재독한국과학기술자협회
Verein Koreanischer Naturwissenschaftler und Ingenieure in Deutschland
Korean Scientists and Engineers Association in Germany

저속 분리유동 풍동실험 연구
(Wind-tunnel tests for low-speed separated flows)

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Chair of aerodynamics and fluid mechanics
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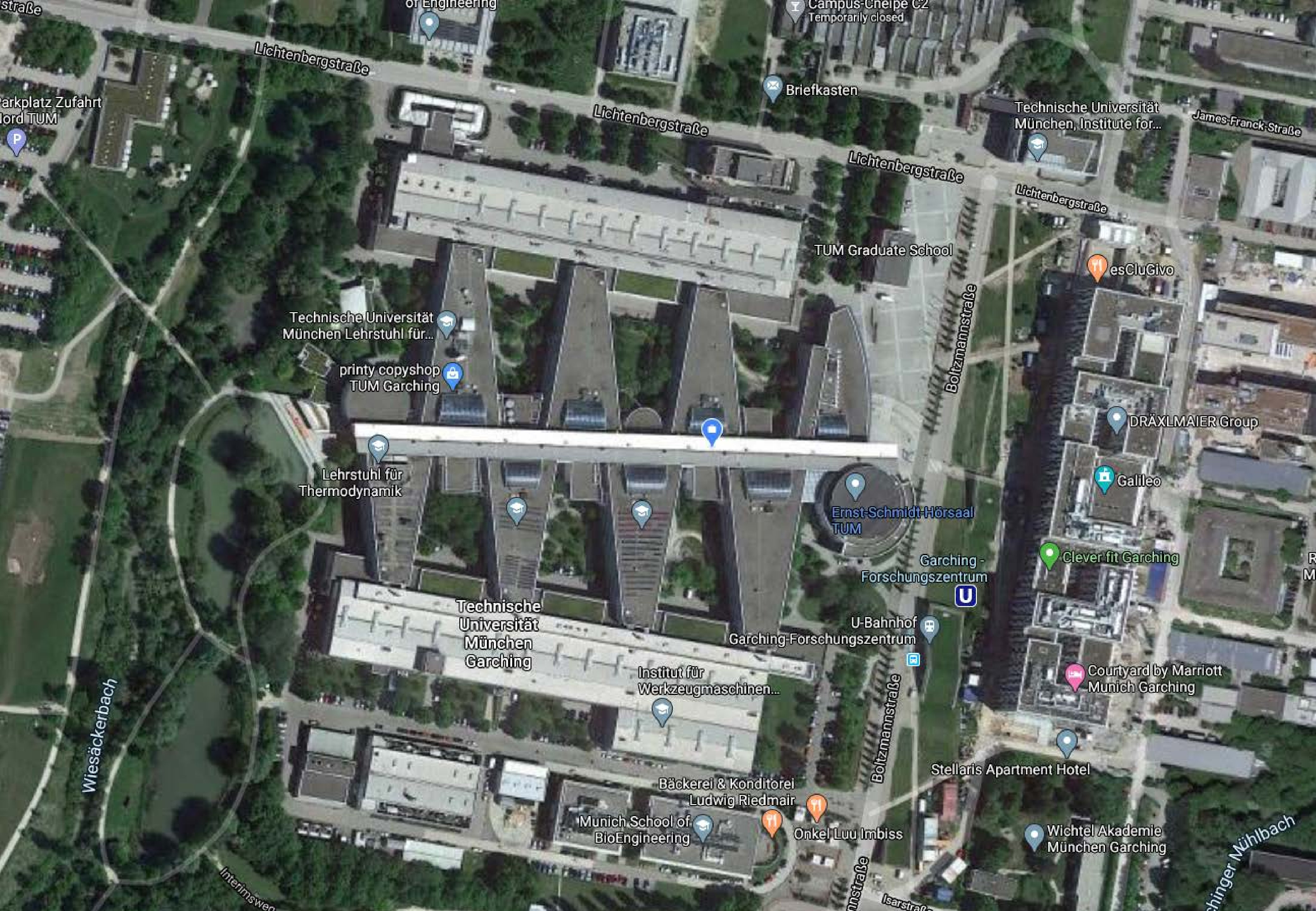
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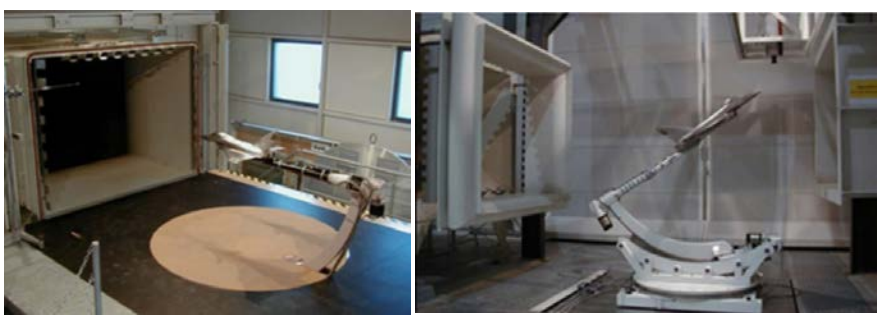
Chair of Aerodynamics and Fluid Mechanics

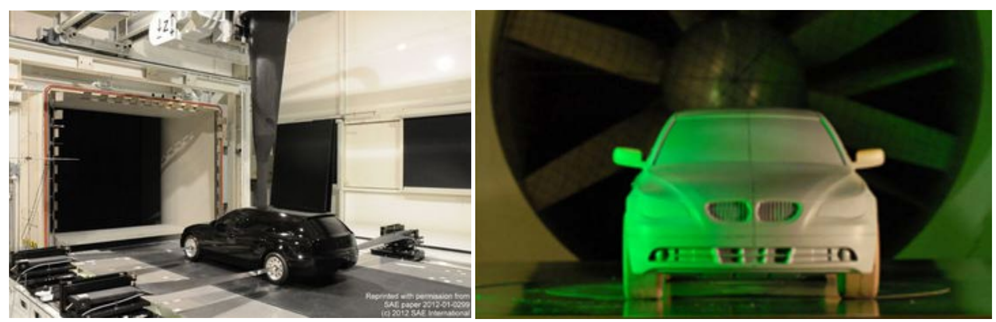
Wind tunnel facilities

Multi-purpose Wind tunnel A (2.4m × 1.8m)

Model wind tunnel B (1.6m × 1.2m)



Fighter jet (Eurofighter typhoon)

