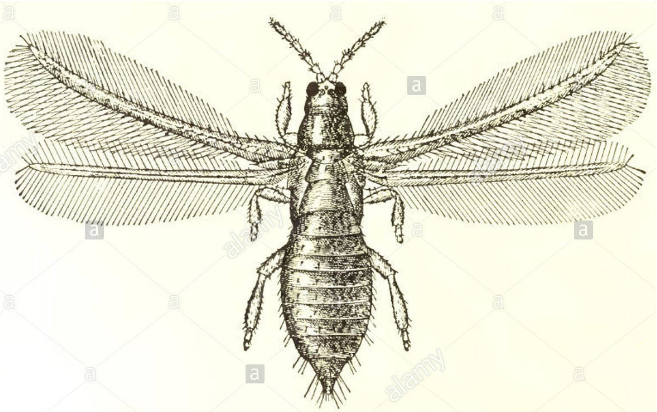




mean porosity **mean porosity**

Conclusions

- Pappus filament boundary layers interact to generate porous media
  - Dandelion seed eliminates oscillating wake resulting in unsteady motion by porosity
  - Stability gained by tuning the porosity
- Two major types of wind-dispersed seeds
  - Large Seeds – Winged
    - High Lift forces due to leading-edge vortex
    - Greater release heights necessary to reach stable lift-generating phase
  - Small seeds- Bristles
    - Completely different type of vortex which reaches stability much faster
- Also observed in animals
  - Small insects have evolved bristly wings!



Adult Pear Thrips (*Tæniothrips inconsequens* Uzel), greatly enlarged. (*From U. S. D. A. Bull.* 173.)

Evolutionary shape optimisation enhances the lift coefficient of rotating wing geometries

Bhat, S., Zhao, J., Sheridan, J., Hourigan, K. & Thompson, M.C.,
Journal of Fluid Mechanics, 868, 369-384, 2019.

Wing shape is an important factor in aerodynamics performance of wings

Design of monocopters and flapping-wing micro air vehicles

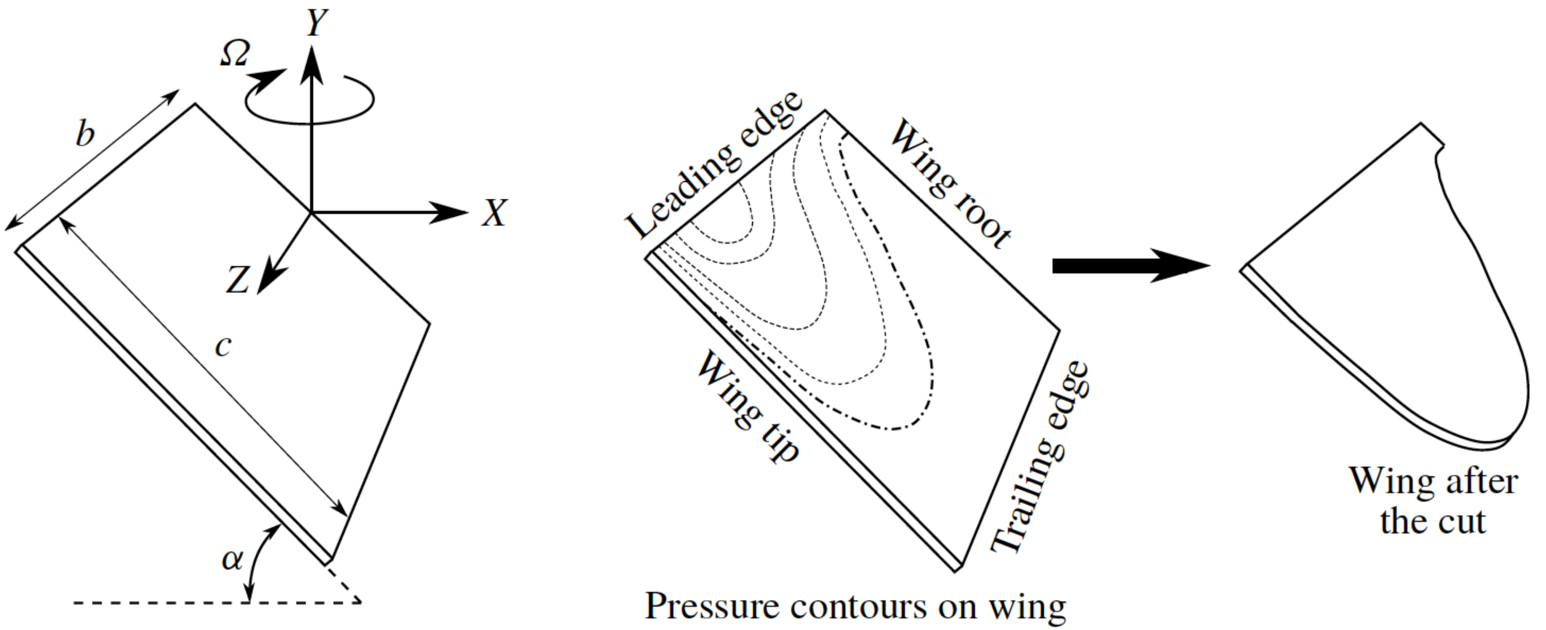
Simulation of falling samara (maple seed):

