Lecture 11

Shear flow transition – case study

AE209 Hydrodynamic stability
Dr Yongyun Hwang

Lecture outline

1. Transition in boundary layer
2. Transition in flow over a circular cylinder
3. Is transition relevant to turbulence?

General features on instabilities in boundary layer

At low noise level

1. Boundary layer instability (TS wave) is convectively unstable.

⇒ sensitive to noise.

At high noise level

2. Large **transient growth** is also possible **below critical Reynolds number of TS instability**.

3. **Primary instabilities** (either TS wave or transient growth) undergo **secondary instability**, eventually leading to turbulence.

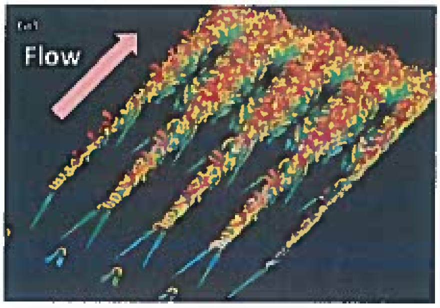
Turbulence spots

1. Transition in boundary layer

Boundary layer

Scenario I : Modal transition via Tollmien-Schlichting wave

Two types of secondary instabilities of TS wave



K-type transition
(Klebanoff 1962)

H-type transition
(Herbert 1988)

Theory by
Orszag and Patera
(1982)

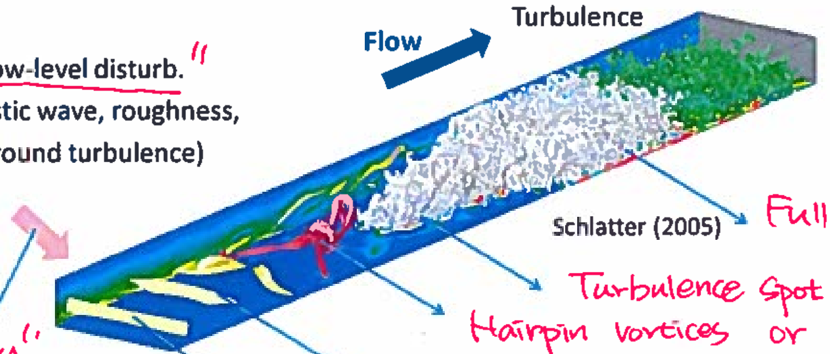
DNS by Sayadi et al. (2012)

Boundary layer

Scenario I : Modal transition via Tollmien-Schlichting wave

Secondary instabilities of Tollmien-Schlichting wave

"Very low-level disturb."
(Acoustic wave, roughness,
background turbulence)



"Receptivity"
: disturbancen entrainment process

T-S wave.

Secondary instability (3D)

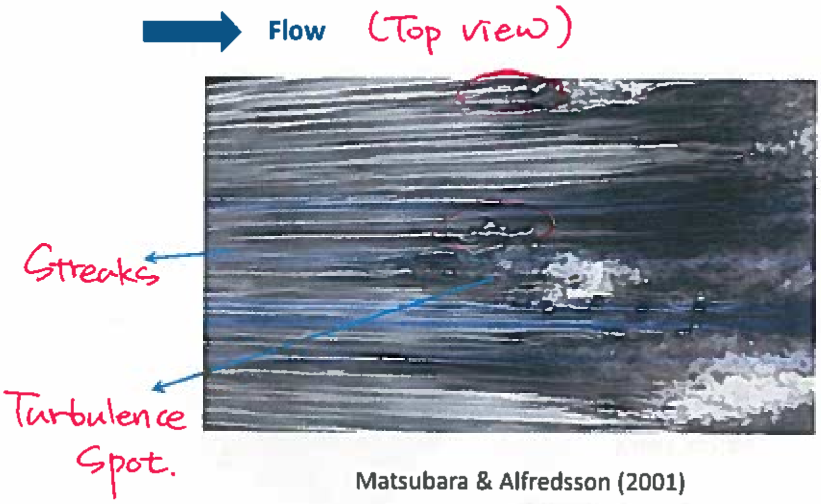
Hairpin vortices or Λ vortices

Turbulence spot.