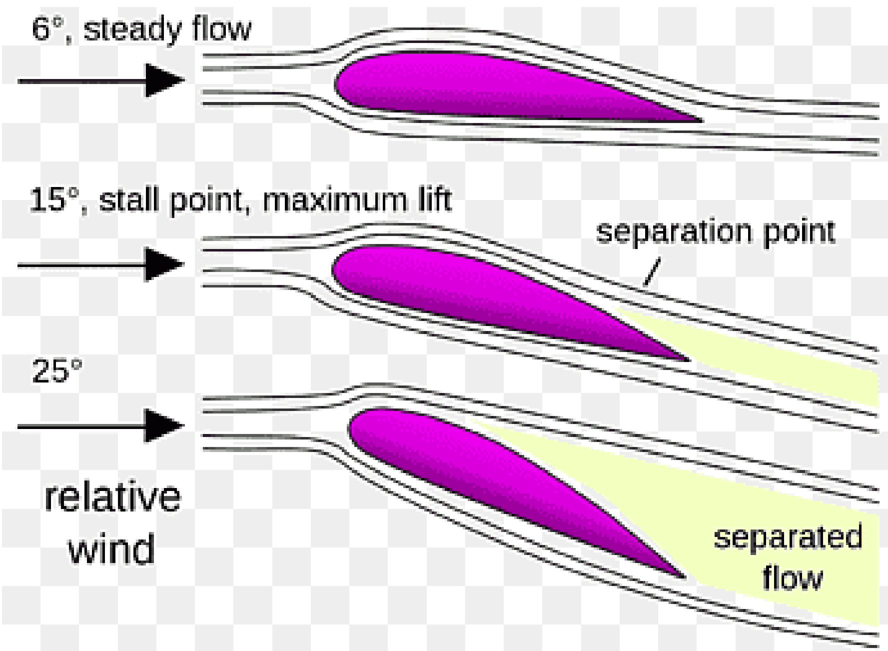


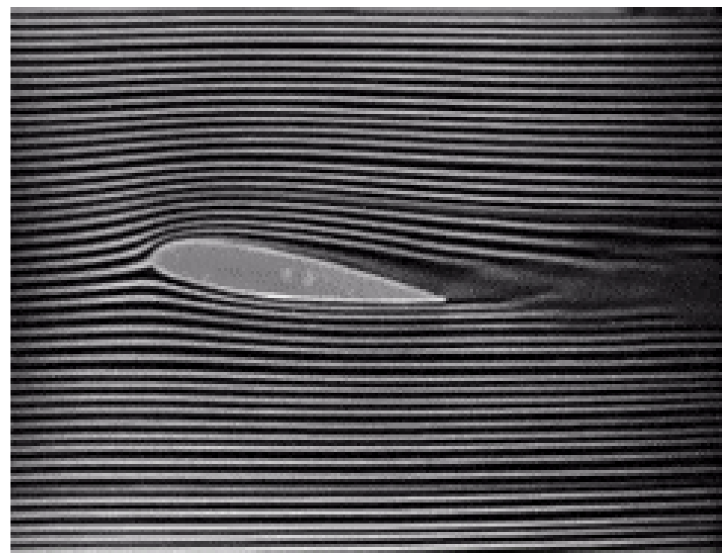
Commercial ground vehicle (left: Golf, right BMW)

Introduction

Conventional aerodynamic design

- Previous design philosophy: faster, higher, further
  → lower drag is the top priority
  → "streamlined exterior operating under the pre-stall region"



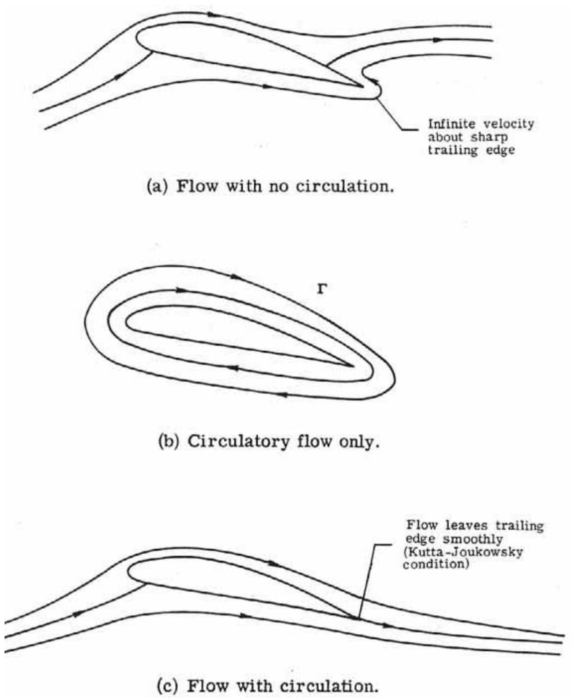


Introduction

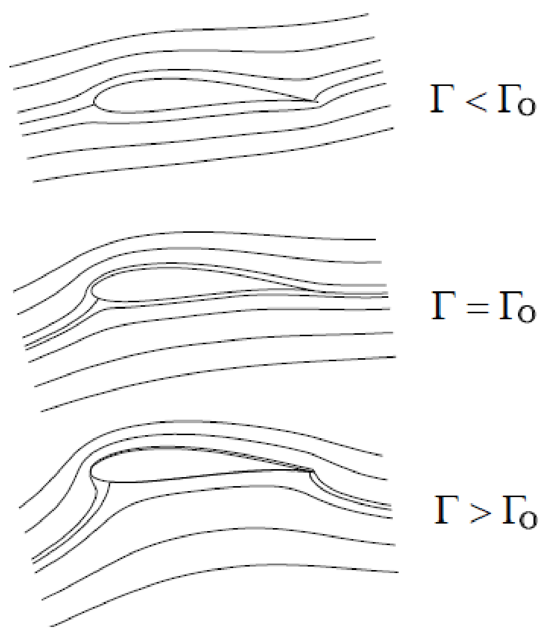
Conventional aerodynamic design

- Pre-stall + negligible BL effect → equation of continuity from "conservation of mass"

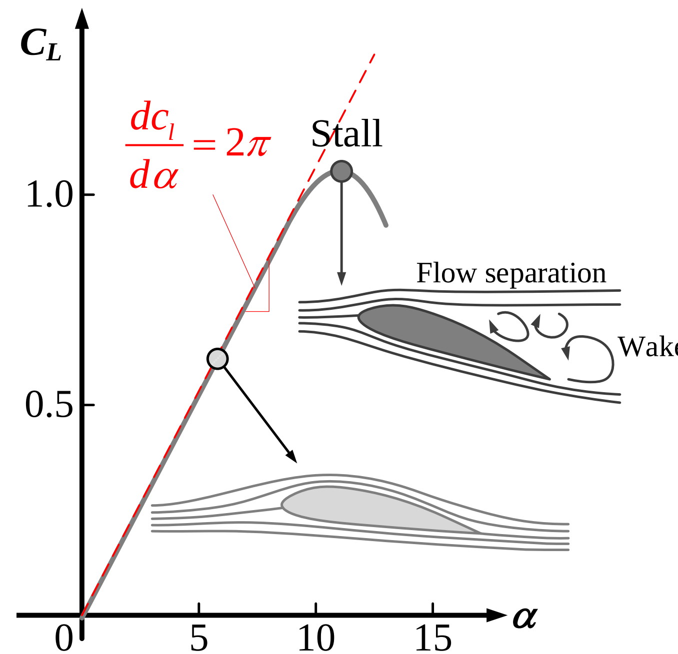
$$\dot{m}=0 \longrightarrow \frac{D\rho}{Dt}+\rho\nabla\cdot\mathbf{V}=0 \longrightarrow \nabla\cdot\mathbf{V}=0 \longrightarrow \nabla^2\phi=0$$



Potential flow with circulation



How to decide the amount of circulation (Kutta condition)

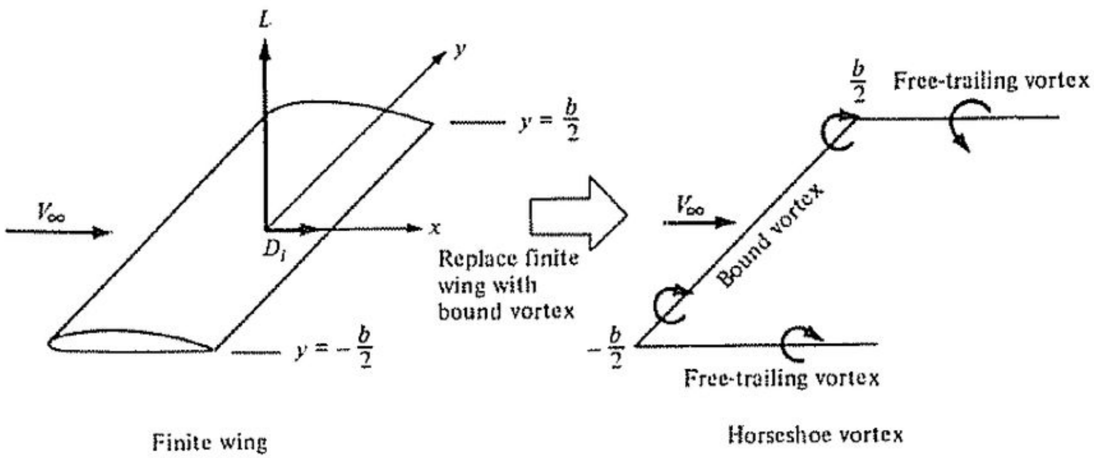


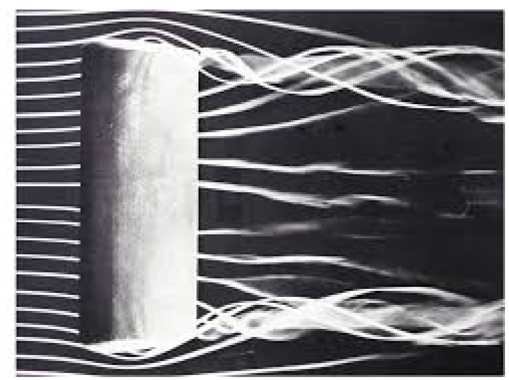
Theory vs. experiments

Introduction

Conventional aerodynamic design

- Attached flow assumption → Prandtl's lifting-line theory





- Replace finite wing (span = b) with bound vortex filament extending from y = -b/2 to y = b/2 and origin located at center of bound vortex (center of wing)

