NORDITA 2010

KTH Mechanics

Stability and transition in wall bounded turbulence

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Literature

Lin (1955)
The theory of hydrodynamic stability

Chandrasekhar (1961)
Hydrodynamic and hydromagnetic stability

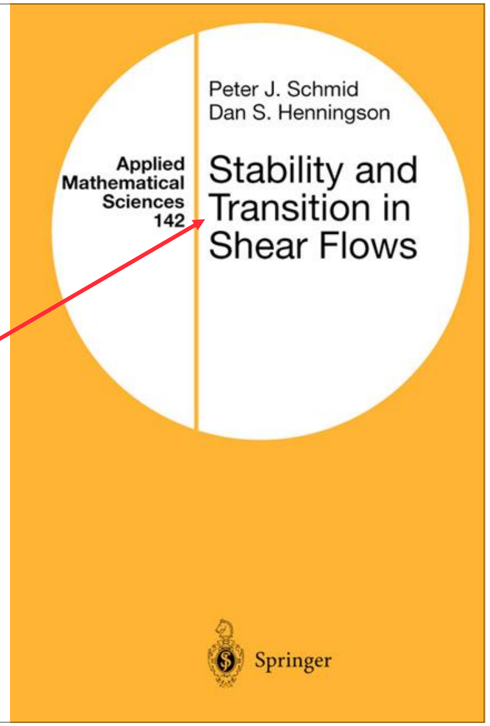
Betchov & Criminale (1967)
Stability of parallel flows

Drazin & Reid (1981)
Hydrodynamic stability

Schmid & Henningson (2001)

Drazin (2002)
Introduction to hydrodynamic stability

Criminale (2003)
Theory and computation in hydrodynamic stability



Lecture 1

1. Introduction to flow instability
2. Linear stability theory for boundary layer flows
   - Rayleigh stability theory (inviscid)
   - Orr-Sommerfeld theory (viscous)
3. Wind tunnels for transition research
4. Transition prediction
5. Transient growth
6. Free stream turbulence

Water jet from kitchen tap

laminar

turbulent

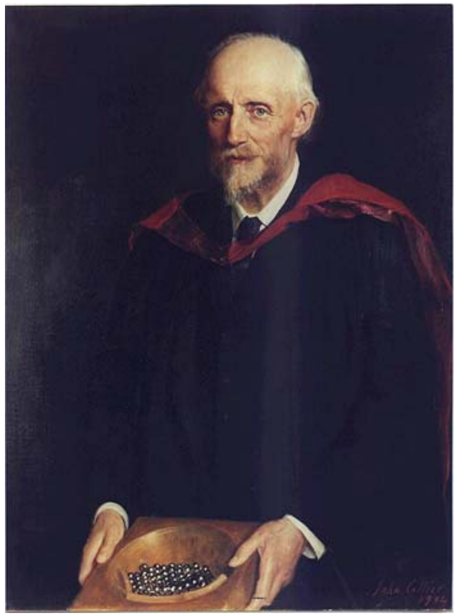
Water jet from kitchen tap

Always unstable to axi-symmetric disturbances with a wavelength larger than the jet circumference, but growth rate $\sim r^{-3/2}$

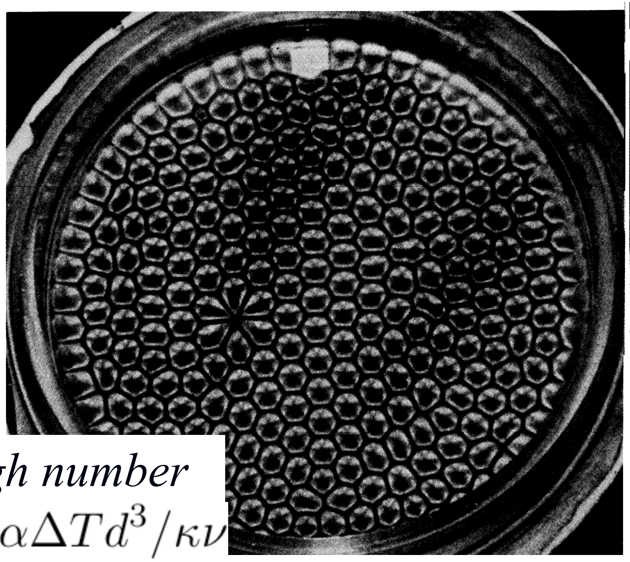
laminar

dripping

Osborne Reynolds (1842-1912)

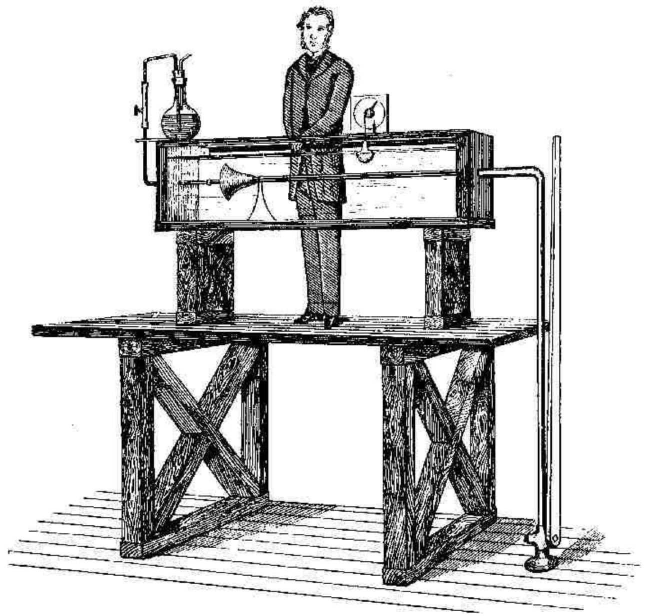


Thermal instability - Bénard convection

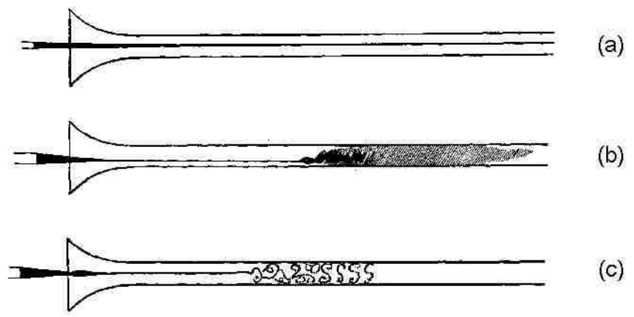


Rayleigh number
$Ra = g\alpha\Delta T d^3/\kappa\nu$

Reynolds experiment (1883)



Reynolds experiment (1883)

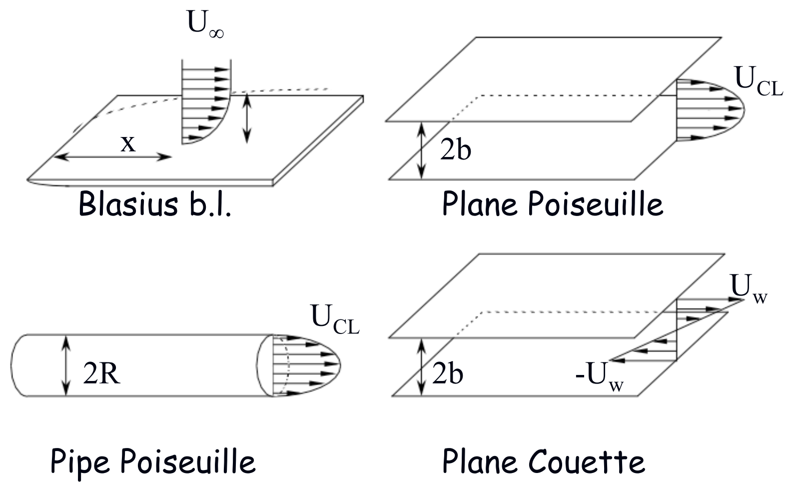


(a) Laminar flow $Re<Re_{transitional}$,

(b)Transition to turbulence $Re>Re_{transitional}$

(c) Same as (b) but "short time exposure"

Canonical wall bounded flows

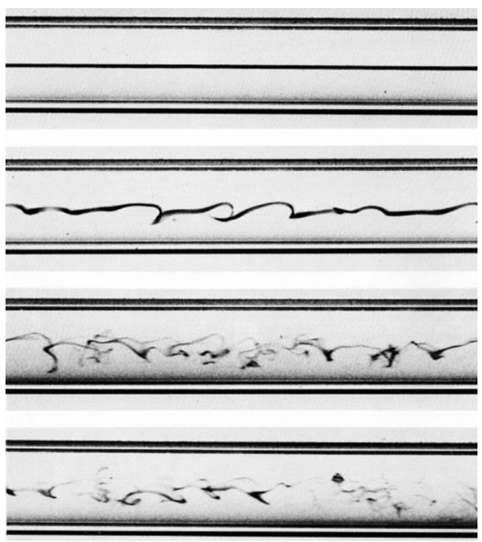


Reynolds experiment (1983)

Same apparatus today!

1883 transitional Re =13000

Lower Re today due to traffic, i.e. external disturbances has increased in amplitude



Transitional Reynolds numbers for the canonical cases

Flow case	*Re*	Re_{tr}
Blasius	$U_\infty \delta^*/\nu$	490
Channel	$U_{CL} b/\nu$	1000
Pipe	$U_{CL} R/\nu$	1760
Couette	$U_w b/\nu$	360

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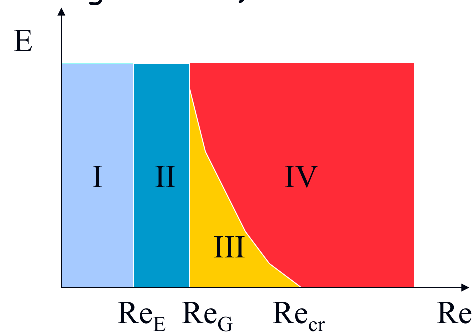
Stability definitions

(from Schmid & Henningson 2001)

Region:

I: Monotonic stability
II: Global stability
III: Conditional stability
IV: Possible instability



Flow case	Re_E	Re_G	Re_{cr}	Re_{tr}
Pipe	81.5	-	∞	1760
Channel	49.6	-	5772	1000
Couette	20.7	125	∞	360

Hydrodynamic stability theory

Idea: Introduce a controlled disturbance and investigate whether it grows or decays (in time or space) for the given flow situation

Control parameter: Typically a Reynolds number (and possible some other non-dimensional variable depending on the flow situation

$$\frac{\text{inertia}}{\text{viscous damping}} \sim \frac{\rho u \cdot \nabla u}{\mu \nabla^2 u} \sim \frac{\rho U^2/L}{\mu U/L^2} = \frac{\rho U L}{\mu} = Re$$