Fully developed turbulence

Boundary layer

Scenario II : Bypass transition via transient growth



Matsubara & Alfredsson (2001)

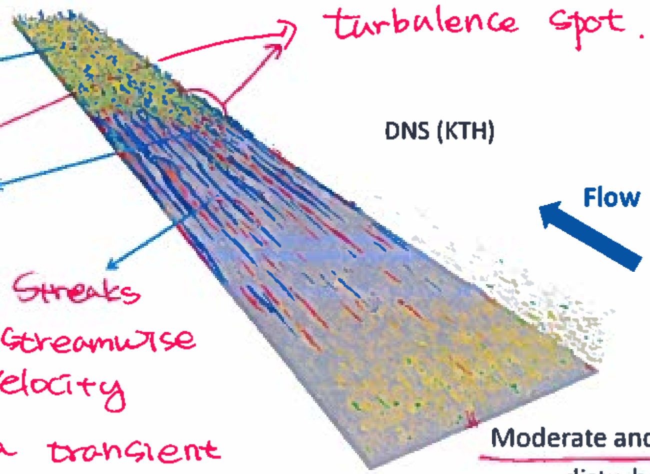
Boundary layer 7/26

Scenario II : Bypass transition via transient growth

Fully-developed turbulence

turbulence spot.

Secondary Instability.

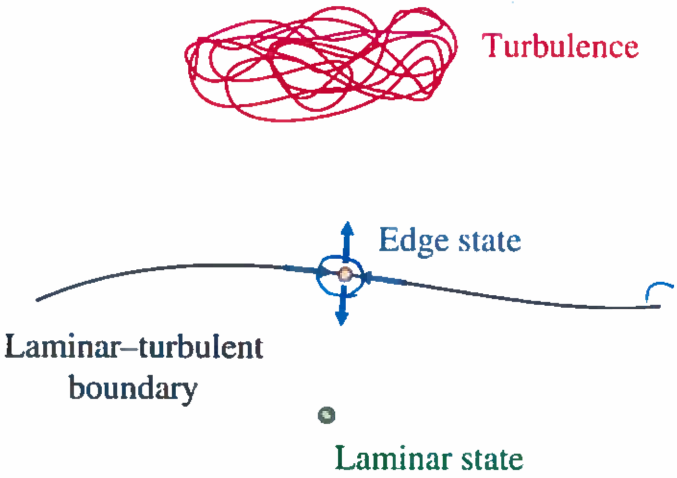


Streaks of streamwise velocity via transient growth.

Moderate and high level disturbance

Boundary layer

Beyond nonlinearity – Dynamical system approach (since mid 2000)

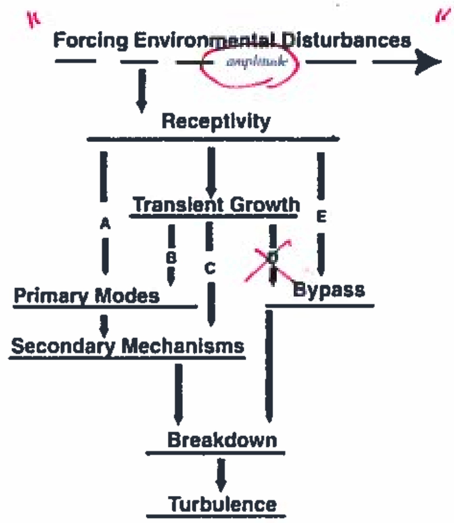


Edge of turbulence.

Boundary layer

Summary

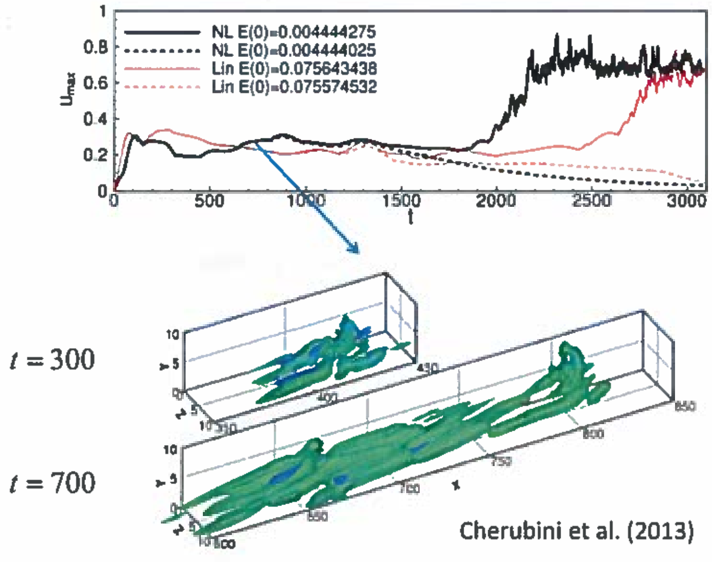
Downstream



Morkovin (1994)