- Helmholtz's vorticity theorem: A vortex filament cannot end in a fluid
  - Filament continues as two free vorticies trailing from wing tips to infinity
  - This is called a '**Horseshoe Vortex**'

Introduction
Conventional aerodynamic design

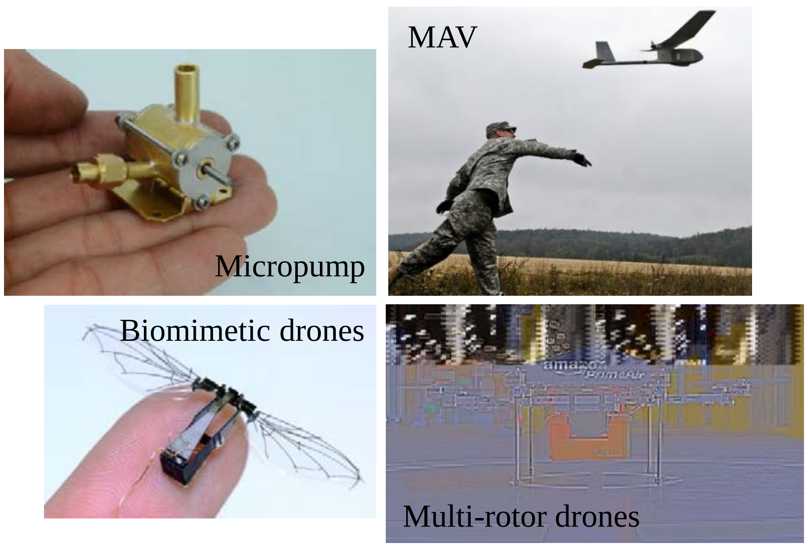
D-ALEM - Lufthansa Lockheed L-1049G Super Constellation (produced 1950-1958; taken at Munich Airport)

Introduction

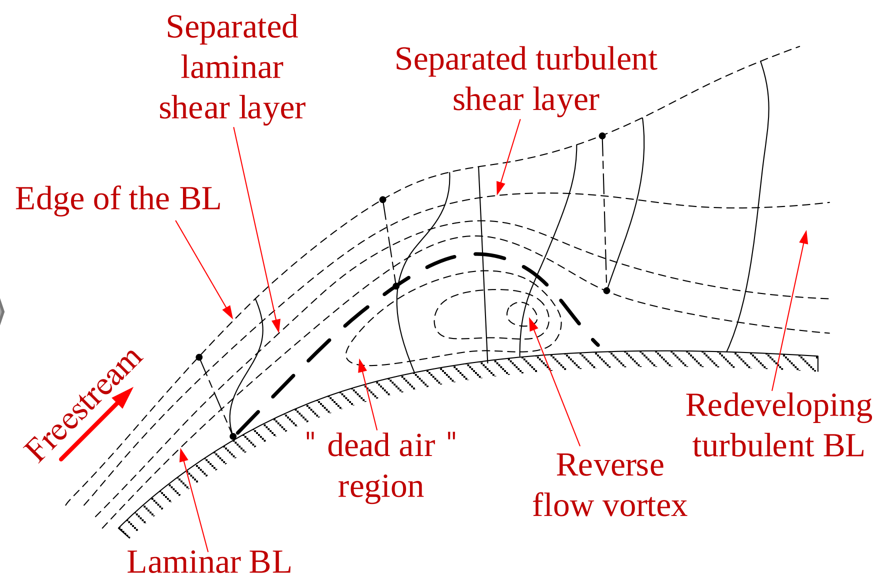
Recent aerodynamic devices

Become smaller for lower production cost & higher overall efficiency

→ lower Re → performance drops due to the flow separation



Various future aerodynamic devices
operating at low Reynolds number



Boundary layer at low Reynolds number
(Horton, University of London, 1968)

Introduction

State-of-the-art aerial vehicles

- State-of-the-art aerial vehicles do NOT obey the conventional design languages.
- 3-dim separated flows with strong vortex-wake interaction are everywhere.

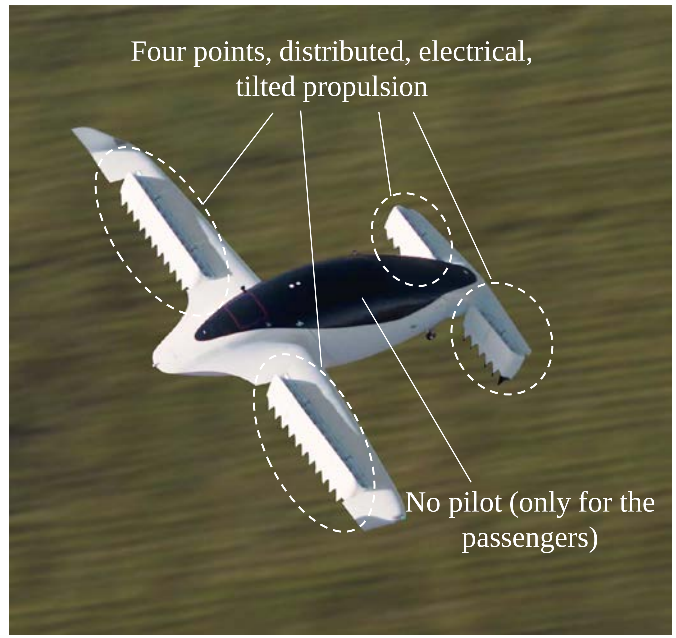
Urban Air Mobility (by Hyundai)

Concept flying car

Air taxi by Boeing

Multi-rotor vehicle

Hover bike

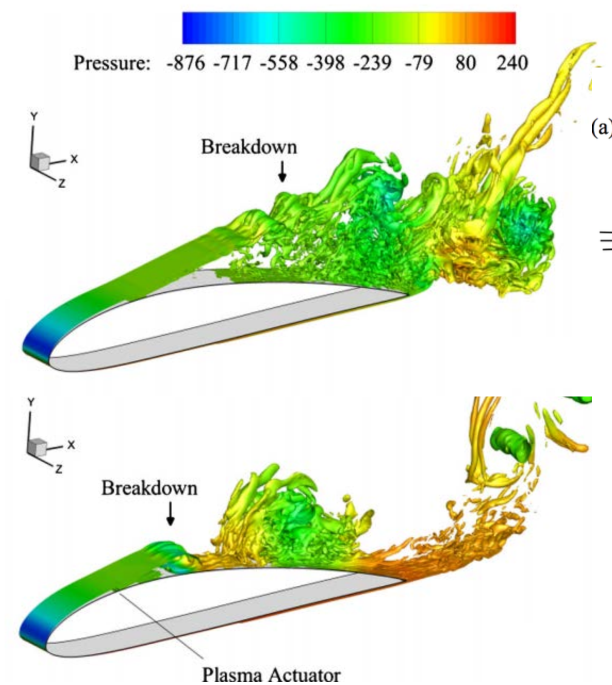


Air taxi concept (by Lilium)

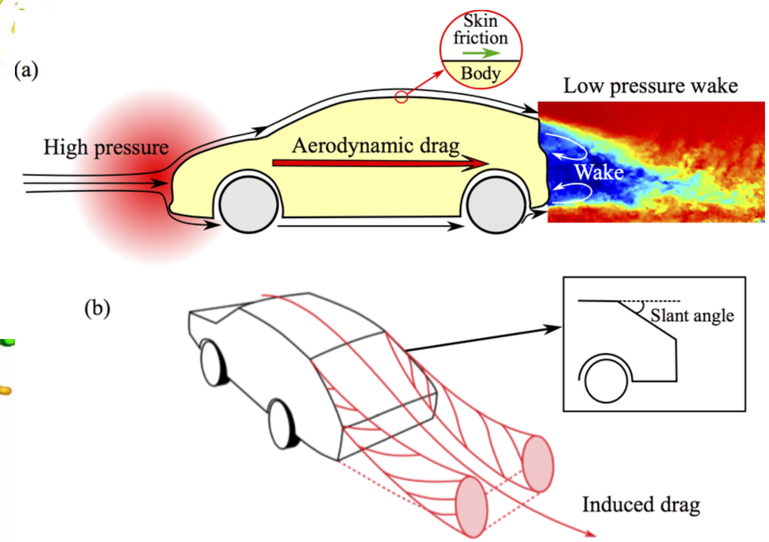
Introduction

Previous flow control strategy for the separated flow

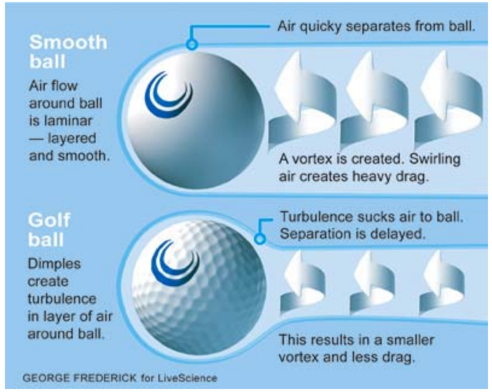
- We have suppressed flow separations with higher kinetic energy.
- This would not be operative for the flow around the recent devices.