Other variables: Amplitude, wave number and frequency of the disturbance

Linear theory: independent of amplitude => modal analysis

Some landmarks of classical stability theory

Rayleigh (1880) - Inviscid theory
Reynolds (1883) - Pipe flow experiments - the importance of the Reynolds number
Orr (1907), **Sommerfeld** (1908) Formulation of viscous disturbance eq.
Heisenberg (1924) First eigenvalues found (Dr-thesis)
Tollmien (1928), **Schlichting** (1933) Solutions to OS-eq.
Schubauer & Skramstad (1948) First exp. Verification of TS-waves
Klebanoff et al. (1962) Exp. on TS-wave breakdown
Orzag (1970) Numerical solution for OS-eq. in channel flow
Fasel & Konzelmann (1990) Numerical work on OS-eq. in Blasius boundary layer flow
Klingmann et al. (1993) New experimental results on TS-waves in Blasius boundary layer flow

Equations of motions

Continuity equation (incompressible flow)

$$\nabla \cdot \overline{u} = 0$$

Navier-Stokes equations

$$\rho[\frac{\partial \overline{u}}{\partial t} + \overline{u} \cdot \nabla \overline{u}] = -\nabla p + \mu \nabla^2 \overline{u}$$

In non-dimensional form

$$\nabla \cdot \overline{u} = 0 \qquad \textbf{and} \qquad \frac{\partial \overline{u}}{\partial t} + \overline{u} \cdot \nabla \overline{u} = -\nabla p + Re^{-1} \nabla^2 \overline{u}$$

where $\qquad Re = \rho U L / \mu$

Equations of motions (contd)

Assume that the base flow is 2D and that disturbances are 2D.
$\Rightarrow \overline{u} = (u, v) = u(x, y)\overline{e_x} + v(x, y)\overline{e_y}$

Momentum eqs. in x and y-directions are obtained through scalar multiplication with $\overline{e_x}$ and $\overline{e_y}$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + Re^{-1}\nabla^2 u \qquad (1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + Re^{-1}\nabla^2 v \qquad (2)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (3)$$

Disturbance decomposition

Assume linear disturbances (capital letters are mean values and prime fluctuations around the mean)

$$u = U + u'$$

$$v = V + v'$$

$$p = P + p'$$

u', v', p' are small disturbances $\Rightarrow$ quadratic terms may be neglected.

We now assume parallel flow, i.e. $V = 0$. Exact for channel flows, good approximation for many boundary layer flows!

Disturbance decomposition (contd.)

$$\frac{\partial(U+u')}{\partial t} + (U+u')\frac{\partial(U+u')}{\partial x} + v'\frac{\partial(U+u')}{\partial y} =$$

$$-\frac{\partial(P+p')}{\partial x} + Re^{-1}\nabla^2(U+u')$$

Write out all the different terms in the equation above, noting that the mean flow is independent of time

quadratic in the disturbance

$$\frac{\partial u'}{\partial t} + U\frac{\partial U}{\partial x} + U\frac{\partial u'}{\partial x} + u'\frac{\partial U}{\partial x} + u'\frac{\partial u'}{\partial x} + v'\frac{\partial U}{\partial y} + v'\frac{\partial u'}{\partial y} =$$

$$-\frac{\partial P}{\partial x} - \frac{\partial p'}{\partial x} + Re^{-1}\nabla^2 U + Re^{-1}\nabla^2 u' \qquad (4)$$

(contd.)

Assume that all disturbances are zero!

$$U\frac{\partial U}{\partial x} = -\frac{\partial P}{\partial x} + Re^{-1}\nabla^2 U$$

Subtract that from equation (4) $\Rightarrow$

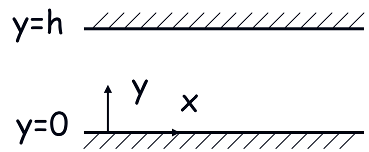
$$\frac{\partial u'}{\partial t} + U\frac{\partial u'}{\partial x} + u'\frac{\partial U}{\partial x} + v'\frac{\partial U}{\partial y} = -\frac{\partial p'}{\partial x} + Re^{-1}\nabla^2 u' \qquad (5)$$

Same operation for eqs. (2) and (3) $\Rightarrow$

$$\frac{\partial v'}{\partial t} + U\frac{\partial v'}{\partial x} = -\frac{\partial p'}{\partial y} + Re^{-1}\nabla^2 v' \qquad (6)$$

$$\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} = 0 \qquad (7)$$

Boundary conditions for channel flow



At $y = 0$ and $y = h$ we get

$v' = 0$ (impermeable wall)

$u' = 0$ (no slip) $\Rightarrow \frac{\partial v'}{\partial y} = 0$

The latter is given from

$$\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} = 0$$

and since $u' = 0$ at the wall $\Rightarrow \partial u'/\partial x = 0$ at the wall as well.

v -disturbance equation

3 equations (5), (6) and (7), 3 unknowns u', v', p' !

Eliminate p' by taking $\frac{\partial}{\partial y}$ (5) - $\frac{\partial}{\partial x}$ (6)

By eliminating u' using eq. (7) we obtain an equation with only v' unknown

$$\left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right)\nabla^2 v' - U''\frac{\partial v}{\partial x} = Re^{-1}\nabla^4 v \qquad (8)$$

Equation (8) needs boundary conditions, 4th order equation $\Rightarrow$ 4 BCs needed.

Normal mode analysis

Analyze eq. (8) in terms of normal modes

$$v' = \hat{v}(y)e^{i(\alpha x - \omega t)}$$

where i is the imaginary number and

$\hat{v}(y)$ is a complex amplitude function

α is the wave number ($= 2\pi/\lambda$ where λ is the wave length)

ω is the angular frequency

We can also define the phase speed of the wave as $c = \omega/\alpha$

Normal mode analysis - spatial growth

Chose spatial or temporal approach, i.e. a disturbance that is growing in space (x) or time (t).

Spatial growth $\Rightarrow$ $\alpha = \alpha_r + i\alpha_i$ and ω is real

Temporal growth $\Rightarrow$ $\omega = \omega_r + i\omega_i$ and α is real

or $c = c_r + ic_i$

Why?

$$e^{i(\alpha x - \omega t)} = e^{i[(\alpha_r + i\alpha_i)x - \omega t]} = e^{i(\alpha_r - \omega t)}e^{-\alpha_i x}$$

$\Rightarrow$ $\alpha_i < 0$ exponentially growing disturbance

$\alpha_i > 0$ exponentially decaying disturbance

The Orr-Sommerfeld equation

Put the normal mode assumption $[e^{i\alpha(x-ct)}]$ into eq, (8)

$$\frac{\partial}{\partial t} \rightarrow -i\alpha c$$
$$\frac{\partial}{\partial x} \rightarrow i\alpha$$
$$\frac{\partial}{\partial y} \rightarrow \frac{d}{dy} = D$$

for instance $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} = -\alpha^2 + D^2$

This gives us the so called Orr-Sommerfeld (OS) equation

$$(U - c)(D^2 - \alpha^2)\hat{v} - U''\hat{v} = \frac{1}{i\alpha Re}(D^2 - \alpha^2)^2\hat{v}$$

Normal mode analysis - temporal growth

For the temporal approach, i.e. a disturbance that is growing time (t).

$$e^{i(\alpha x - \omega t)} = e^{i\alpha(x - ct)} = e^{i\alpha(x - c_r t)}e^{\alpha c_i t}$$

$\Rightarrow$ $c_i > 0$ exponentially growing disturbance

$c_i < 0$ exponentially decaying disturbance

The Rayleigh equation

Let us investigate the OS-eq. when $Re \rightarrow \infty$ $\Rightarrow$ Rayleigh eq.

$$(U - c)(D^2 - \alpha^2)\hat{v} - U''\hat{v} = 0$$

BC ? Only two BCs can be retained! $\hat{v}(0) = \hat{v}(h) = 0$

Rewrite :

$$(D^2 - \alpha^2)\hat{v} - \frac{U''}{(U - c)}\hat{v} = 0$$

Multiply with $\hat{v}^*$, the complex conjugate of $\hat{v}$ and integrate the eq. from $y = 0$ to $y = h$

$$\int_0^h \left[\hat{v}^*(D^2\hat{v} - \alpha^2\hat{v}) - \frac{U''}{(U - c)}\hat{v}\hat{v}^*\right] dy = 0$$

The Rayleigh equation (contd)

By using partial integration we get

$$\int_0^h \hat{v}^* D^2 \hat{v} dy = \underbrace{\{\hat{v}^* D\hat{v}\}_0^h}_{=0} - \int_0^h (D\hat{v}^*) D\hat{v} dy = -\int_0^h |D\hat{v}|^2 dy$$

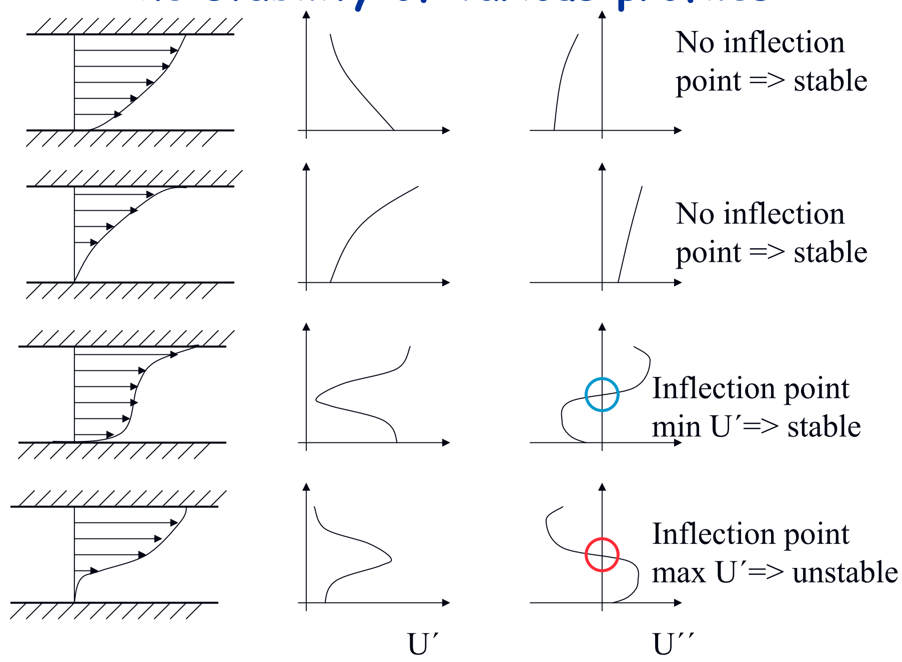
Using $c = c_r + ic_i$

$$\frac{1}{U-c} = \frac{1}{U-c_r-ic_i} = \frac{U-c_r+ic_i}{(U-c_r-ic_i)(U-c_r+ic_i)} = \frac{U-c_r+ic_i}{(U-c_r)^2+c_i^2}$$

we then can write

$$\int_0^h \left[|D\hat{v}|^2 + \alpha^2|\hat{v}|^2 + \frac{U''(U-c_r+ic_i)}{(U-c_r)^2+c_i^2}|\hat{v}|^2 \right] dy = 0$$

The stability of various profiles



The Rayleigh equation (contd.)