Boundary layer

Edge state in boundary layer

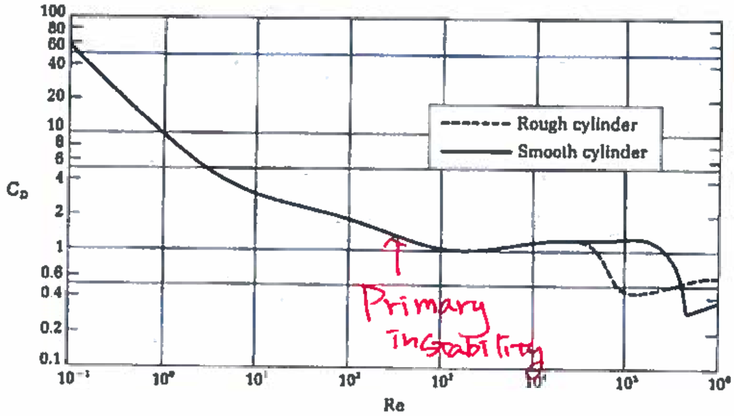


Cherubini et al. (2013)

2. Transition in flow over a circular cylinder

Wake behind a circular cylinder

Drag coefficient with Re



$$\mathrm{Re} = \frac{\rho U_\infty D}{\mu}$$

ρ = density of fluid (M/L^3)
U_∞ = free-stream fluid velocity (L/T)
D = diameter of cylinder (L)
μ = viscosity of fluid ($F \cdot T/L^2$)

Wake behind a circular cylinder

General features on instabilities in bluff-body wake

1. Instability (Karman vortex shedding) is **absolutely unstable** and is driven by **inflectional mechanism** (Rayleigh criterion).

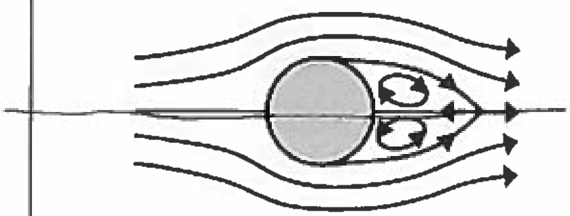
Insensitive to noise : ~~Fore~~ There exists a very well defined Critical Re.

2. The role of **transient growth** is **not very important** typically because the critical Reynolds number of instability itself is also quite low.

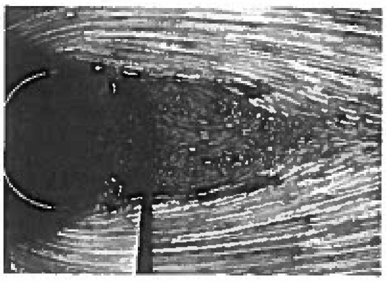
3. **Spatial development** is **not of main interest**, as the instability process is often dominated by the near-wake region.

Wake behind a circular cylinder

Steady symmetric flow ($5<Re<47$)



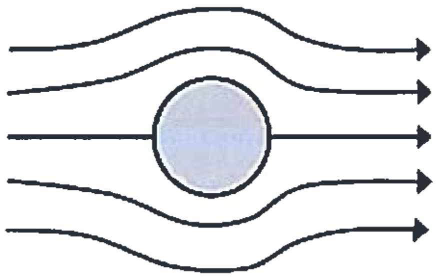
Sketch



Coutanceau & Bouard (1977)

Wake behind a circular cylinder

Creeping flow (0<Re<5): Hele-Shaw flow



Sketch

Schlichting (1979)

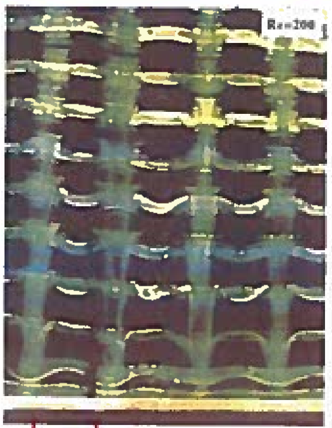
Wake behind a circular cylinder

Onset of three-dimensional Karman vortex shedding ($189<Re<300$)

Turbulence appears at far downstream ($300<Re<1000$)

Secondary Instability of vortex Shedding.