DNS study for DBD plasma
(Ebrahimi, AST, 2018)



Pulsed jet study using linear genetic program for a ground vehicles (Li, 2017)



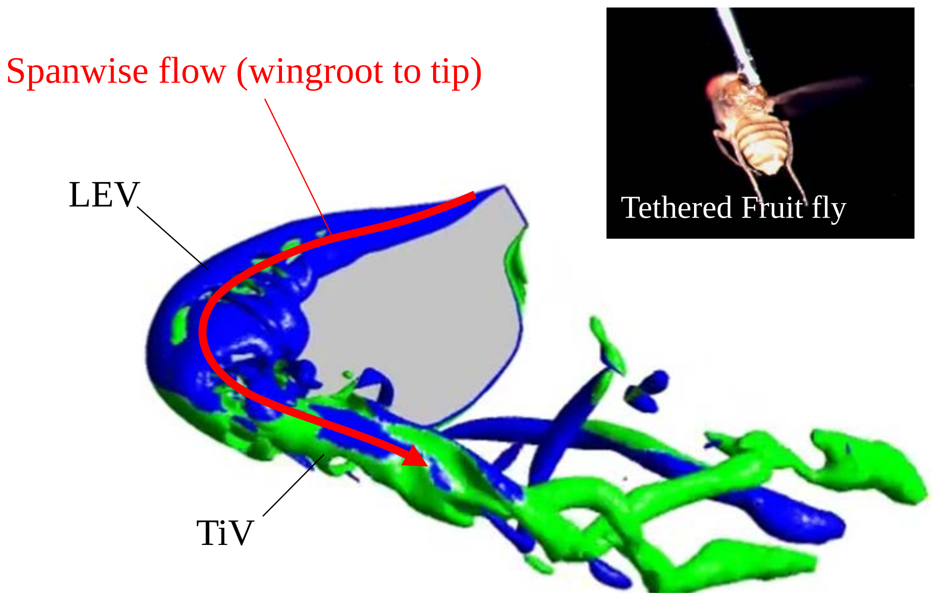
Why Do Golf Balls Have Dimples?
(Bryner, 2013, Live Science)

Introduction

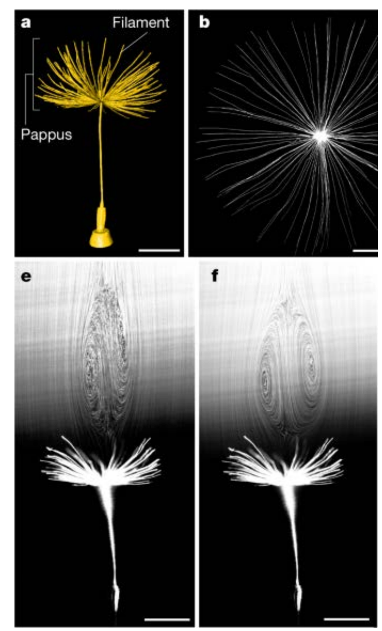
Understanding the separated flow

- Bodies in nature cope with the low-Re separated flow with stable vortices.
- Need to understand 3-d detailed vortex-wake characteristics.

Anguilliform swimming
(Lucas 2020 PNAS)



Vortices on a flapping wing
(Harbig et al. 2013 J Fluid Mech)

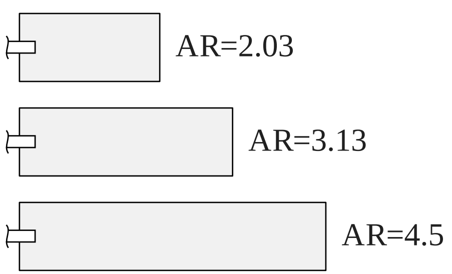


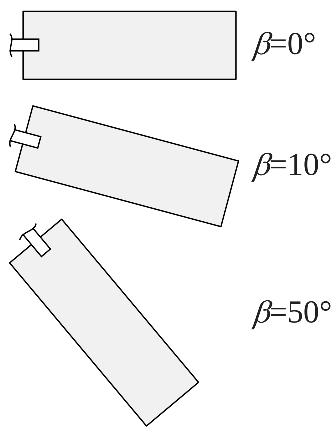
Vortex ring on the dandelion
(Cathal et al. 2018 Nature)

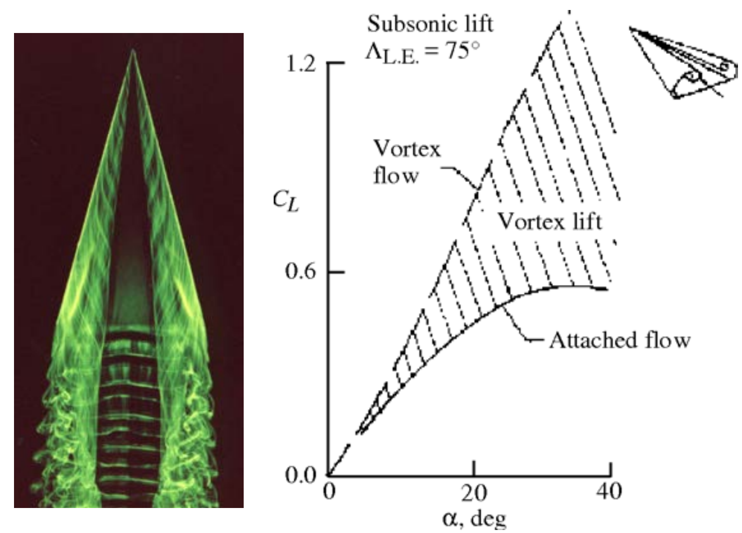
Introduction

Understanding the separated flow

- Research objective
  - Understanding LEV behaviors on low-aspect-ratio plates at low Re.
- Methodology
  - Giving sweptback angle as a way of control the spanwise flow,
  - to see the aerodynamic force and the flow structures .







Additional lift from a vortex (Polhamus 1966 J Aircraft)


Experimental setup
Wind-tunnel B in TUM-AER
Traverse system (3-axis)
Testroom
Test section