Taking the imaginary part of the equation

$$\int_0^h \left[\frac{U'' c_i}{(U-c_r)^2+c_i^2}|\hat{v}|^2 \right] dy = 0$$

or

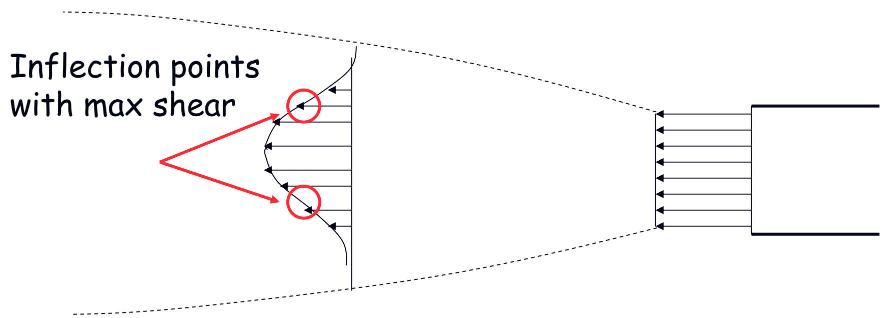
$$c_i \int_0^h \left[\frac{U''}{(U-c_r)^2+c_i^2}|\hat{v}|^2 \right] dy = 0$$

This means that U'' must change sign in the interval if $c_i \neq 0$, i.e. U has to have an inflection point in the interval. This is **Rayleighs inflection point criterion** !

Fjørtofts criterion says that for the inflection point to be unstable, the shear, i.e. U' has to have a maximum at the inflections point! (see Schmid & Henningson, page 21).

Inflectional instability of jet flows

Rayleighs stability criterion (1880) explains why jets and wakes are very unstable, they have inflectional mean velocity profiles!



Inflectional instability of jet

QuickTime™ and a decompressor are needed to see this picture.

Example: channel flow

Boundary conditions at both channel walls:
$\hat{v} = 0 \quad D\hat{v} = 0$

$\Rightarrow$ Trivial solution $\hat{v} = 0$

Other boundary conditions needed!

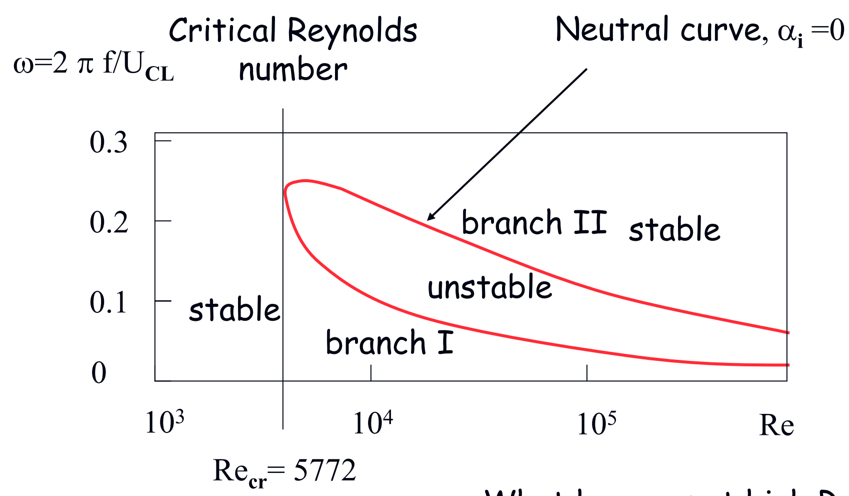
symmetric mode => $D\hat{v} = D^3\hat{v} = 0$ on CL

anti-symmetric mode => $\hat{v} = D^2\hat{v} = 0$ on CL

How to solve the OS-equation ?

The solution to the OS-equation can be seen as an eigenvalue problem.
Input data: Mean velocity profile, BC, Reynolds number, α (ω).
Output: Eigenfunction $\hat{v}(y)$, eigenvalue ω (α).
Solution method: Shooting method
Spectral method

Example: channel flow - symmetric mode



What happens at high Re ?

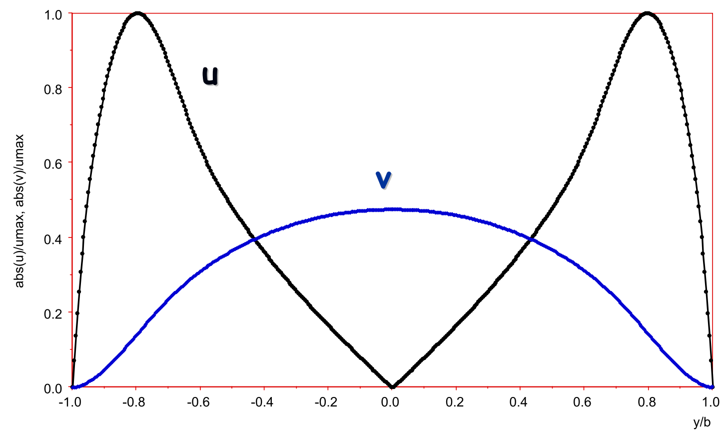
How do we verify the theory ?

Introduce a single frequency 2D wave with a vibrating ribbon (old method) or through a thin, long spanwise slit connected to a loudspeaker (current method).

Measure the development of the wave amplitude in the downstream direction. Check also the eigenfunction (phase and amplitude)!

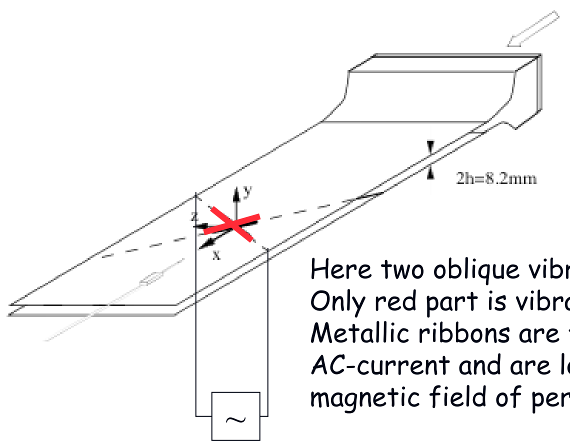
Amplitude functions - channel flow

Re=1600, ω=0.40



Experimental channel set-up

(P. Elofsson, PhD thesis 1998, KTH)



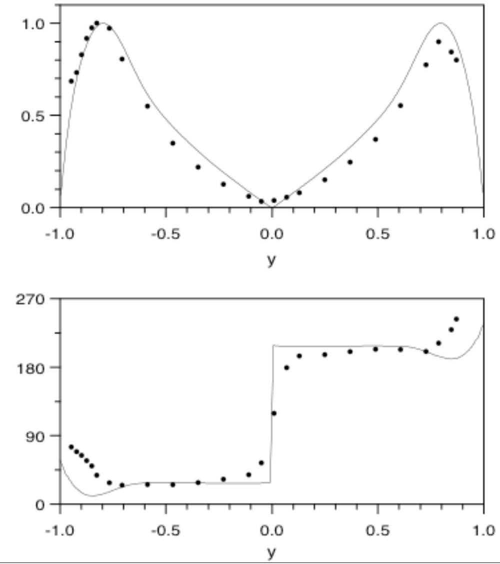
Here two oblique vibrating ribbons.
Only red part is vibrating.
Metallic ribbons are fed with
AC-current and are located in the
magnetic field of permanent magnets

Amplitude function for channel flow

(Re=1600, ω=0.42, x/b=40)

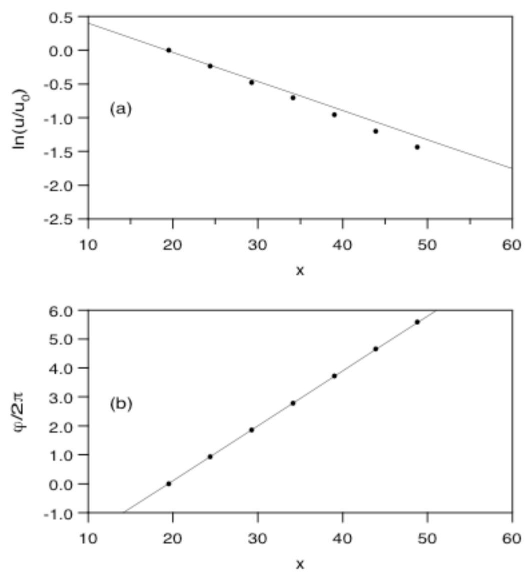
A/A_{max}

phase



Amplitude and phase development

(Re=1600, ω=0.42)



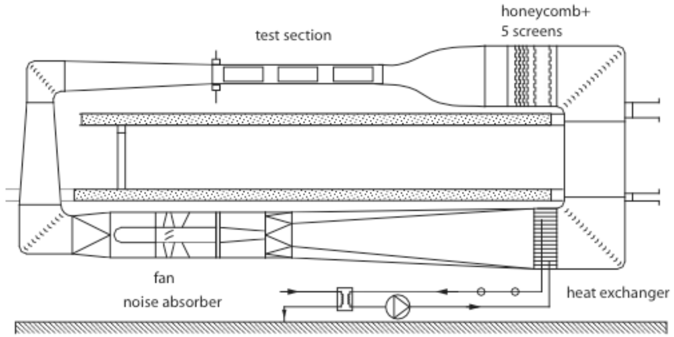
α_i=0.043 (theory)

α_i=0.048 (exp)

c=0.35 (theory)

c=0.33 (exp)

MTL wind tunnel for stability and transition research



- Low turbulence (<0.03%) and sound noise level
- Low vibration level
- Velocity and temperature stability at low velocities

