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Aerodynamics and Numerical Simulation Methods

Boundary Layer Transition
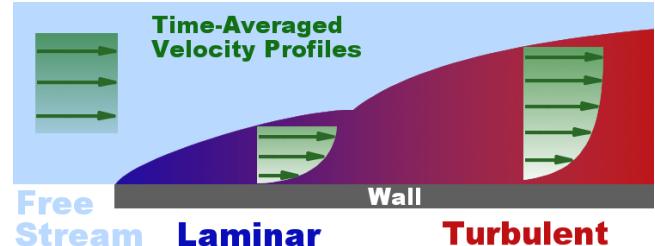
University of BRISTOL

# **Outline**
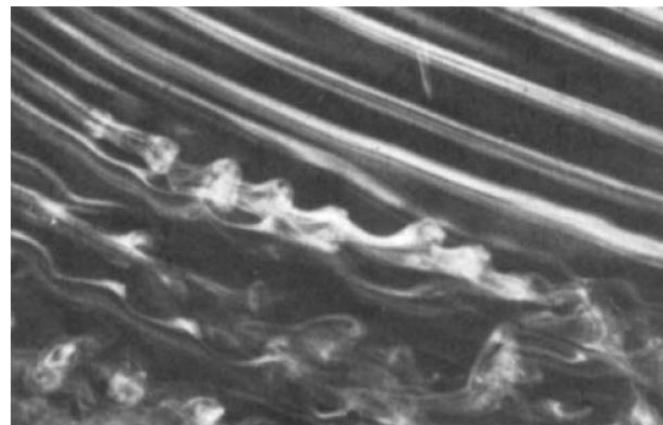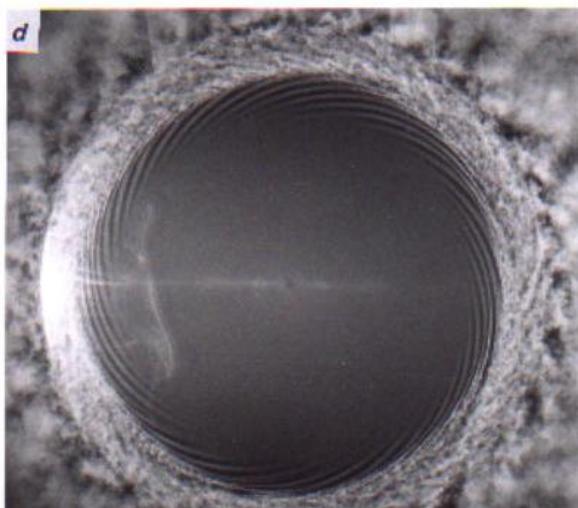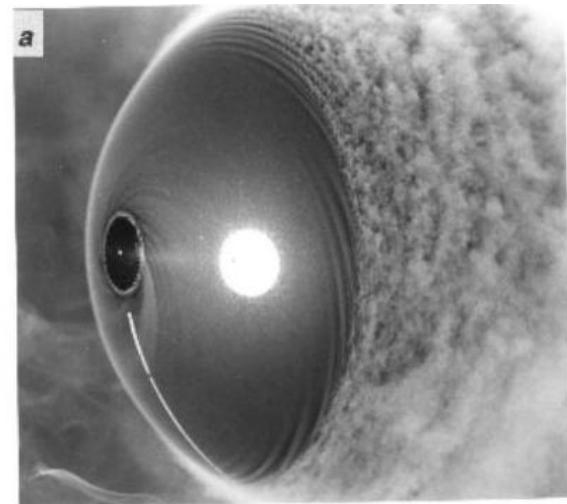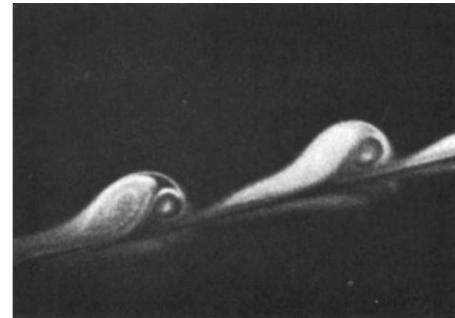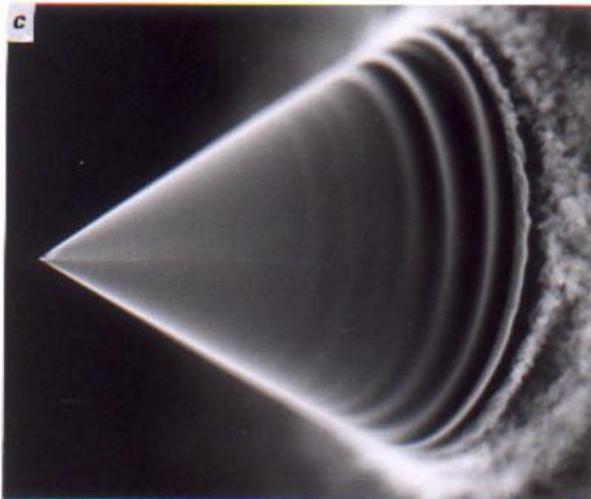
- What is transition?
- Review of experiments visualising transition
- *Tollmien-Schlicting* waves
- Interpreting transition with Schubauer and Skramstad's Results
- Typical Transition Models

- Transition in 3D condition:
  – Cross flow instability
  – Attachment line transition