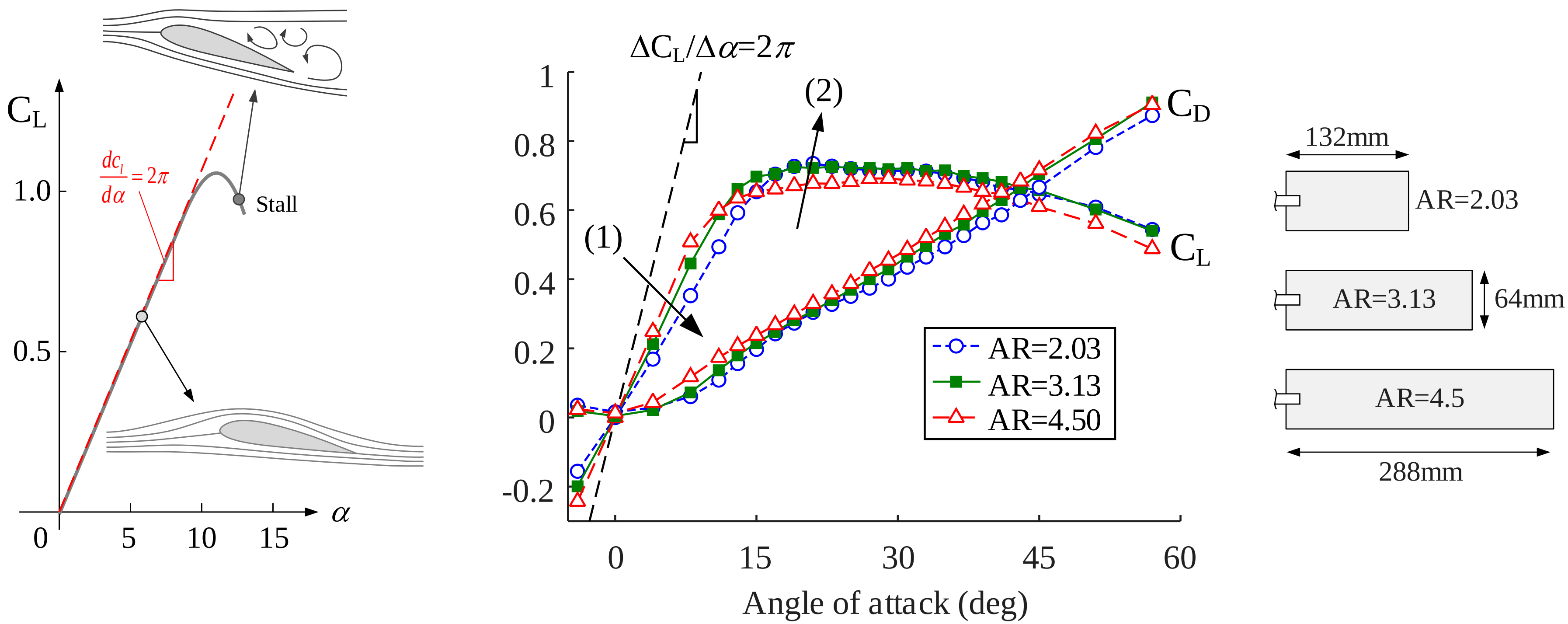
Experimental setup

Installation in the wind-tunnel B

Results

Effect of the aspect ratio

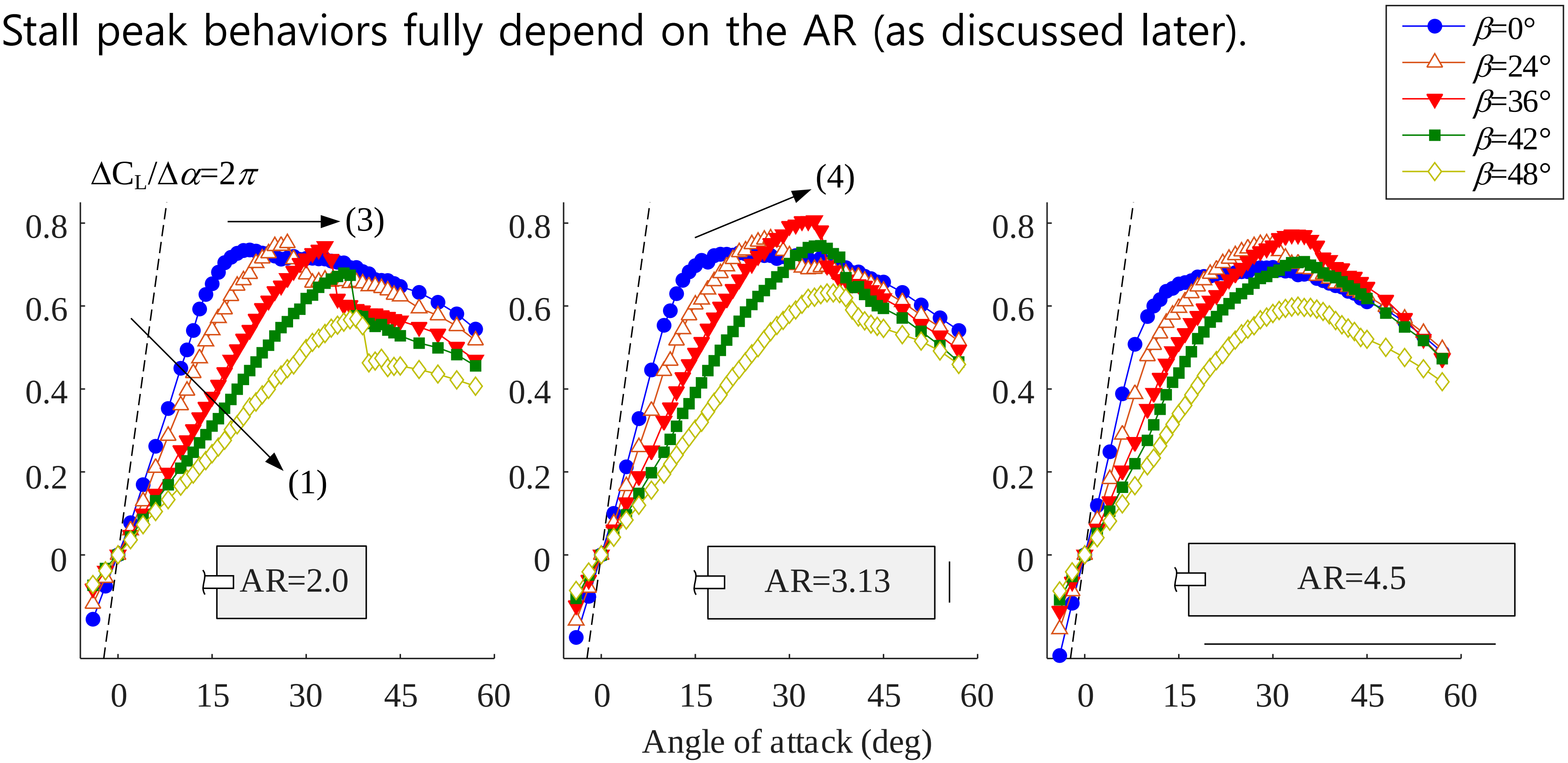
- No stall peak due to the low Re.
- Decrease in the AR results in (1) less CL/a slope, (2) higher CL,max.



Results

Effect of the sweptback angle

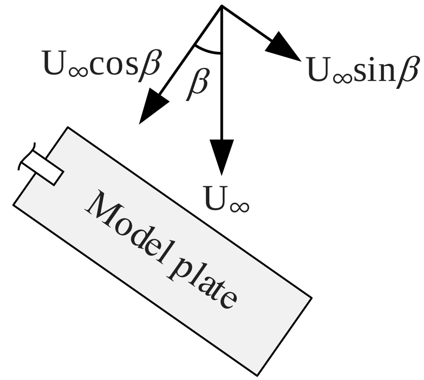
- Increasing sweptback angle delay the stall.
- Stall peak behaviors fully depend on the AR (as discussed later).