www.youtube.com/watch?v=Rm_KoTBtVz4

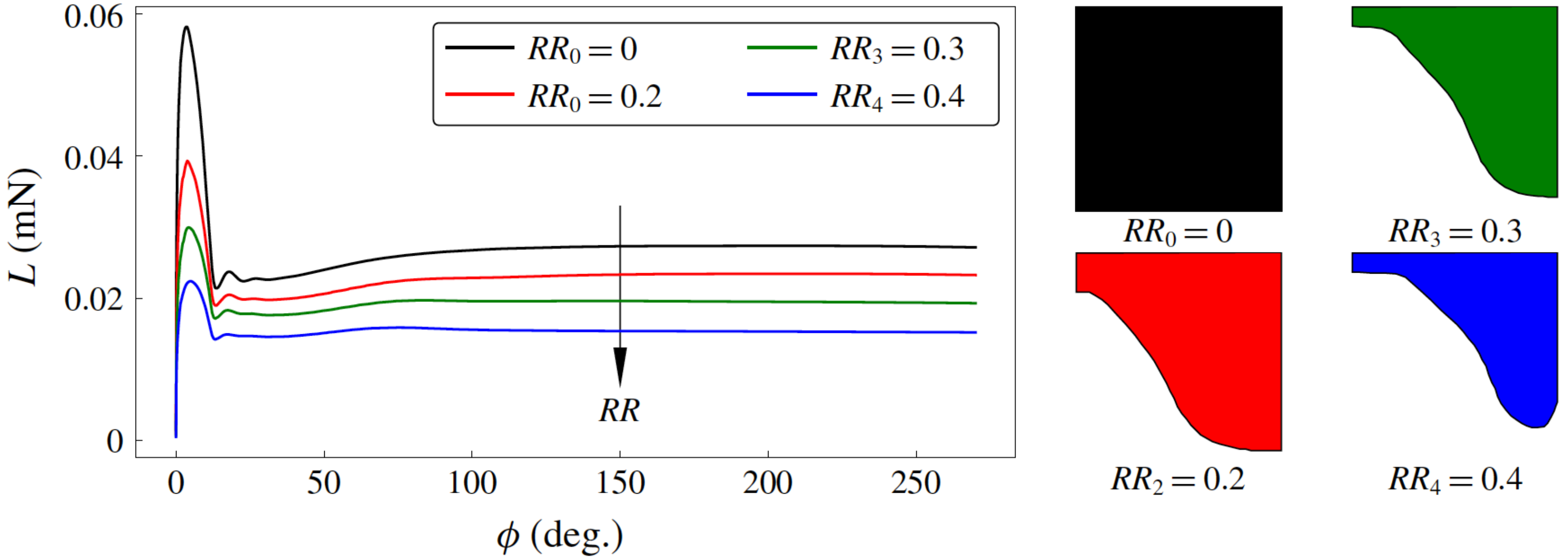
Video of Lockheed Martin “Samarai” monocopter UAV at:

www.youtube.com/watch?v=UY38uho9ZdE

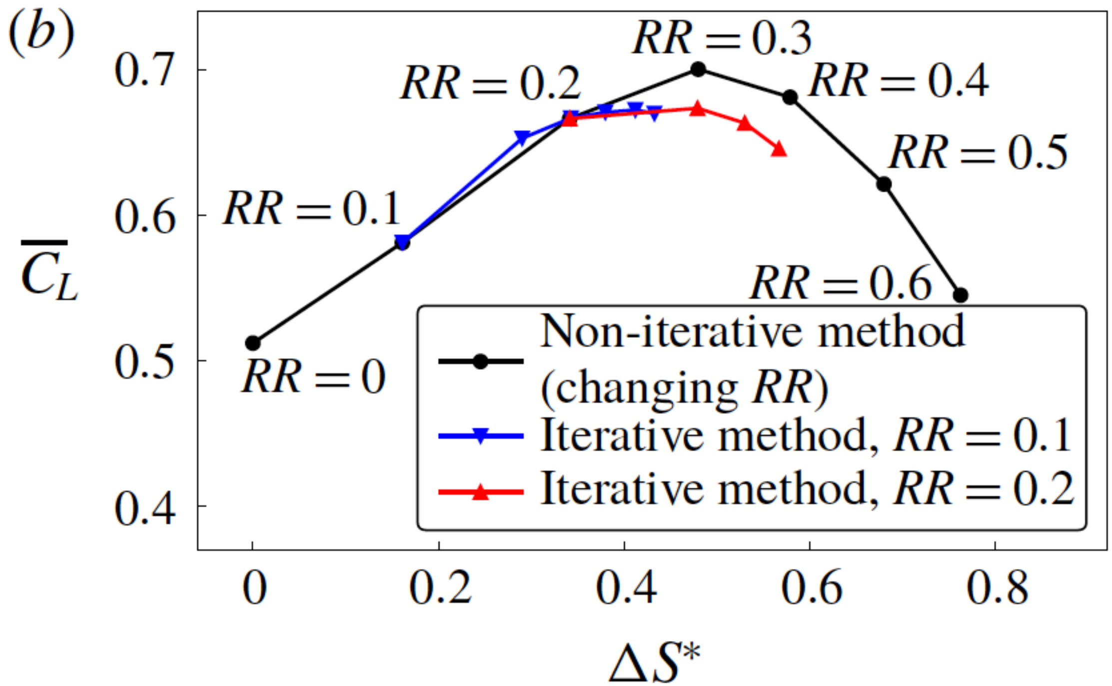
Start with rectangular wing and remove x% (e.g. 10%, 20%) with least lift