# What is Transition?
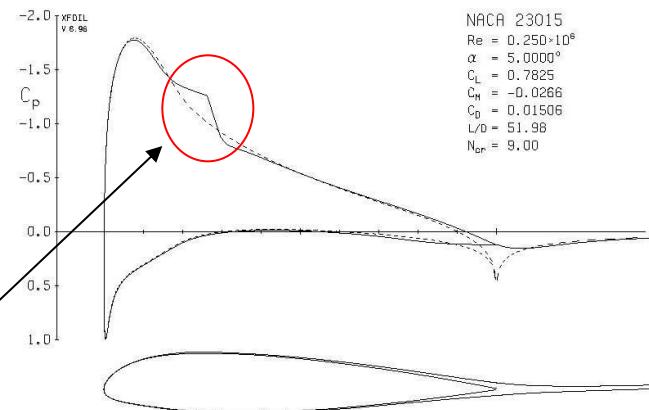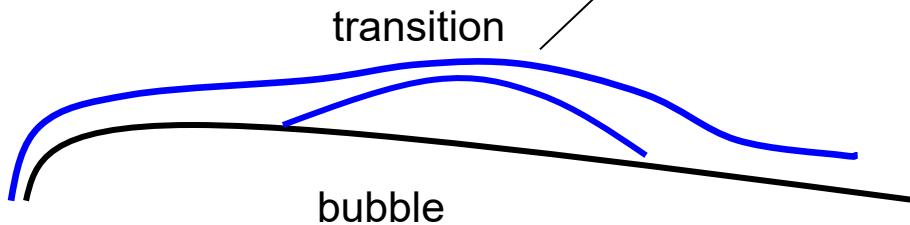
- Nearly all boundary layers begin laminar.

- At sufficient distance downstream, nearly all are turbulent

- How do we get from one to the other?

- Answer is the process called transition. But

  – This process is *very* complex

  – Not very well understood

  – Hence we shall treat it largely empirically and qualitatively

Reference: Frank White Page 347-352
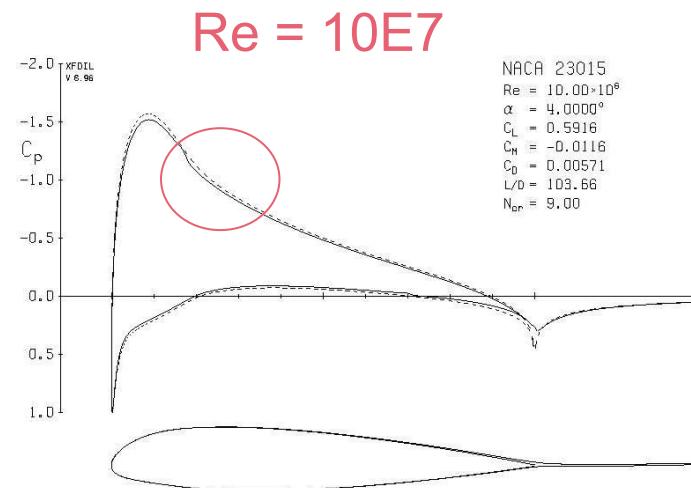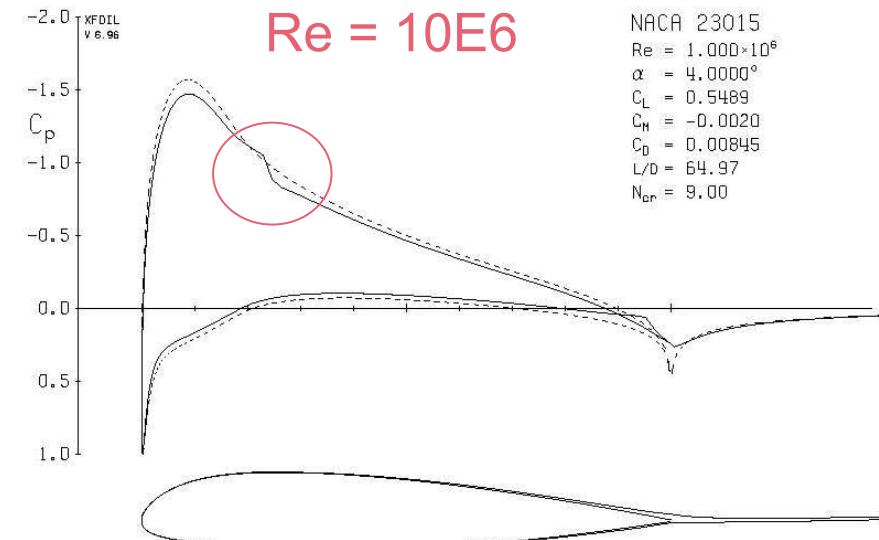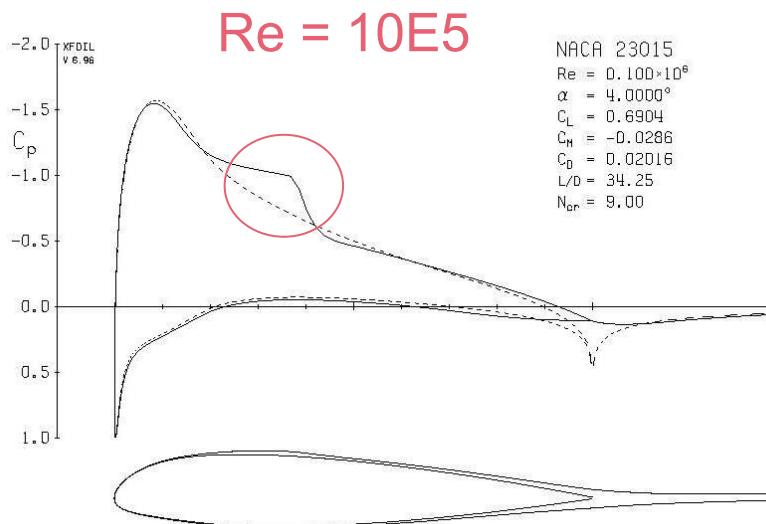
Transition