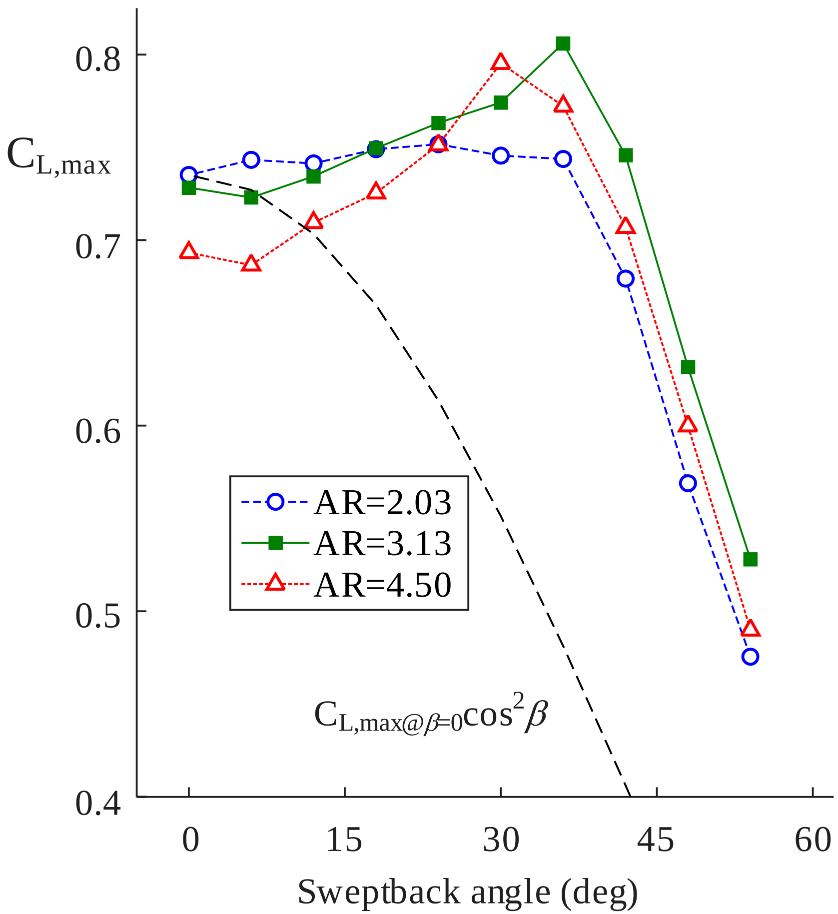


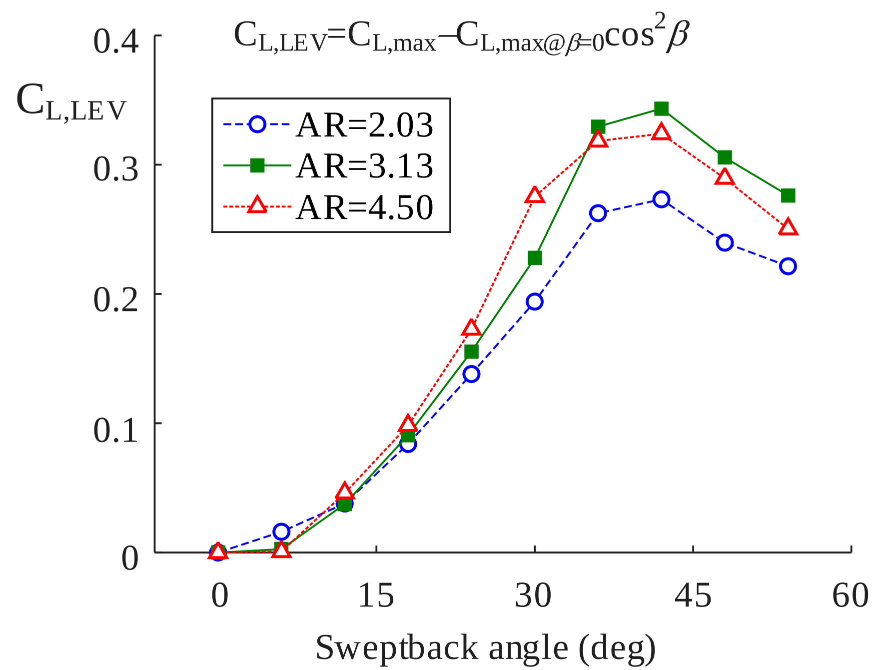
Results

Effect of the LEV

- Contribution of the LEV on the lift production.

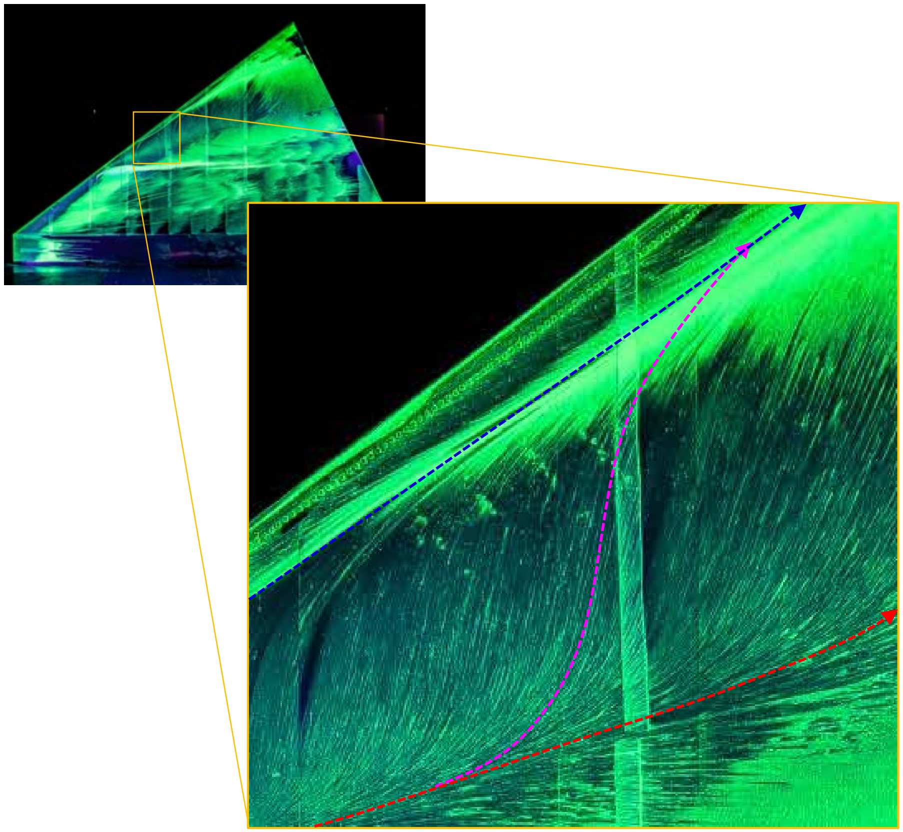


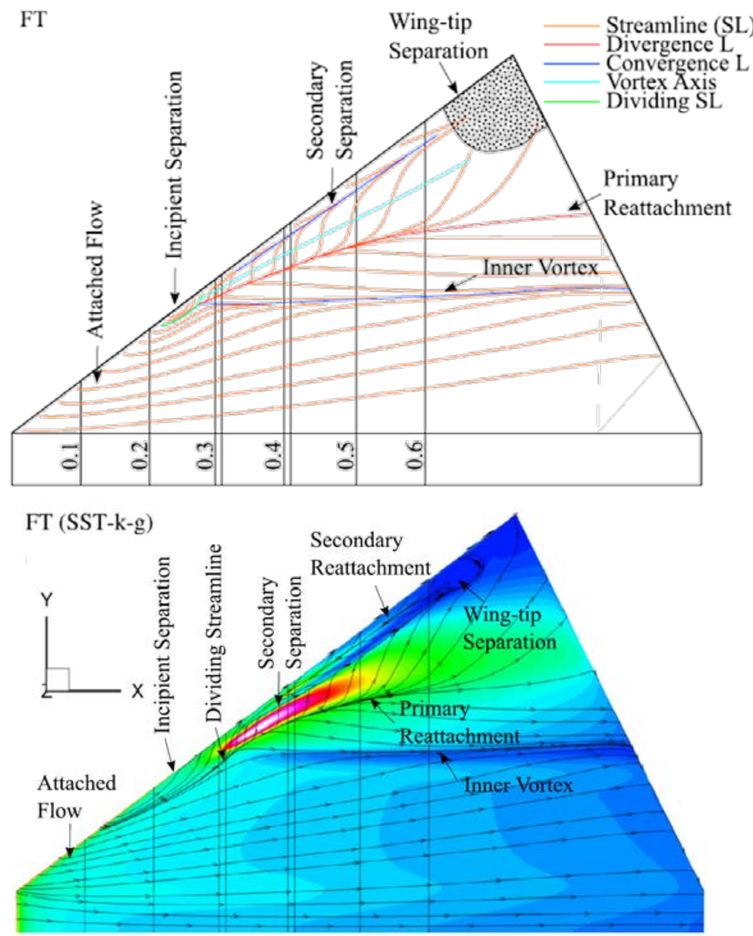




Surface oil-flow visualization

- Best approach to see the boundary layer separation.