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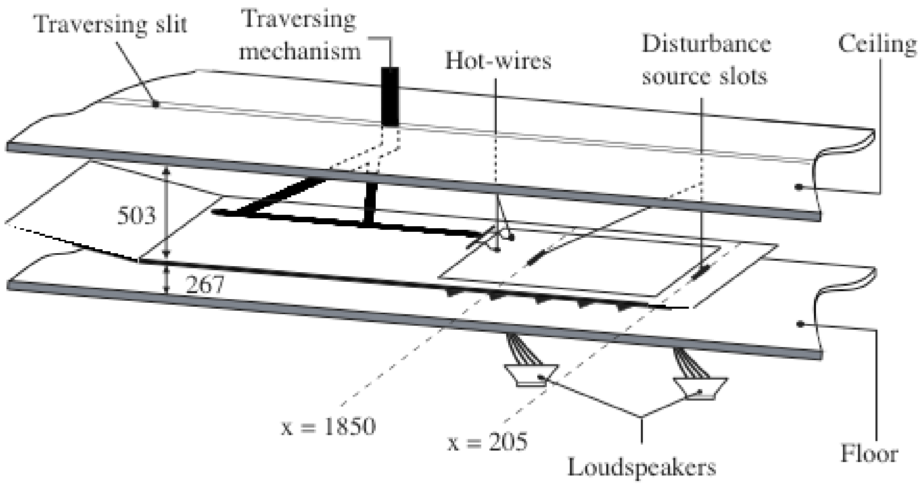
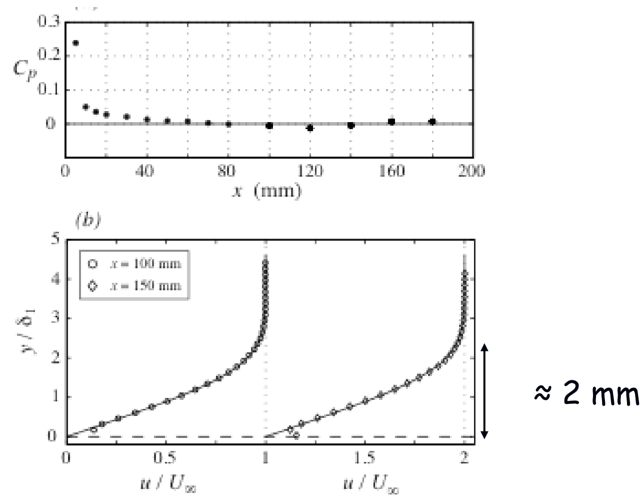
MTL test section looking upstream

Experimental set-up

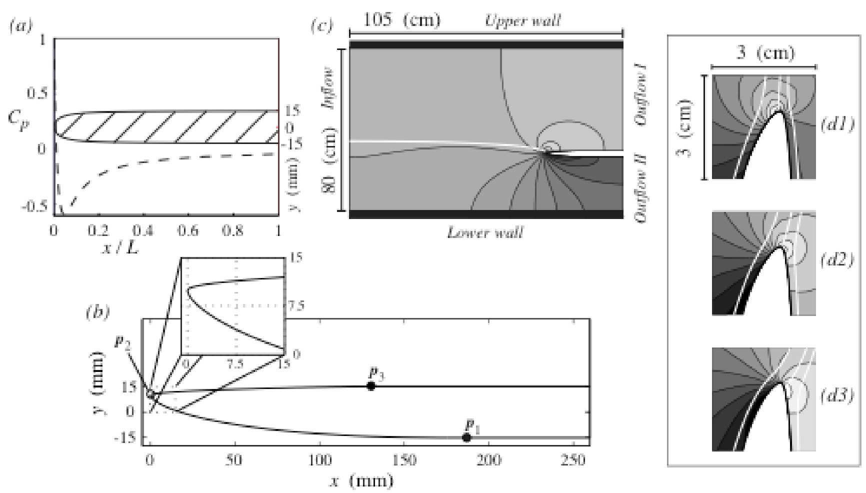
(J. Fransson Ph.D. Thesis 2003, KTH)



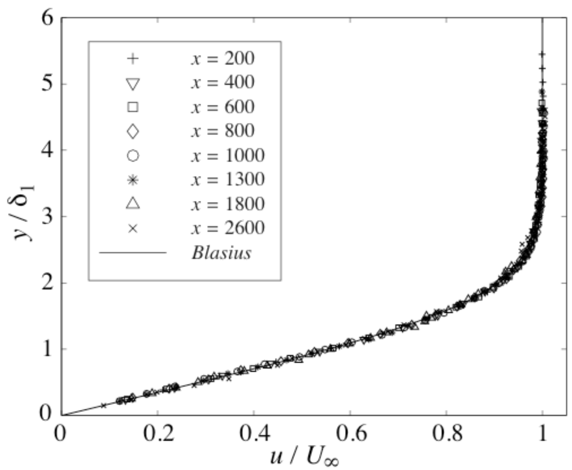
Pressure coefficient and velocity profiles near leading edge



Leading edge geometry



Experimental boundary layer profiles



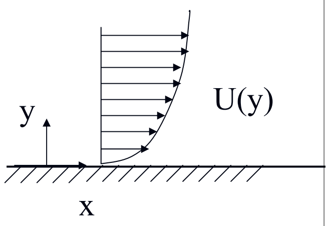
$\delta_1 = (\nu x / U_\infty)^{1/2}$

Boundary conditions for the Blasius boundary layer

Boundary conditions at the wall

$$v' = 0 \quad \text{at} \quad y = 0$$

$$\frac{\partial v'}{\partial y} = 0 \quad \text{at} \quad y = 0$$



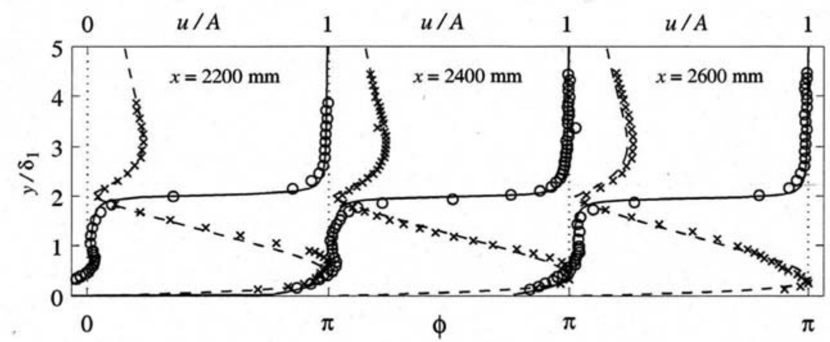
and boundary conditions in the free stream

$$v' \to 0 \quad \text{as} \quad y \to \infty$$

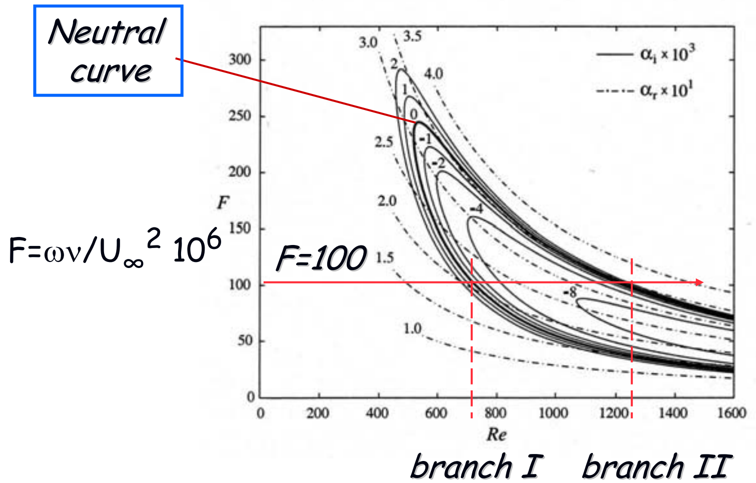
$$\frac{\partial v'}{\partial y} \to 0 \quad \text{as} \quad y \to \infty$$

Example of disturbance profiles

x: exp amplitude, - - - theory
o: exp phase, —— theory



Stability diagram for Blasius b.l.



Behaviour of disturbance profiles as y–>∞

$$(U-c)(D^2-\alpha^2)\hat{v} - U''\hat{v} = \frac{1}{i\alpha Re}(D^2-\alpha^2)^2\hat{v}$$

Solve the OS-equation in the free stream where $U = 1$ (i.e. U_∞) $\Rightarrow U'' = 0$

This gives the following form of the OS-equation:

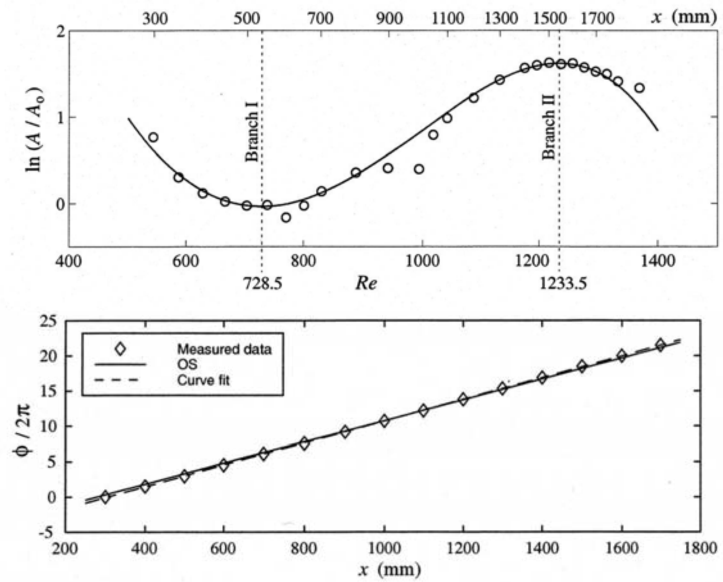
$$\{D^2 - [\alpha^2 + i\alpha Re(1-c)]\}(D^2-\alpha^2)\hat{v} = 0$$

Solution:

$$\hat{v} = \underbrace{Ae^{\alpha y}}_{y\to\infty \Rightarrow A=0} + Be^{-\alpha y} + C\underbrace{e^{\sqrt{\alpha^2+i\alpha Re(1-c)}y}}_{y\to\infty \Rightarrow C=0} + \underbrace{De^{-\sqrt{\alpha^2+i\alpha Re(1-c)}y}}_{\text{small if } Re \text{ is large}}$$

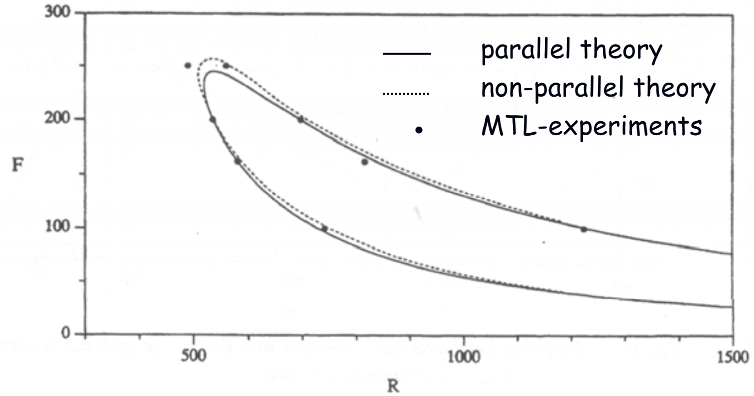
As $y \to \infty$ $\hat{v} \sim e^{-\alpha y}$ and $D\hat{v} \sim -\alpha e^{-\alpha y}$ which gives $|\hat{u}| = |\hat{v}| \sim e^{-\alpha y}$