Transition Bubbles
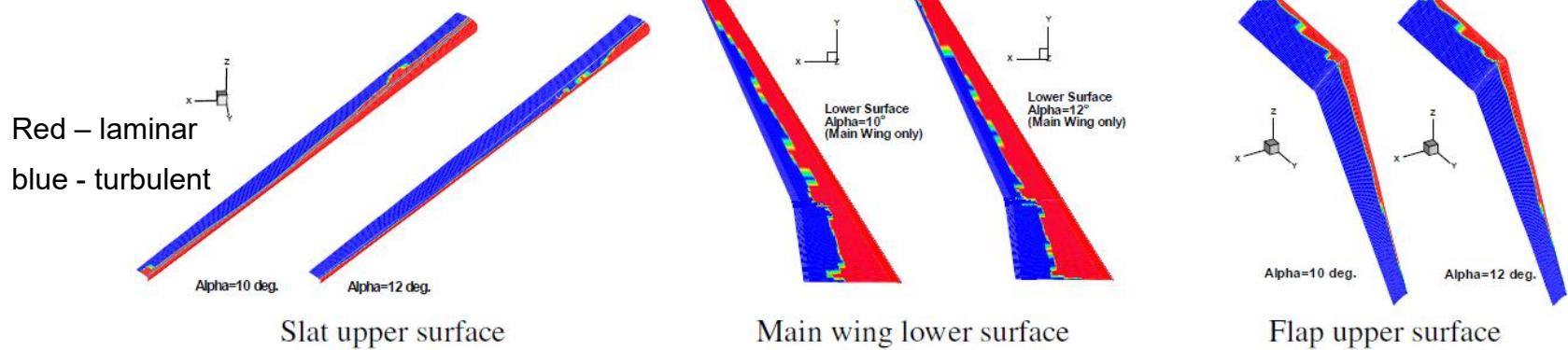
- Laminar Boundary layers cannot tolerate even mildly adverse pressure gradients
  - hence separate
  - but also undergo transition
- Turbulent free shear layers grow much more rapidly than laminar, hence can reattach to surface, forming a separation bubble

transition

bubble
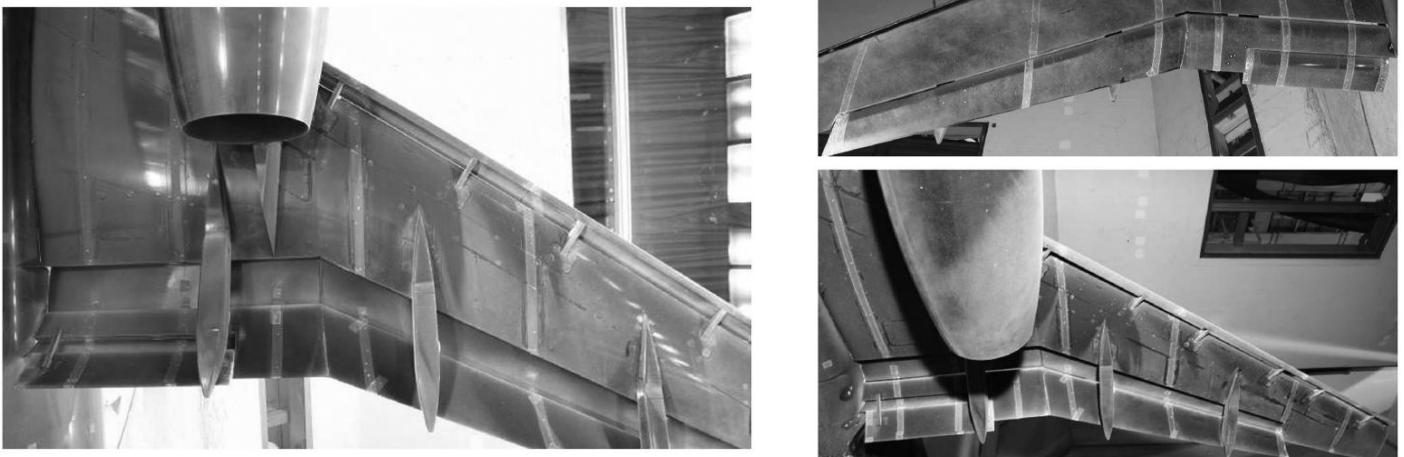
Re Influences Transition

3D Transition examples

Red – laminar

blue - turbulent

Slat upper surface

Main wing lower surface

Flap upper surface

Black - laminar

Glossy – laminar

Matt - turbulent

What causes Transition?

- At all times, tiny disturbances are introduced into the flow within the boundary layer:
  - Noise and vibrations
 - turbulence in the external flow
  - non-uniformities in the surface
- These disturbances travel in a wave like manner, and are called *Tollmien-Schlicting* waves.
- Their direction, amplitude, and growth/decay can be calculated, and shown to be functions of Re and Pressure gradient
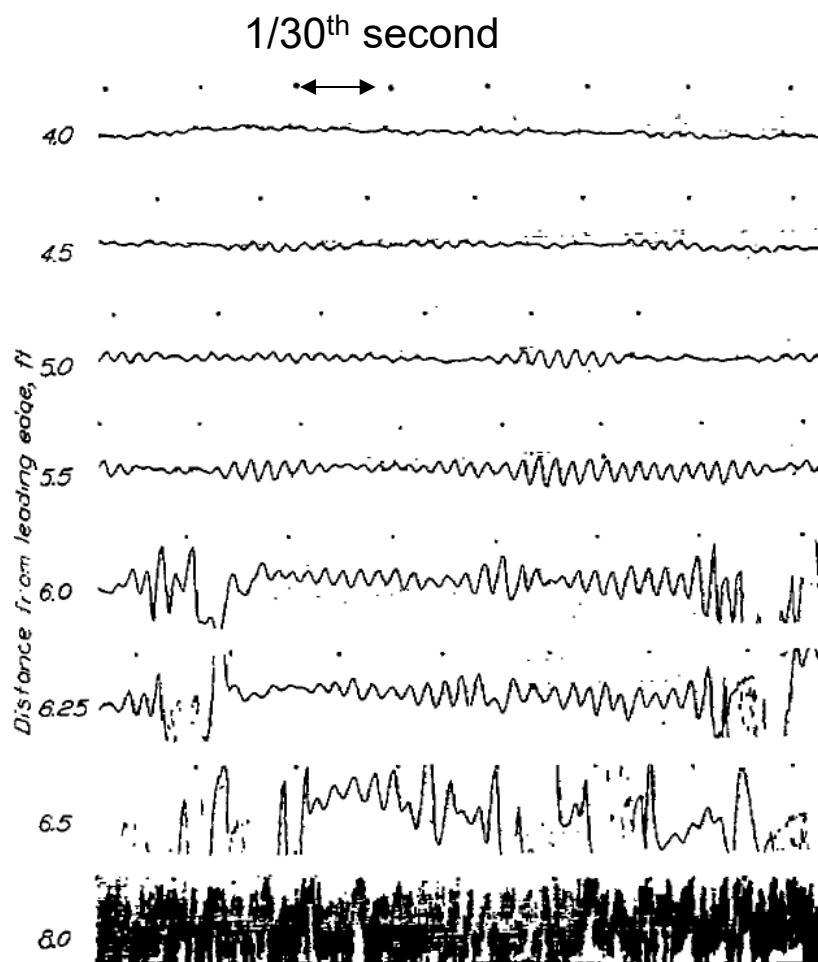
Tollmein-Schlicting Waves