Surface oil-flow visualization

Leading-edge vortex characteristics of sweptback plates at Re ~ 2.6×10^4

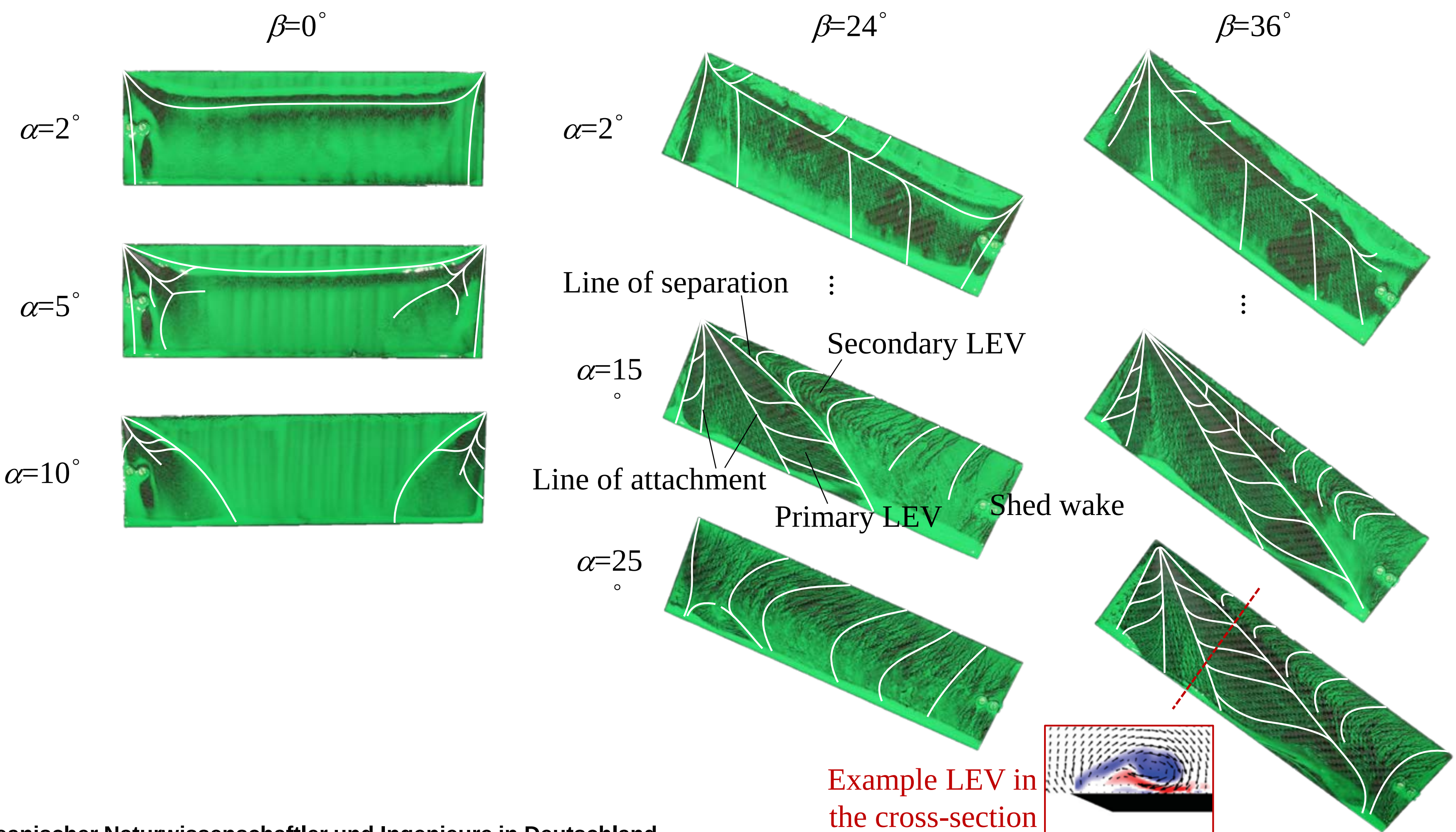
Jong-Seob Han* and Christian Breitsamter