Flow



4D. (diameter)

Mode A $Re_D = 200$

1~2D

Mode B $Re_D = 270$

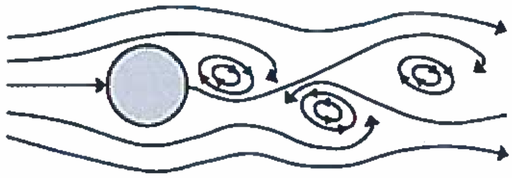
Williamson (1996)

Wake behind a circular cylinder

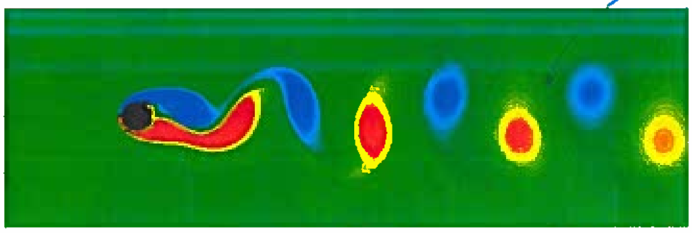
Two-dimensional laminar Karman vortex shedding (47<Re<189)

$Re_c \simeq 47$

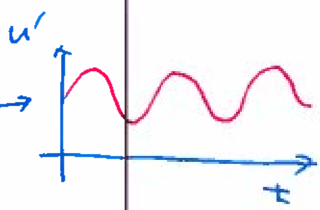
No variation in spanwise direction



Sketch



Hwang (2005) $\mathrm{Re}_D = 100$

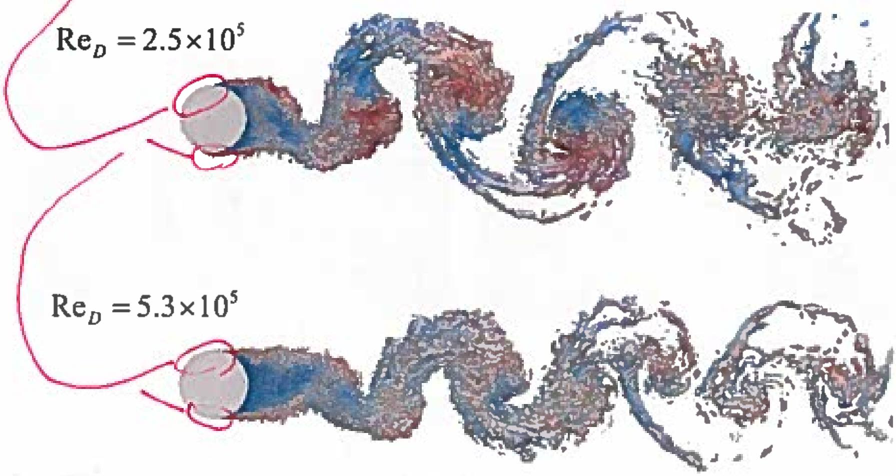


"Completely periodic in time"

⇒ Supercritical Hopf bifurcation

Wake behind a circular cylinder

Transition in boundary layer (15000<Re<10^6)

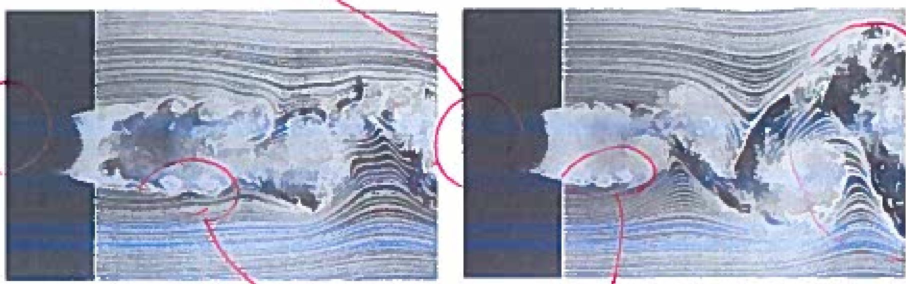


Lehmkuhal et al. (2014)

Wake behind a circular cylinder

Instability in separating shear layer (1000<Re<15000)

Laminar.



turbulence.