- In a laminar flow, where Re is relatively low, viscous forces damp these waves out

- As Re increases, however:

  - Inertial forces grow relative to viscous

  - There comes a point where the waves are no longer damped

  - And transition begins
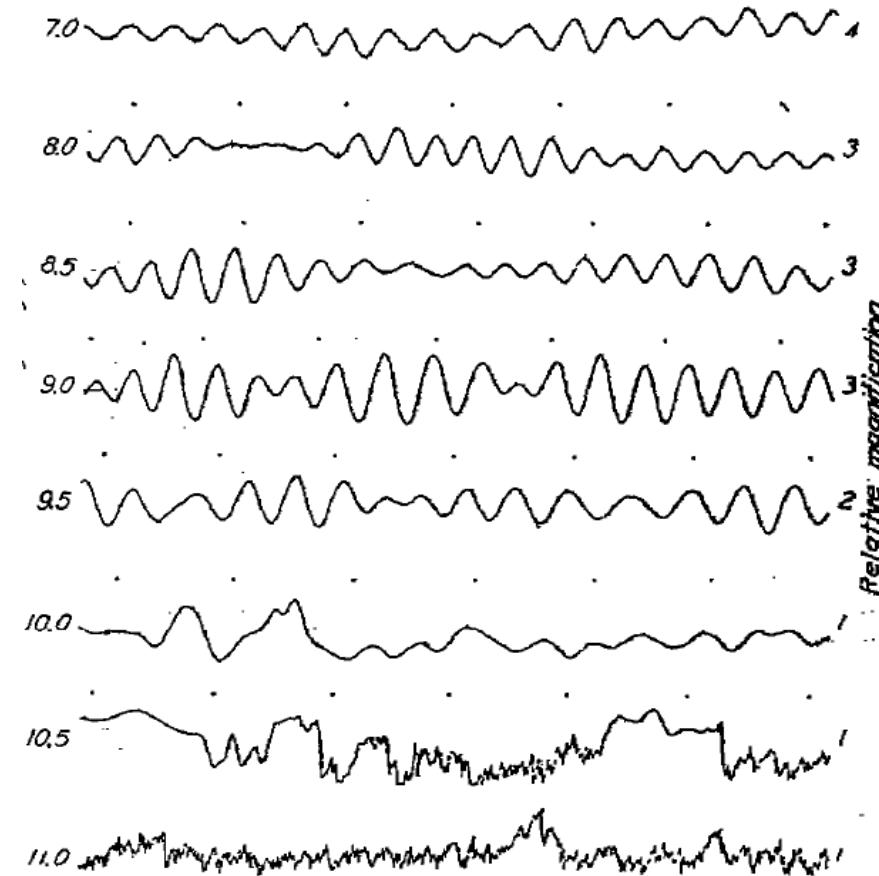
Schubauer and Skramstad's Results
(NACA Report No. 909 'Laminar boundary layer oscillations and transition on a flat plate',1943)