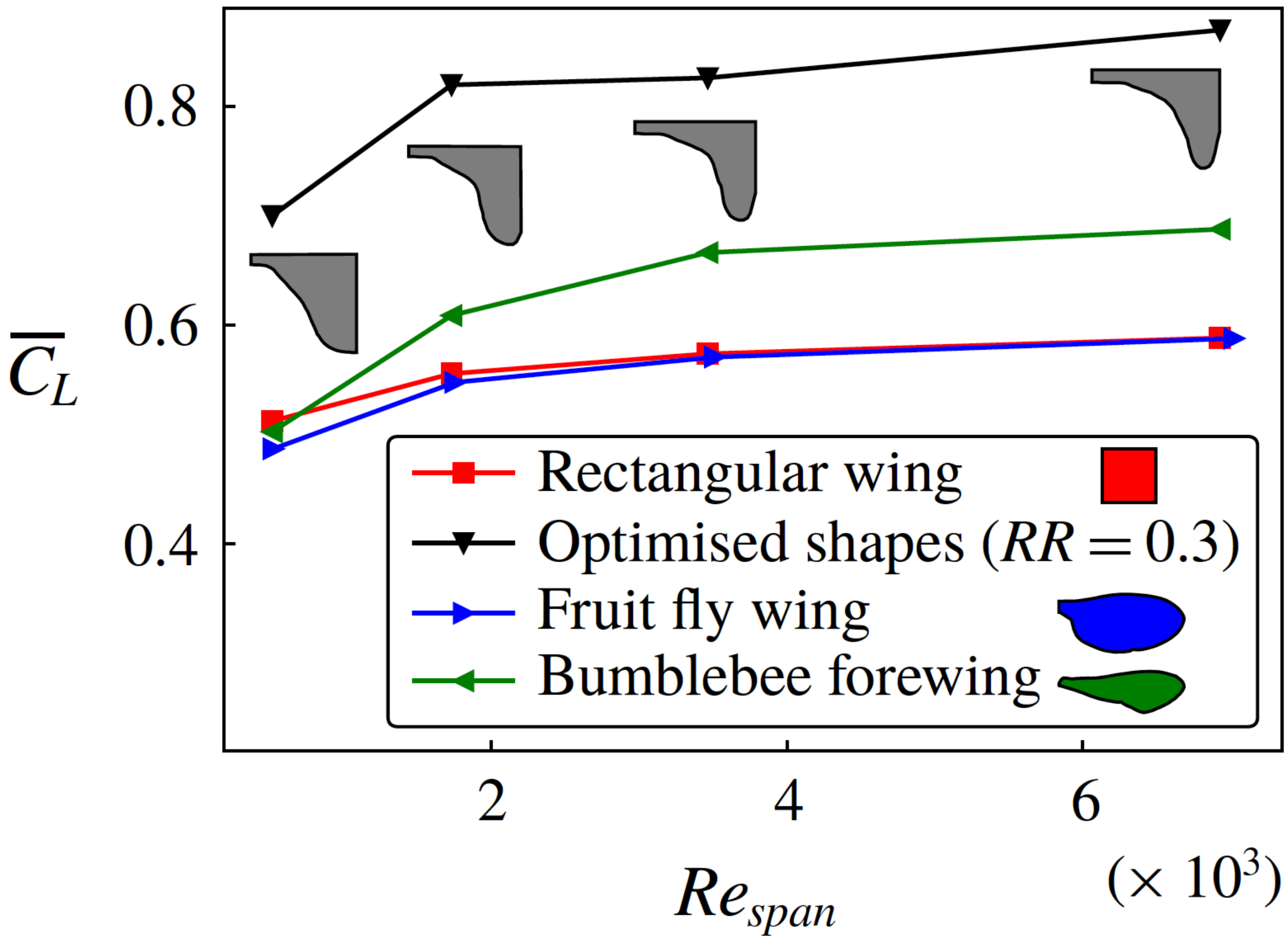
Plot total lift for each iteration of cuts



Lift coefficient increases until optimal value, then decreases with more wing removal



Optimised shape changes with Reynolds number



Conclusions

- Wing shape is an important parameter affecting the flight performance of MAVs
- An <u>evolutionary approach</u> ``optimised" the shapes of rotating wings as Reynolds number was varied, using 3D CFD
- Mean lift coefficient of the wing (C_L) significantly improved in successive evolution steps
  - The artificial increase in C_L was partially due to the increased radius of the second moment of inertia
  - However, it was found to be limited by the increasing AR, which limited the growth of the LEV, such that the maximum C_L was obtained for RR of 0.3
- The optimised shapes showed a reasonable variation with Reynolds number
- Autorotating samaras do not require an internal power
  - The force driving their motion is provided by gravity
  - However, they require some additional features, such as a spanwise twist in the wing, to be able to autorotate