$\mathrm{Re}_D = 7000$ $\mathrm{Re}_D = 10000$

Prasad & Williamson (1997)

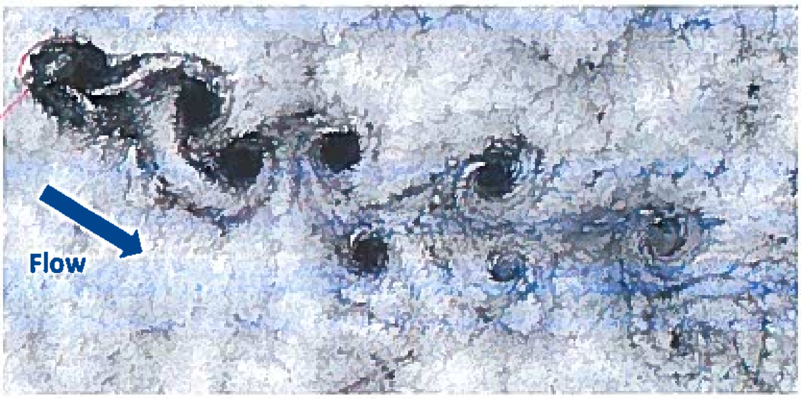
K-H istability in the seperating shear layer.

Lecture outline

1. Transition in boundary layer
2. Transition in flow over a circular cylinder
3. **Is transition relevant to turbulence?**

Wake behind a circular cylinder

Fully turbulent everywhere ($Re>10^6$)

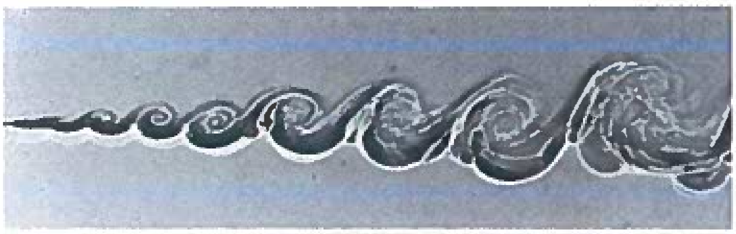


island.

Instabilities & coherent structures in turbulent flow

Transitional and turbulent mixing layers

Low Re

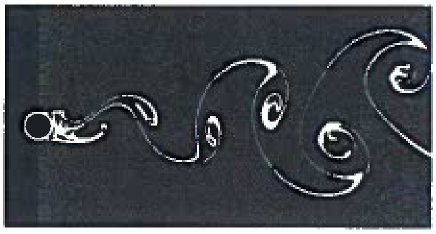


High Re

Brown & Roshko (1974)

Instabilities & coherent structures in turbulent flow

Laminar and turbulent vortex shedding in bluff body wakes



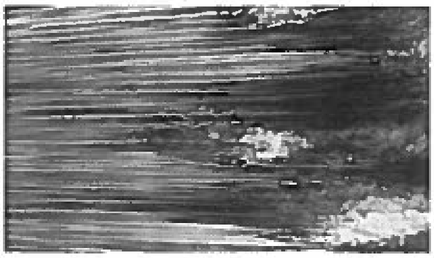
Low Re

High Re

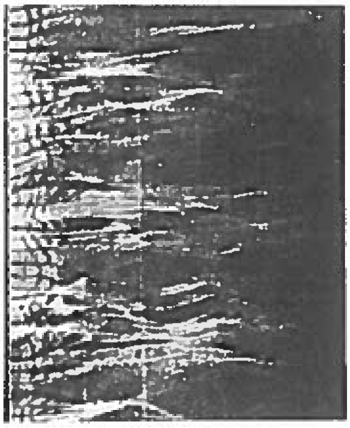
Instabilities & coherent structures in turbulent flow 25/26

Boundary layers

Streaks in bypass transition



Matsubara & Alfredsson (2001)



Streaks in buffer layer

Kline et al. (1967)

1. Transition in boundary layer
2. Transition in flow over a circular cylinder
3. Is transition relevant to turbulence?