Graphs show u'
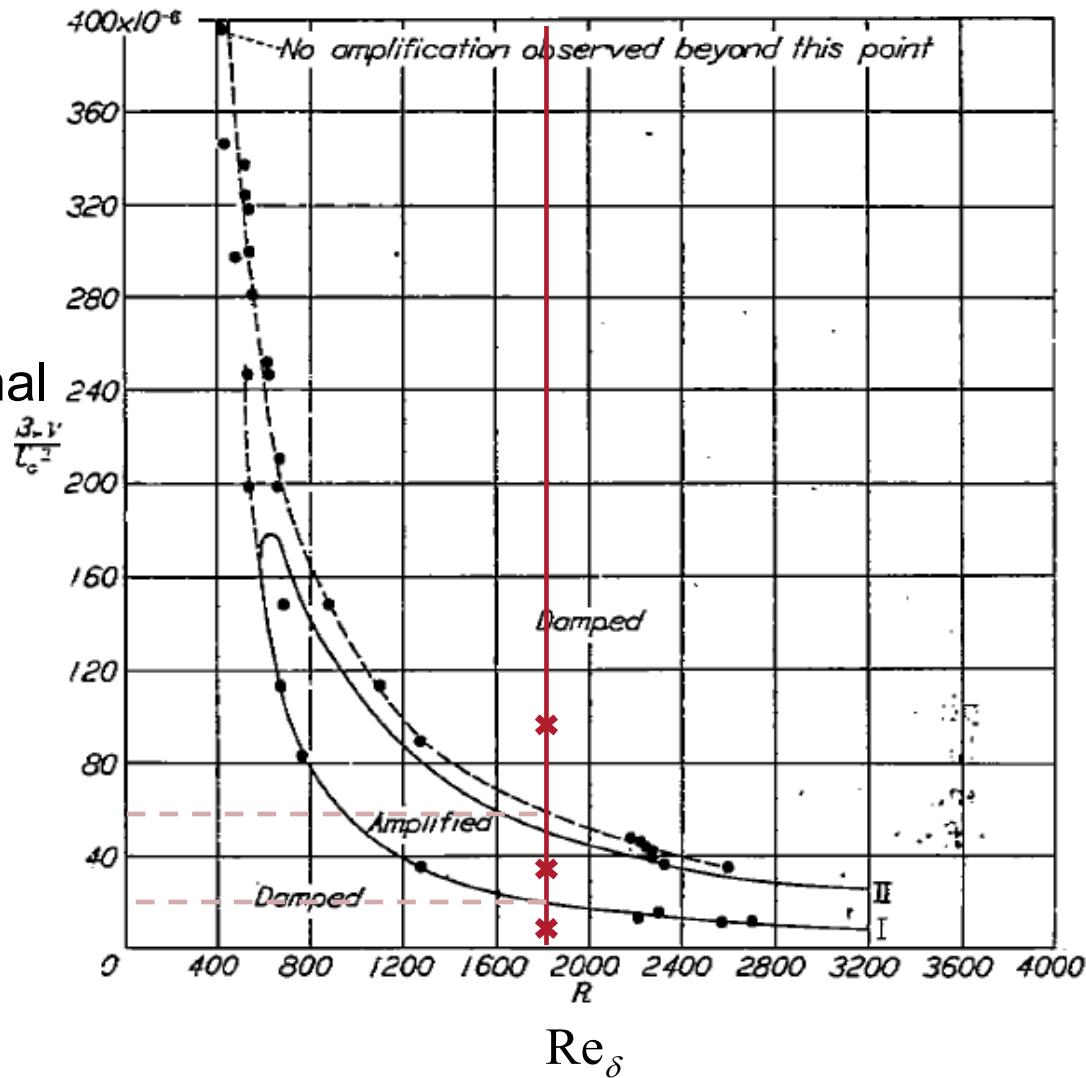
Higher speed
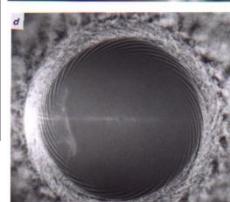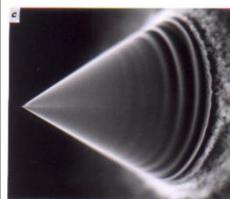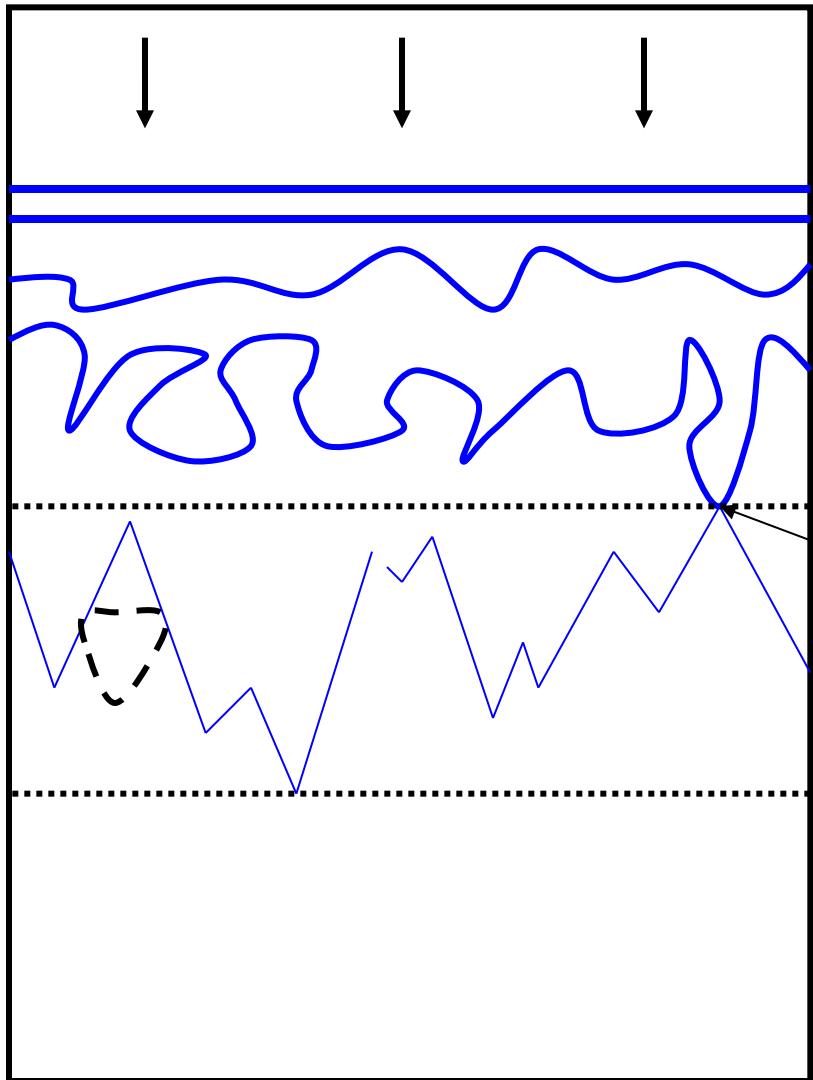
Lower speed