9 Mar. 2020

Lehrstuhl für Aerodynamik und Strömungsmechanik
Technische Universität München

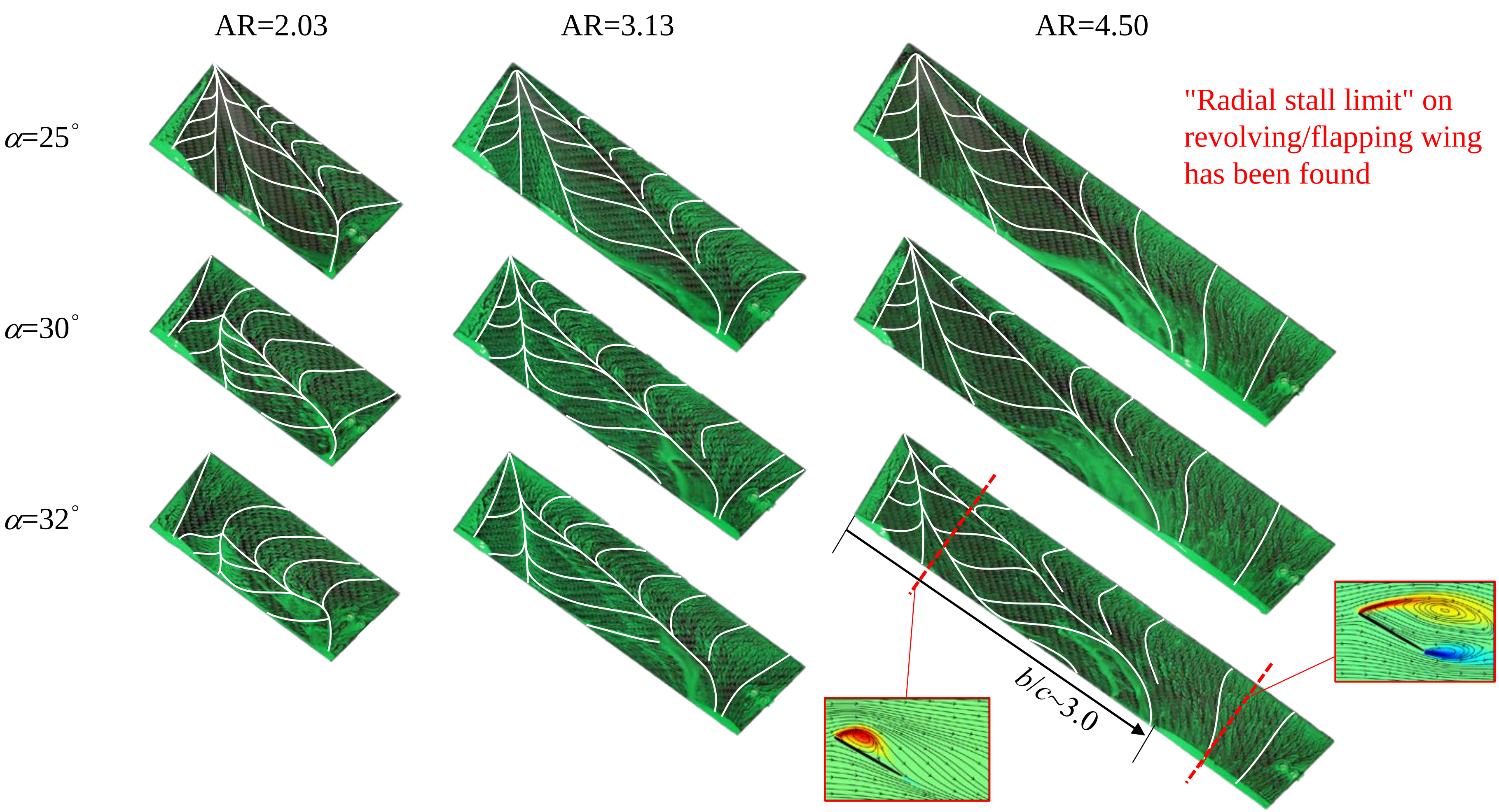
Results

Surface oil-flow pattern #1



Results

Surface oil-flow pattern #2

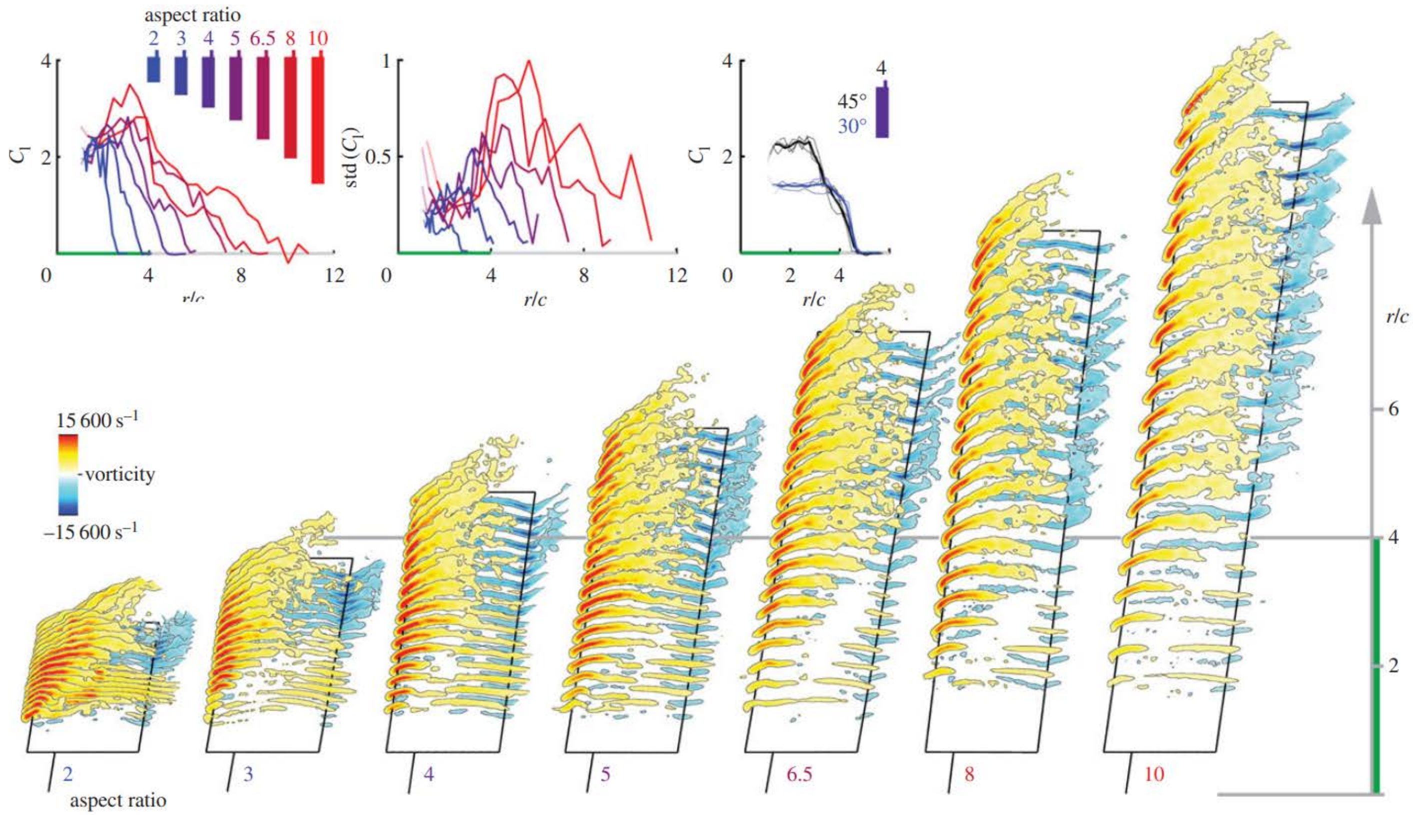


"Radial stall limit" on revolving/flapping wing has been found

Discussion

Similarity between the two

- Radial stall limit on revolving/flapping wing (Kruyt et al., 2015, J Roc Interface)

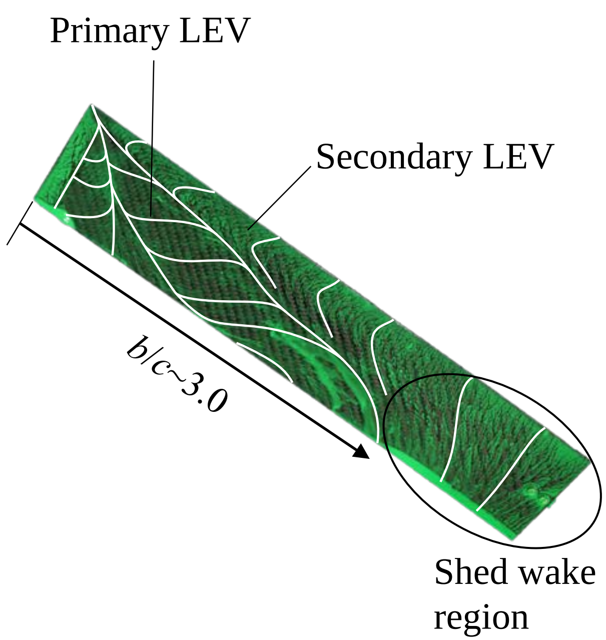


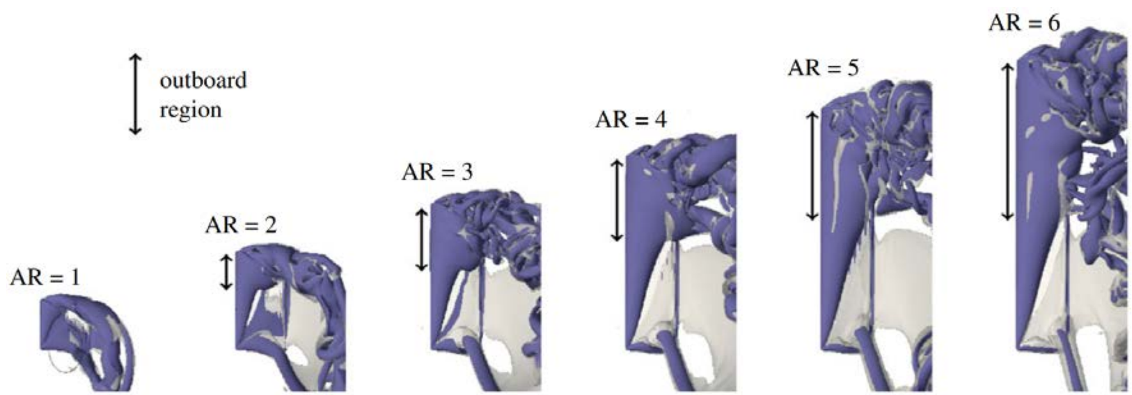
Sliced vorticity fields depending on the AR (Kruyt et al., 2015, J Roc Interface)

Discussion

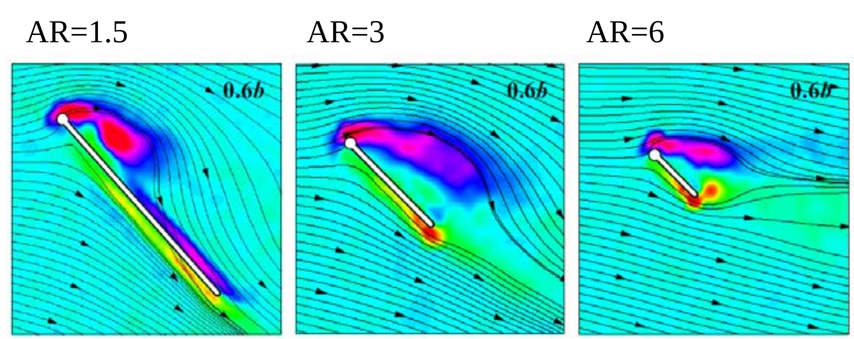
Similarity between the two

- Optimum aspect ratio of flapping/revolving wing ~ 3.0
- (Han et al. 2015 Exp Fluids; Lee et al. 2016 Bioinspir Biomim, Jardin 2018 J Fluid Mech)





Q-criterion on 6 different AR revolving wings (Jardin and Colonius 2018 J Fluid Mech)



PIV results at 60% spanwise section (Han et al. 2015 Exp Fluids)

Conclusion

- Strong influence of the vortex was confirmed in stationary low-AR wings.
  - A great resemblance in between the two different LEVs.
  - Superior lift production at the AR=3.13 vs. optimum performance at AR~3.
  - Critical length of the LEV, b/c ~ 3.1 vs. 'radial stall limit' of R/c < 4.0.

- Future plan
  - Check the combination of the two ways, which give a novel idea for the UAMs.
  - Consider different shapes, leading-edge planforms, airfoil shapes, elastic bodies, etc.

Q/A

Thank you!