Growth and phase development



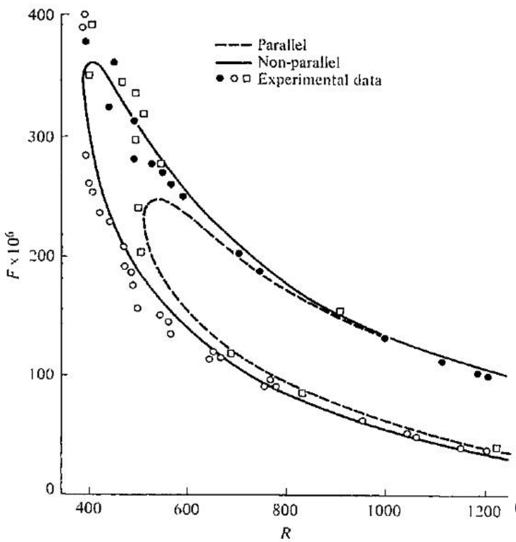
Neutral stability curve for Blasius b.l. with experimental points from MTL

(Klingmann et al. Eur. J. Mech/Fluids 1993)



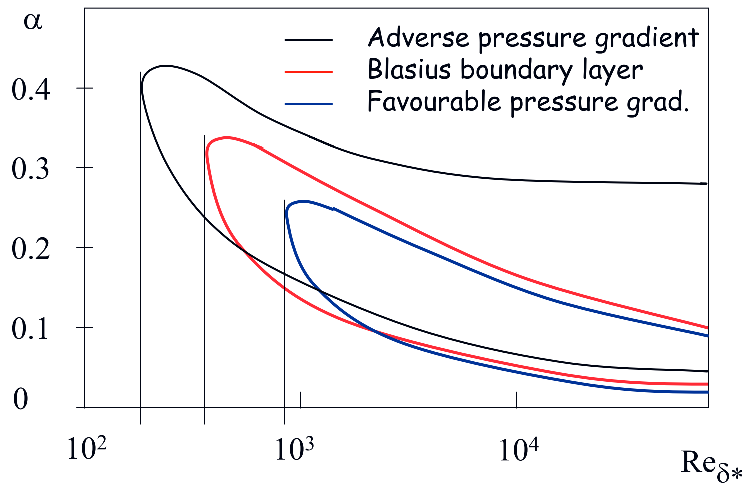
The influence of non-parallel effects (V≠0) are small ! Local analysis sufficient for Blasius b.l.

Early experimental data and theory



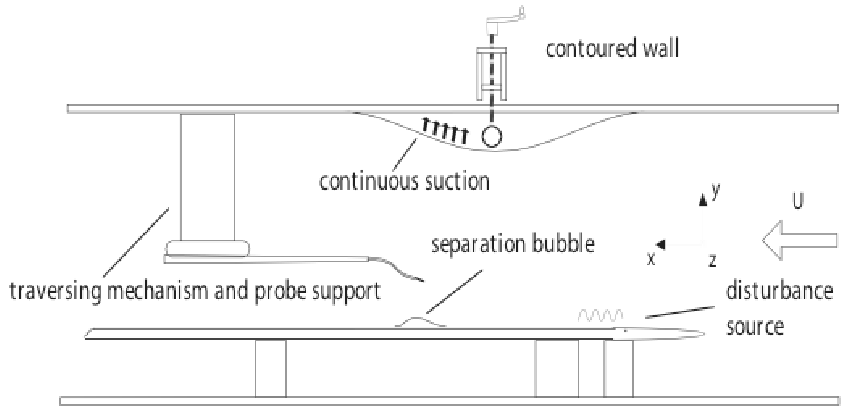
(Saric & Nayfeh, 1975)

Neutral stability curve for flat plate b.l. for various pressure gradients

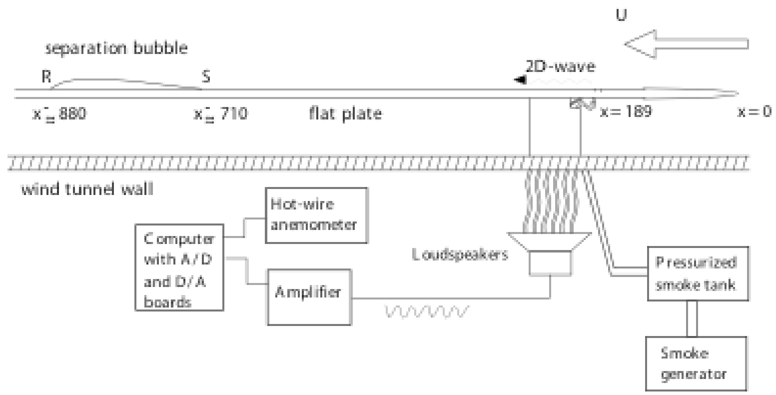


Setup for laminar separation bubble experiment

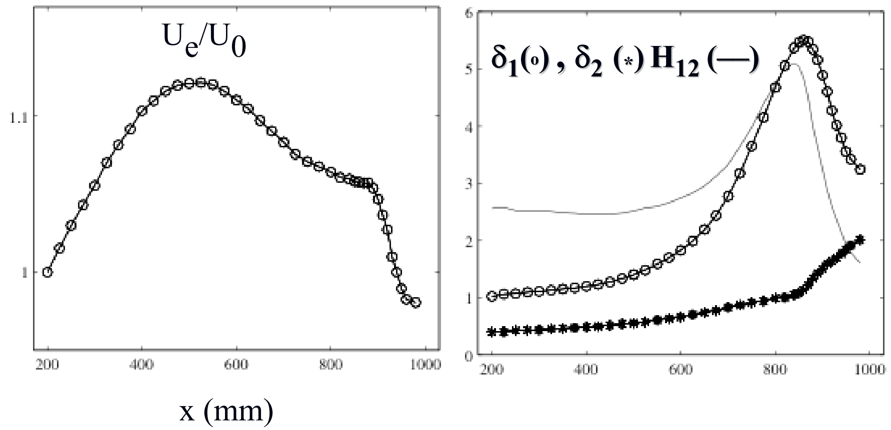
(C. Häggmark, Ph.D. thesis 2000, KTH)



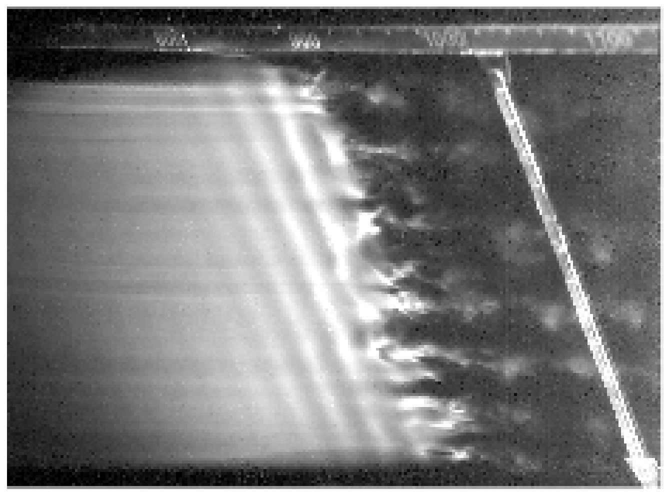
Experimental setup - laminar separation bubble



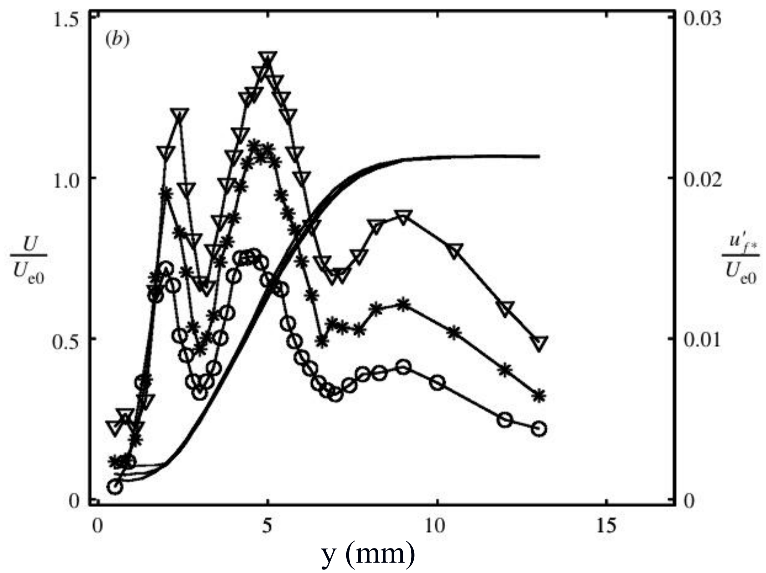
Boundary layer development



Flow visualization of forced instability waves



Disturbance velocity profiles



Lecture 1

1. Introduction to flow instability
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   - Orr-Sommerfeld theory (viscous)
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4. Transition prediction
5. Transient growth
6. Free stream turbulence