Schubauer and Skramstad's Results

Non-dimensional frequency

$$\text{Re}_\delta$$
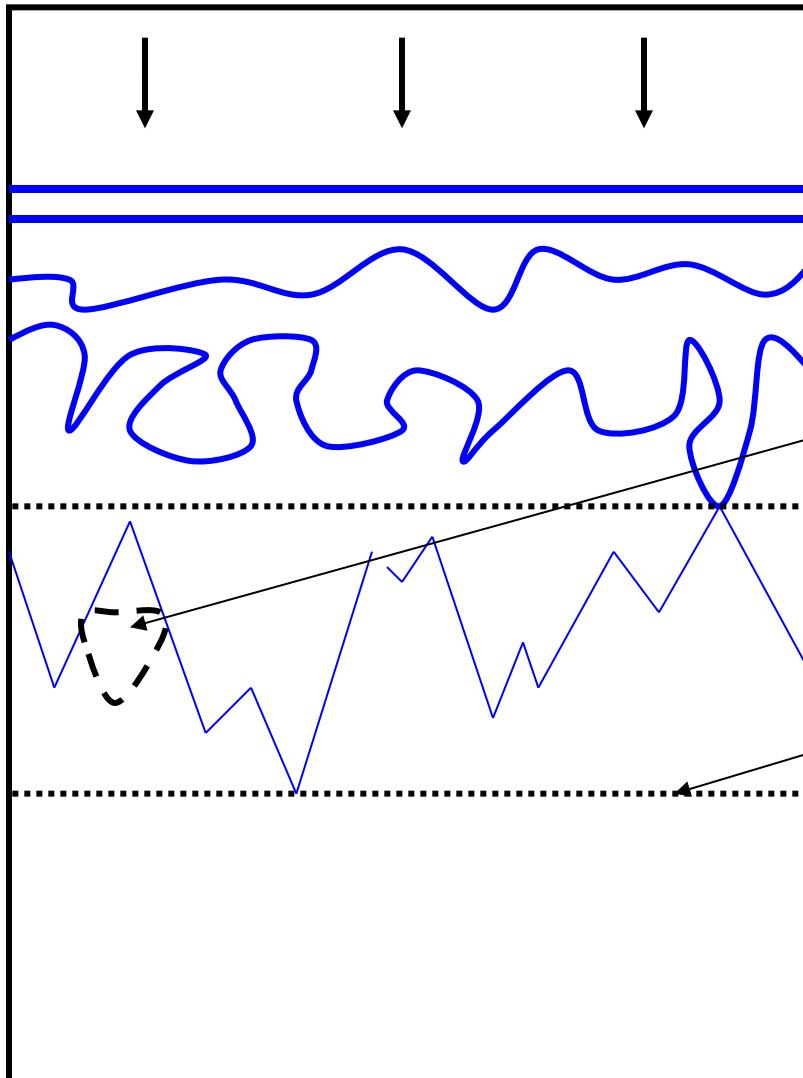
The Transition Process on a Flat Plate (1):
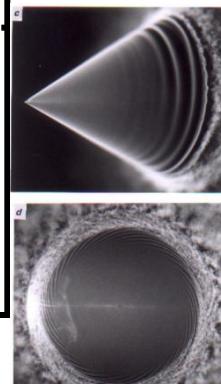
- 2d waves propagate
- Waves become looped due to non-uniformities in the flow
- Loops cause `Turbulent spots' and transition begins

The Transition Process on a Flat Plate (2):
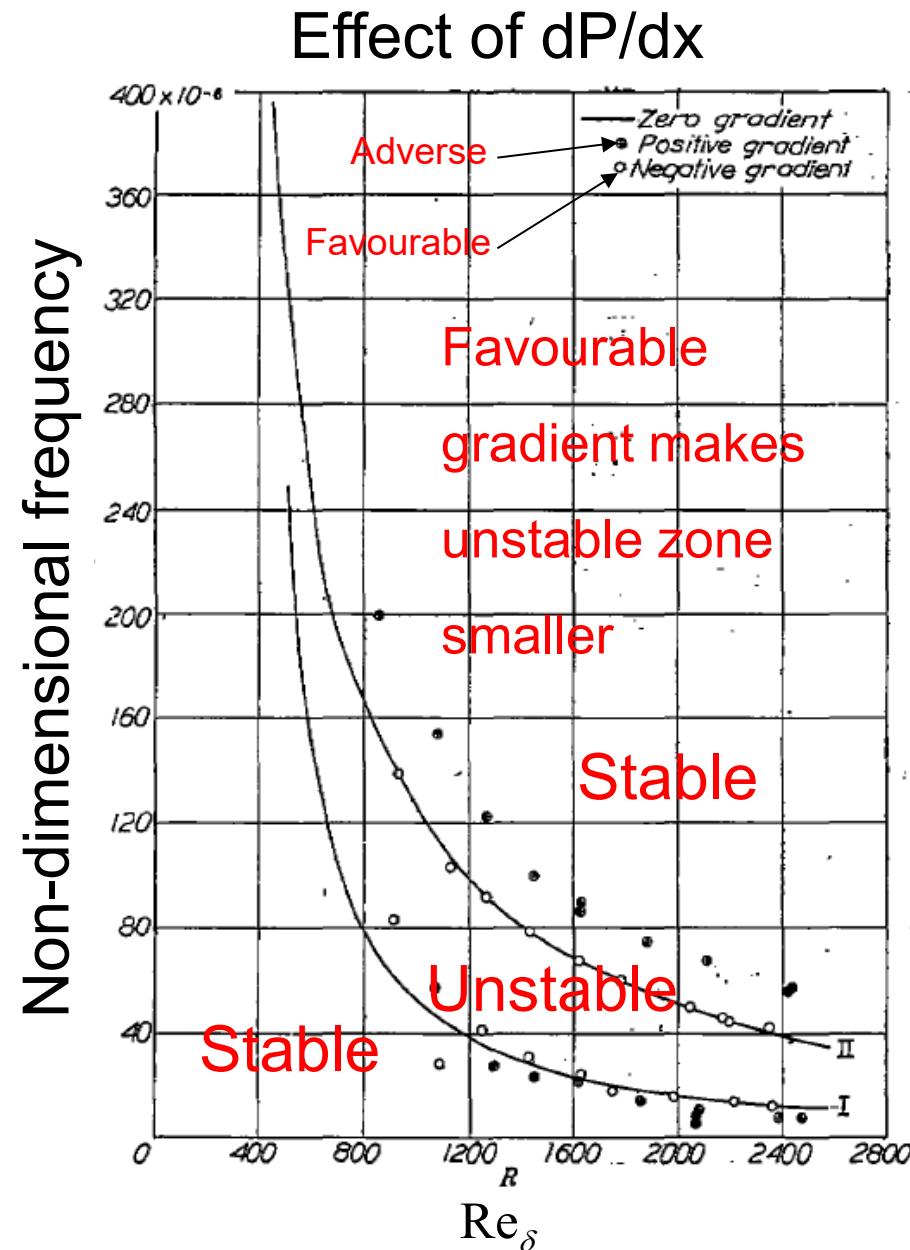
- Formation of turbulent spots is *dynamic*