Disturbance growth

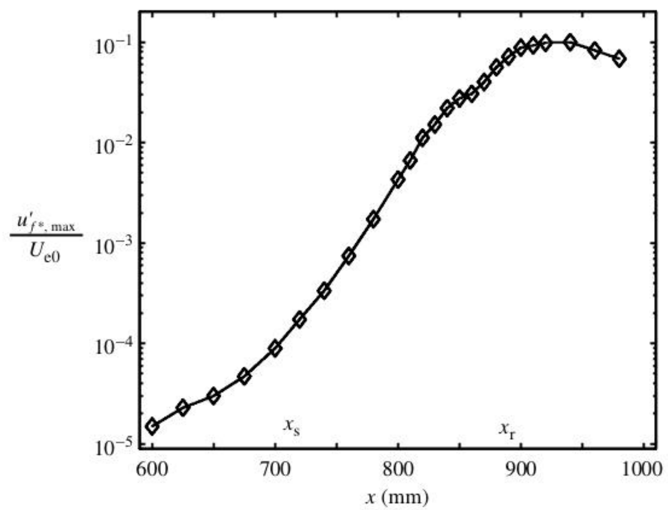
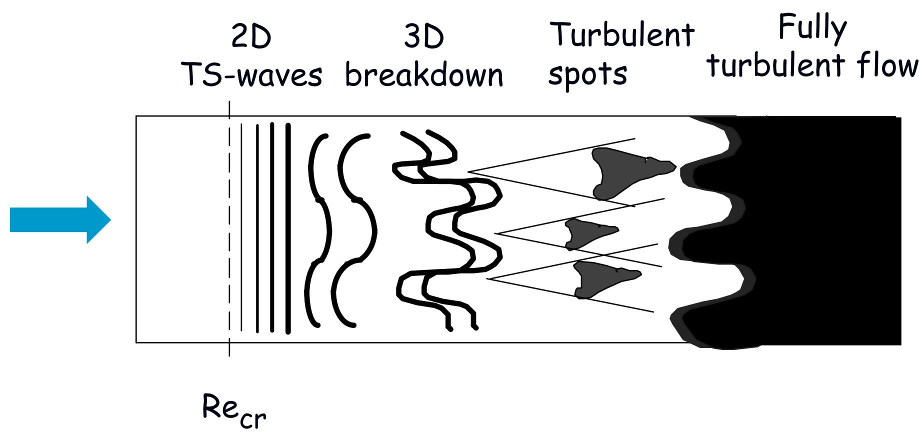
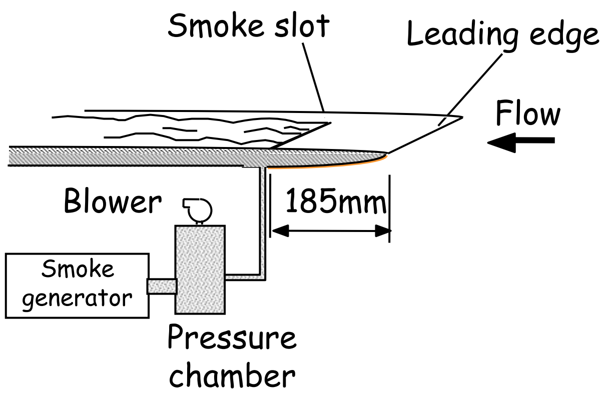


Figure 9. Amplification curve of forced two-dimensional instability wave in the separation bubble with $f^* = 83.3$ Hz.

Transition in boundary layer flows



Set-up for flow visualization



Transition prediction with the e^N-method

Idea: Assume that transition occurs where the linear eigenmodes (waves) have reached a certain amplification from the start of amplification. Describe this amplification as e^N.

Experiment shows that, in low disturbance environments, the onset and end of transition are about amplifications (N) of 8 and 11, respectively.

Transition is often said to be at N=9.

Smoke visualization of TS-waves and K - breakdown

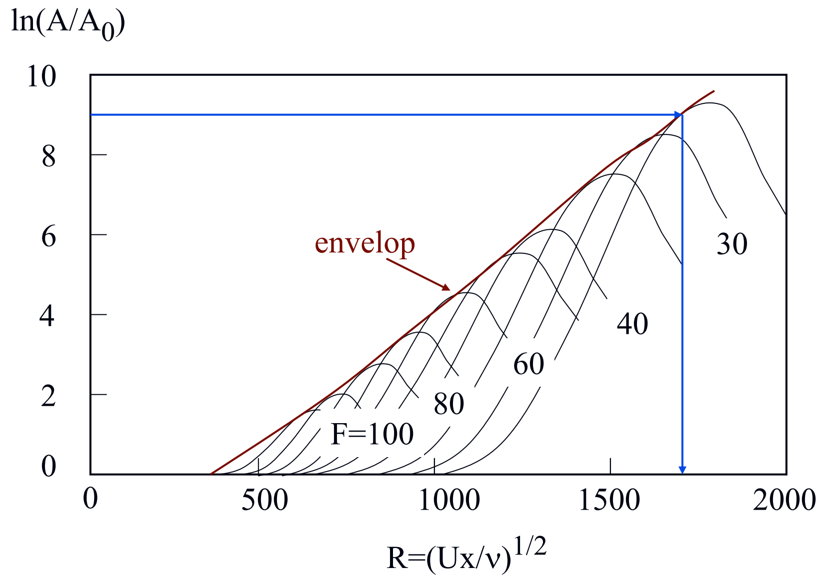
$F = 168$

$U_\infty = 7.5$ m/s

$A_{IN} = 0.8\%$

QuickTime™ and a DV - PAL decompressor are needed to see this picture.

Illustration of the e^N-method



By pass transition with Tu = 2.2 %

(Matsubara & Alfredsson, 2001)

Flow direction

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Transition prediction at high turbulence levels

Observation: At high turbulence levels (Tu) transition occurs earlier corresponding to a smaller N-factor.

Idea: Correlate the N-factor with Tu !

Experiments show that: N=8.4 - 2.4 Tu

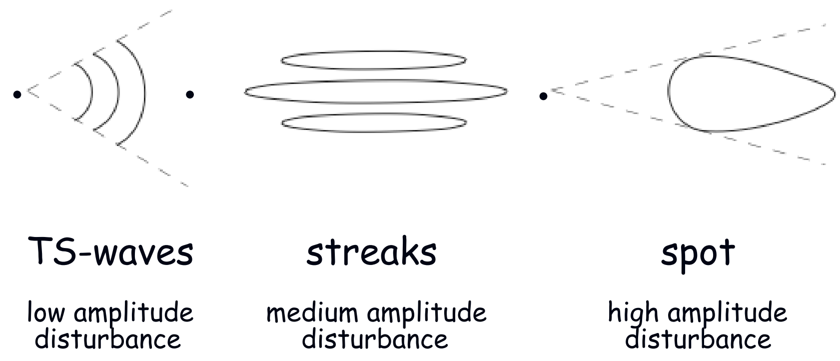
But of course it has nothing to do with the physics !

Failure of modal wave theory to predict the transitional Re

Flow case	*Re*	Re_{cr}	Re_{tr}
Blasius	$U_\infty \delta^*/\nu$	≈500	490
Channel	$U_{CL} b/\nu$	5772	1000
Pipe	$U_{CL} R/\nu$	∞	1760
Couette	$U_w b/\nu$	∞	360

Three different disturbances

(Grek, Kozlov & Ramazanov, 1984)



Two different instability mechanisms

Modal growth

- **Theory - inviscid**

Rayleigh (1880)

- **Theory - viscous**

Orr (1907)
Sommerfeld (1908)
Tollmien (1928)
Schlichting (1933)
Orzag (1970)
Fasel & Konzelmann (1990)

- **Experiments**

Schubauer & Skramstad (1948)
Klebanoff et al. (1962)
Klingmann et al. (1993)

Non-modal growth

- **Theory - inviscid**

Ellingsen & Palm (1975)
Landahl (1980)

- **Theory - viscous**

Gustavsson (1991)
Schmid & Henningson (1992)
Butler & Farell (1992)
Luchini (1996, 2000)

- **Experiments**

Grek, Kozlov & Ramazanov (1984)
Breuer & Haritonidis (1990)
Klingmann (1991)
Elofsson et al. (1998)

Two different instability mechanisms

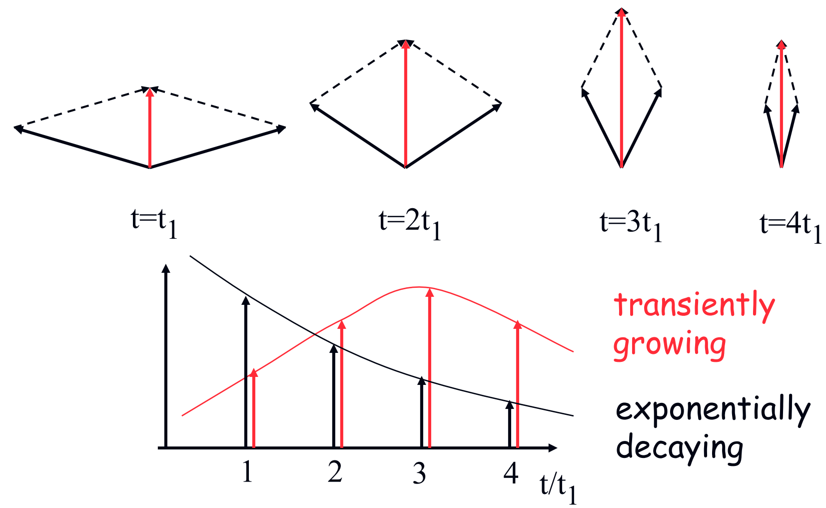
Modal growth

- Tollmien-Schlichting waves
- Exponential growth ~ e^x
- Amplitude ≈ 1- 2 %
- 3D deformation
- Formation of Λ-structures (staggered or aligned)
- Breakdown

Non-modal growth

- Streaky structures
- Algebraic growth ~ x^s
- Amplitude ≈ 10 %
- Localized high frequency wave packet
- Local breakdown to (turbulent spot)

Growth of decaying waves ?!

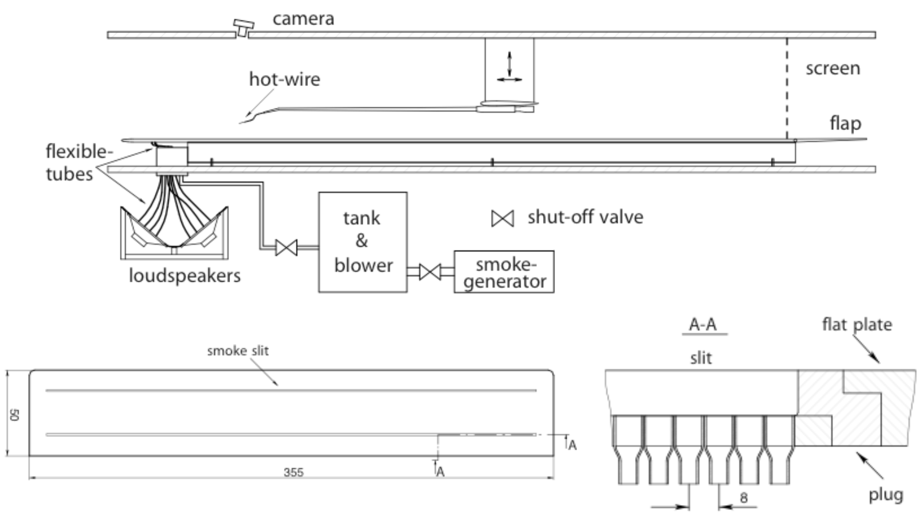


Main results from theoretical work on transient, algebraic or optimal growth

1. Elongated streaks most amplified (α = 0)
2. Disturbance energy grows proportional to x
3. Amplitude maximum in centre of boundary layer (compare TS-waves)
4. Spanwise scale close to boundary layer thickness

Experimental set-up

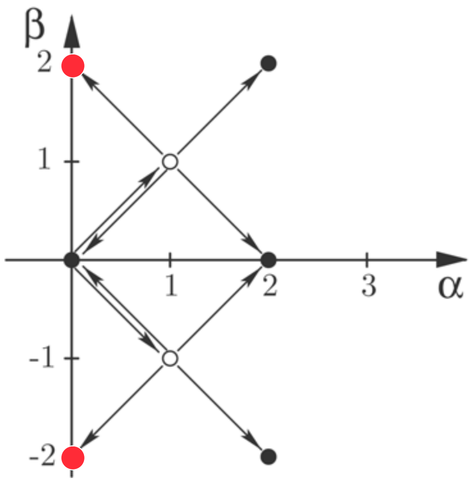
(P. Elofsson, PhD hesis 1998, KTH)



Principle of oblique transition

$\text{Wave}_1 \sim \exp[i(\alpha x + \beta z - \omega t)]$

$\text{Wave}_2 \sim \exp[i(\alpha x - \beta z - \omega t)]$

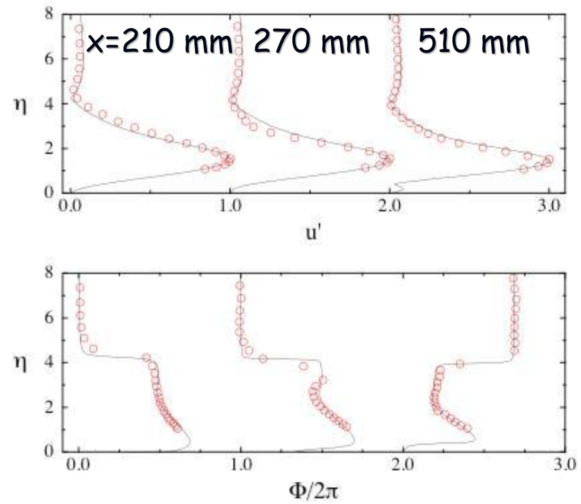


Eigenfunctions for one oblique wave - theory and experiments

U=8.2 m/s

F=106

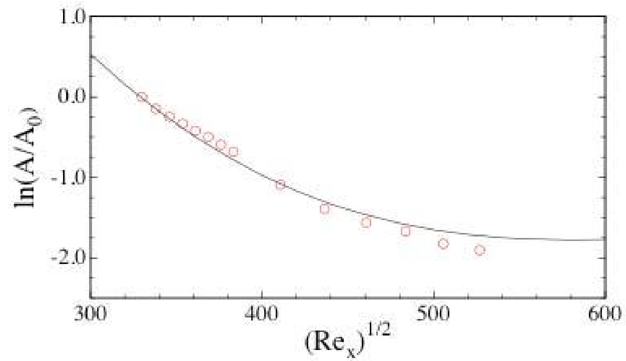
$\alpha/\beta \approx 1$



Deacy of oblique wave

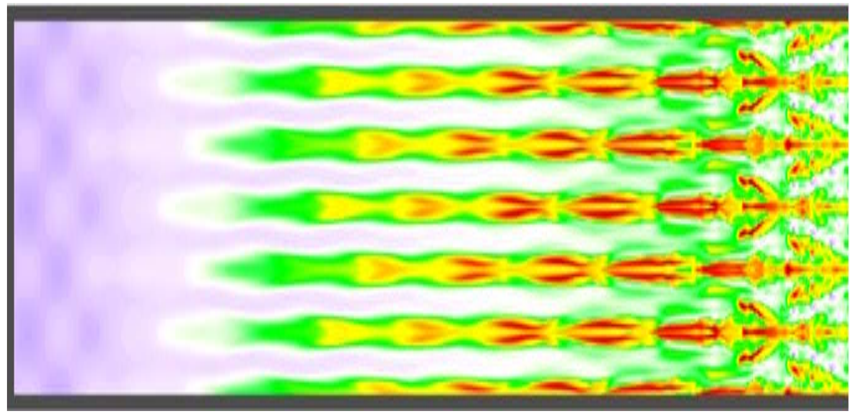
o : exp.

—— : theory

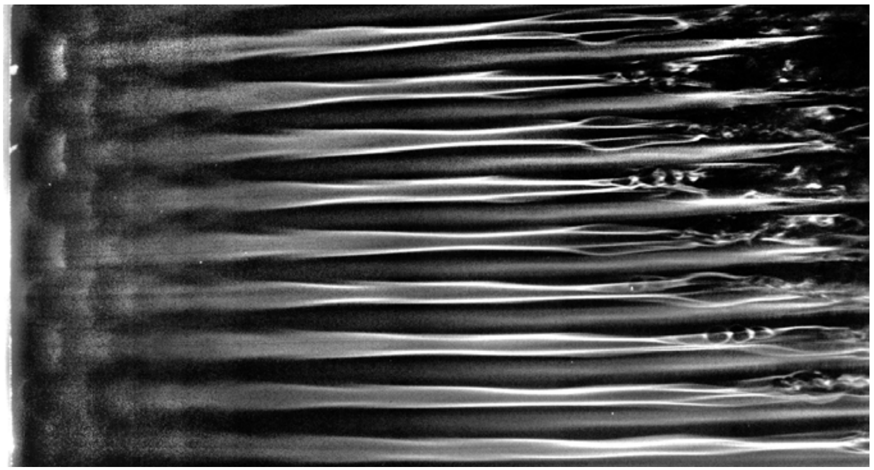


Oblique transition in BBL (DNS)

(S. Berlin, PhD thesis 1998, KTH)



Oblique transition in BBL (experiment)



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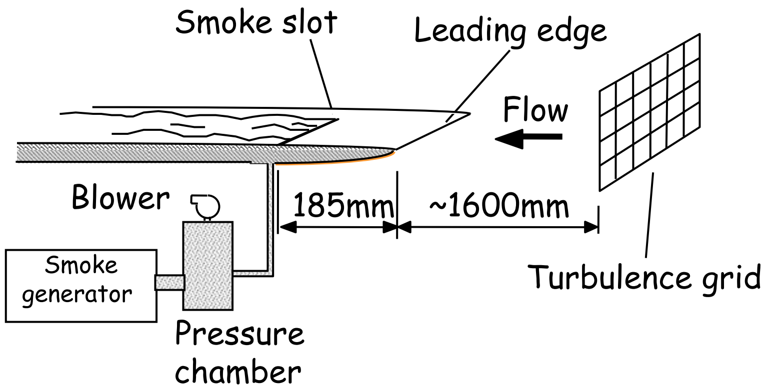
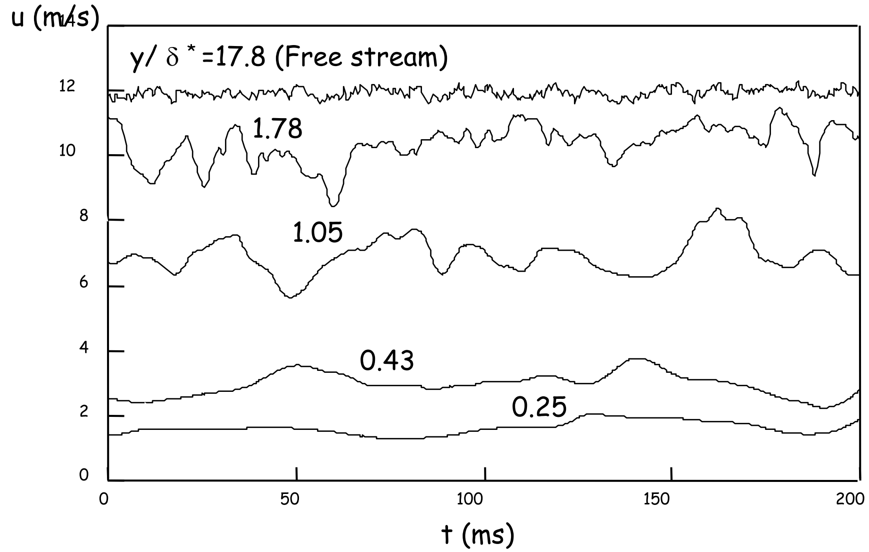
Set-up for flow visualization of FST induced by-pass transition



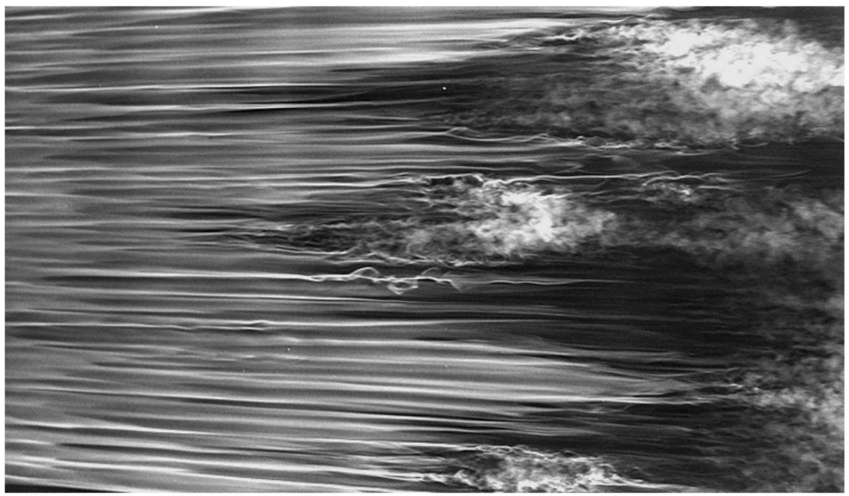
By pass transition - the linear wave mode scenario is by-passed

Streamwise velocity for varying y



Streaky structures and turbulent spots

(Matsubara & Alfredsson, JFM 2001)



Flow direction

FST induced transition- various stages

- Receptivity
- Streak formation and algebraic growth
- Secondary instability
- Turbulent spot formation
- Spot growth, merging and formation of a turbulent boundary layer