- `Packet' of turbulent flow moves downstream

- Finally packets merge to form continuous turbulent flow

Transition in other situations

Effect of dP/dx

- Process Effected by:
 - dP/dx: +ve speeds transition, -ve delays
  - Roughness: speeds transition by forming turbulent spots directly, as does:
  - high turbulence in the external flow
  - Suction delays transition by removing mass
  - Cooling delays transition by removing energy

- On a flat plate, transition occurs between $Re_x=1.4\times10^5$ and $Re_x = 3.2\times10^6$ depending on the above factors

Non-dimensional frequency

Adverse

Favourable

Favourable gradient makes unstable zone smaller

Stable

Unstable

Stable

Re_δ

Typical Transition Models:

• As discussed, transition is very complex, and difficult to model accurately/reliable in different situations

• Fortunately, for high Re's, generally happens in a very short distance, so we assume a point transition (line in 3D)

• Simplest method (and most common) is to specify a critical Re

• Alternatively, use Pressure gradients (e.g. in your code)

• Or…
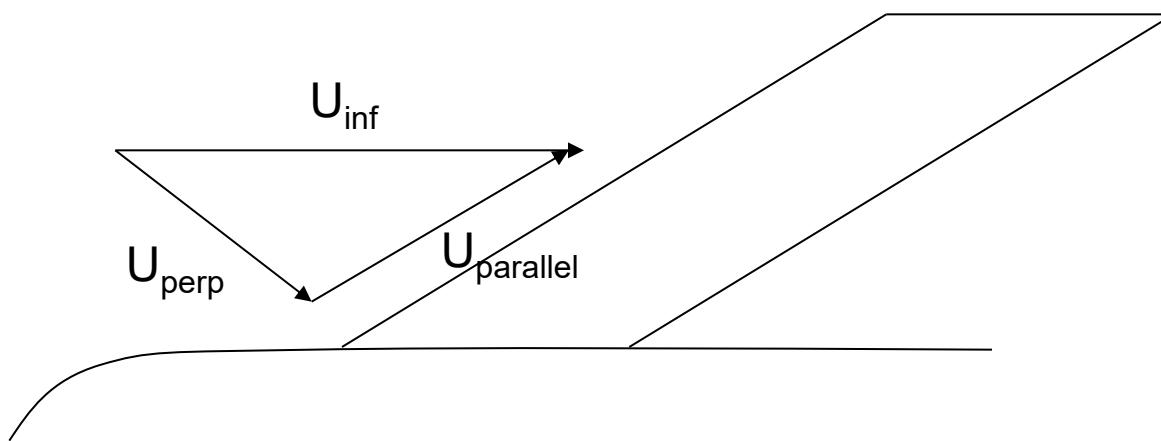
Michel has shown for an aerofoil type transition the formula

$$Re_\theta = 1.174 \left(1 + \frac{22400}{Re_x} \right) Re_x^{0.46}$$
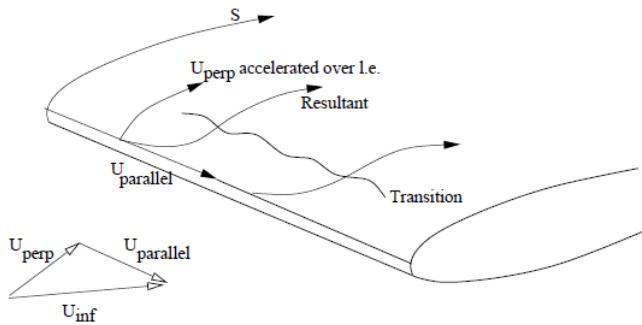
may be used to determine the point of transition

3D effects on swept wings

• Tollmein-Schlicting waves and separation bubbles are 2D effects

• Sweep on a 3D wing introduces two other transition mechanisms, due to the introduction of a parallel and perpendicular velocity component

Cross Flow Instability:

U_{perp} is 0 at the l.e., but grows rapidly along the aerofoil surface
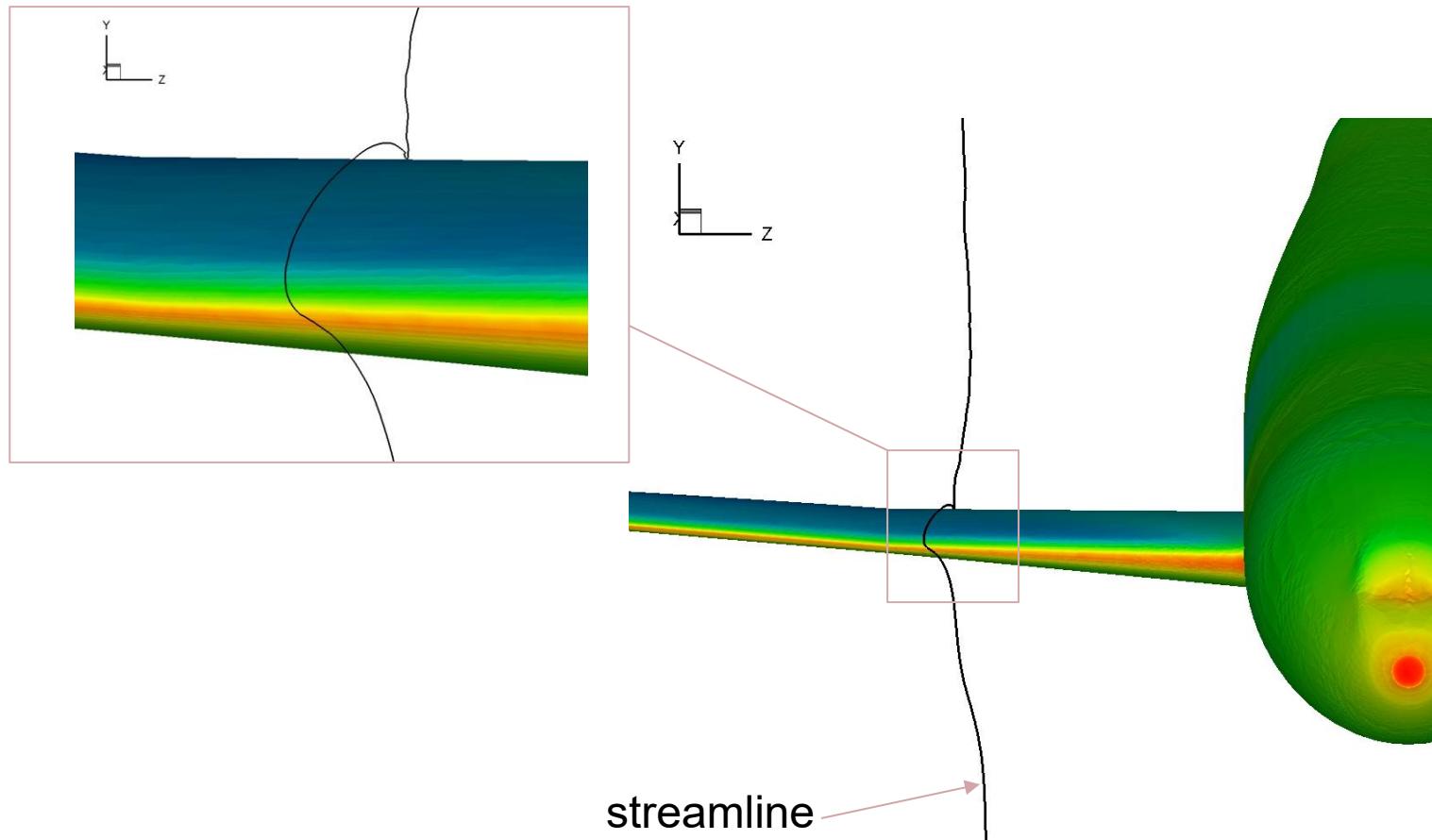
$U_{parallel}$ is approximately constant

Can avoid by reducing dU_{perp}/ds, i.e. alter aerofoil shape.

These two factors combine to give an inflection in the boundary layer, destabilising it
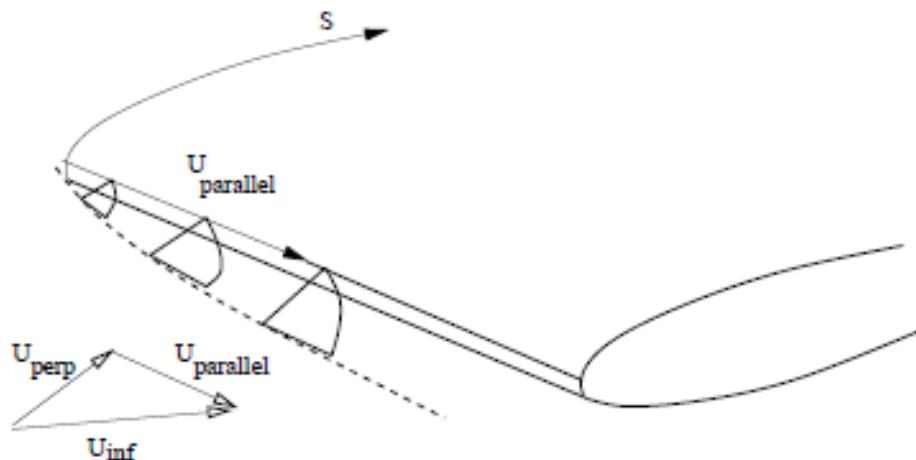
Cross Flow Instability – example streamline

streamline

Attachment line transition (1)
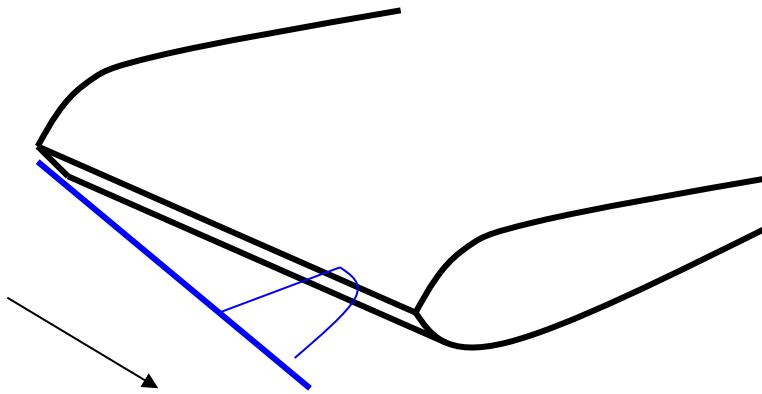
Re_{al} is defined as $$Re_{a.l.} = \frac{U_{parallel}}{\nu}\left(\frac{\nu}{\frac{\partial U_{perp}}{\partial s}}\right)^{\frac{1}{2}}$$

$U_{parallel}$ causes a boundary layer to grow along the attachment line

If the Re_{al} along this is > 800, we get transition, and the *whole wing* is then in a turbulent boundary layer -> unnecessarily high drag

Attachment line transition (2)

- Can be avoided by:

  - Reduce $U_{parallel}$ (i.e. reduce sweep)

  - Increase dU_{perp}/ds, (i.e. opposite of cross flow! 🥶)

  - Use suction on L.E. (not very practical – small holes are a maintenance nightmare as they block with insects and rubbish etc.)

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