FST induced transition

Turbulent spot production

U_∞ = 3 m/s
Tu = 2.2%

FST induced transition

Tu = 5.3 %

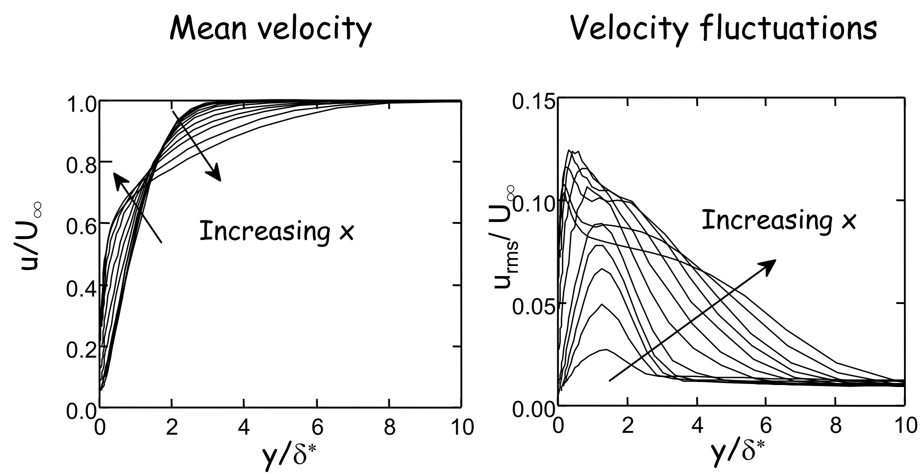
U_∞ = 2 m/s

FST induced transition

Secondary instability

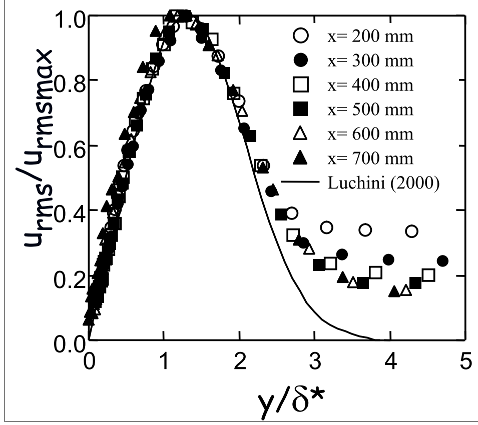
U_∞ = 3 m/s
Tu = 2.2%

Mean and fluctuating velocity development

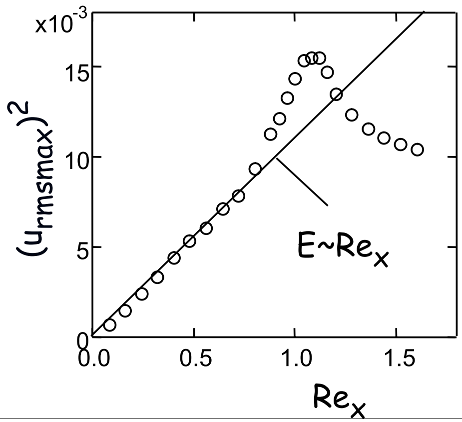


Amplitude development - experiments and spatial non-modal growth theory

Disturbance amplitude



Disturbance energy growth



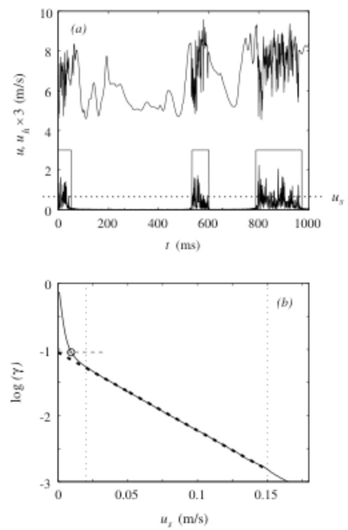
Intermittency detection scheme

(Fransson et al, JFM 2004)

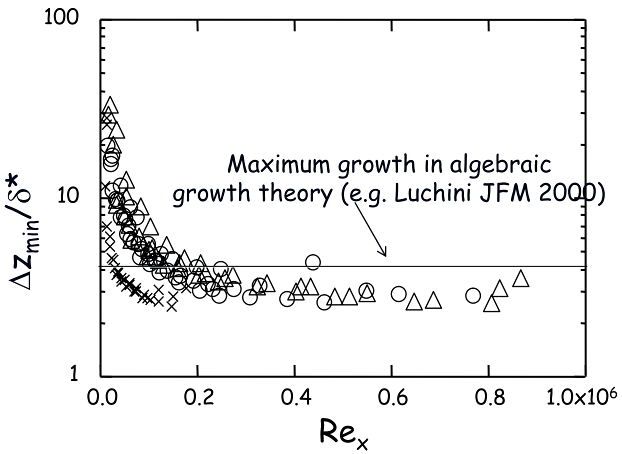
Intermittent velocity signal

Detection signal and detector function

Method to determine threshold value



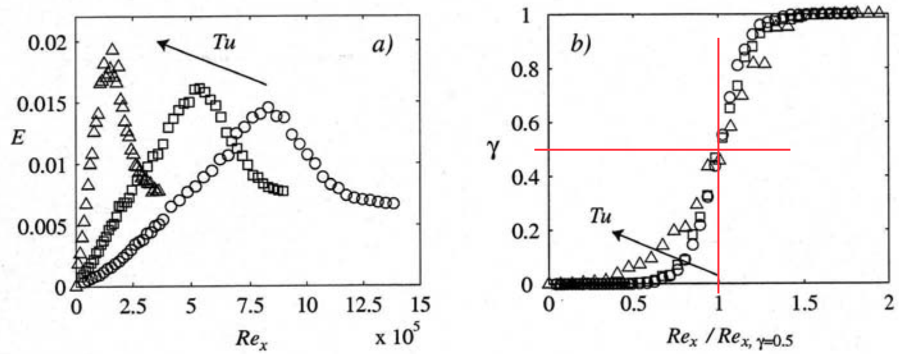
Spanwise distance to correlation minimum



Energy growth and intermittency

Energy growth

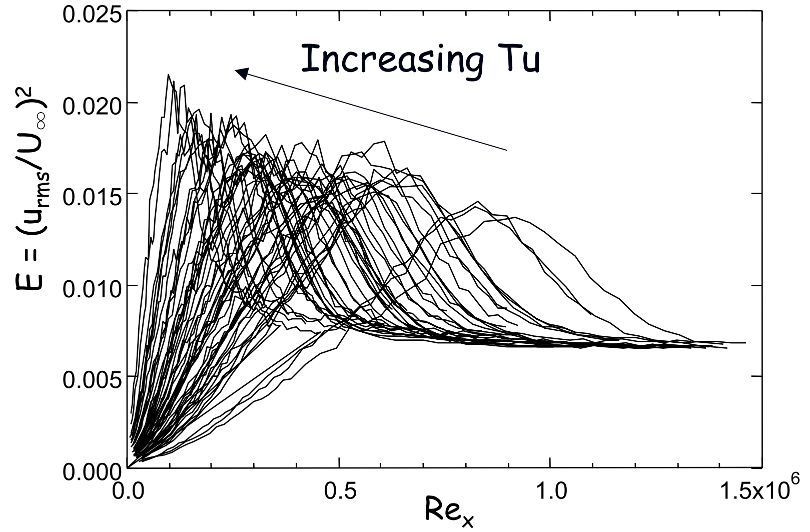
Intermittency function



Transition location where γ=0.5

Streamwise development of energy

$y=1.4\,\delta^*$



Transition prediction

(Andersson, Berggren & Henningson, Phys Fluids 1999)

Disturbances in boundary layer are assumed to be proportional to input (i.e. linear receptivity) and grow as

$$A(x) = C \cdot Tu \cdot Re_x^{1/2}$$

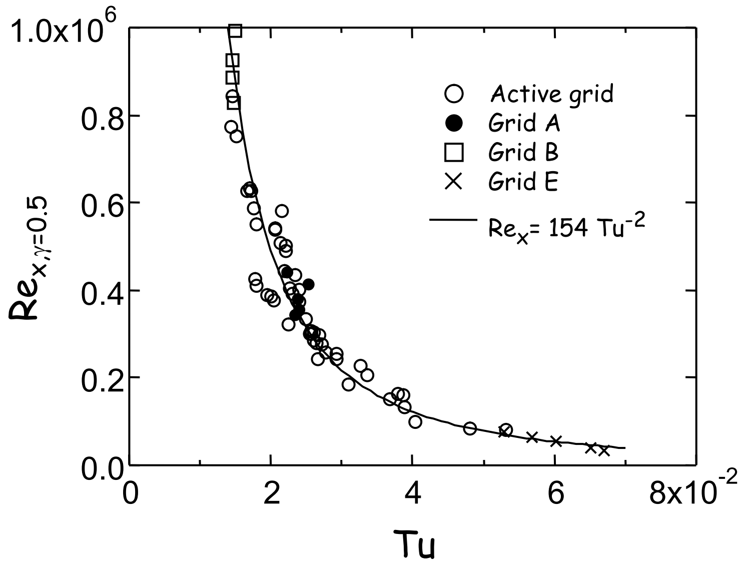
Assume that transition occurs at a certain amplitude (when secondary instability grows exponentially)

$$A_{tr} = C \cdot Tu \cdot Re_{tr}^{1/2}$$

Solve for Re_{tr}

$$Re_{tr} = (A_{tr}/C)^2 \cdot Tu^{-2}$$

Transition Reynolds Number

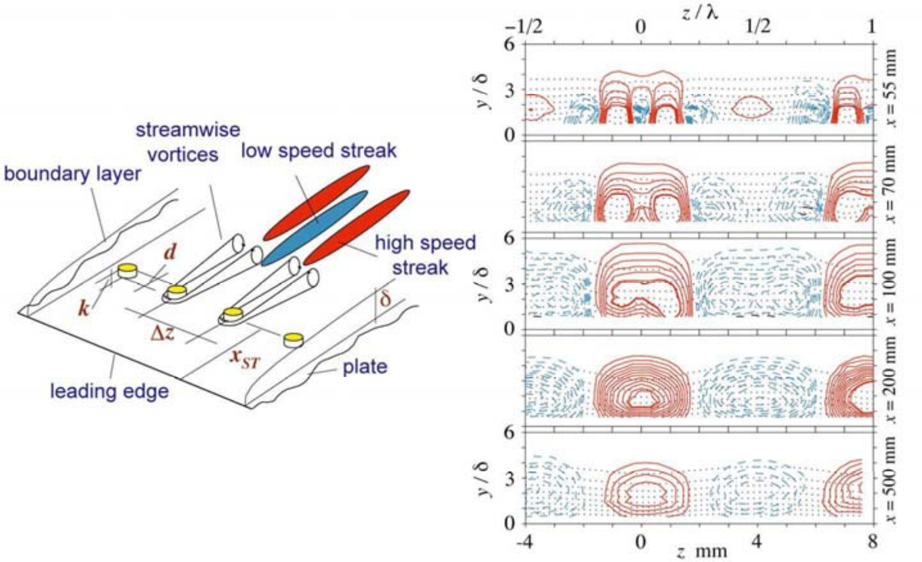


Passive control with roughness elements

Observation: TS-waves grow slower in FST affected boundary layer !?!

Use of streaks to control TS-waves ?

Streak generation with roughness
(Fransson et al. Phys Fluids 2004)



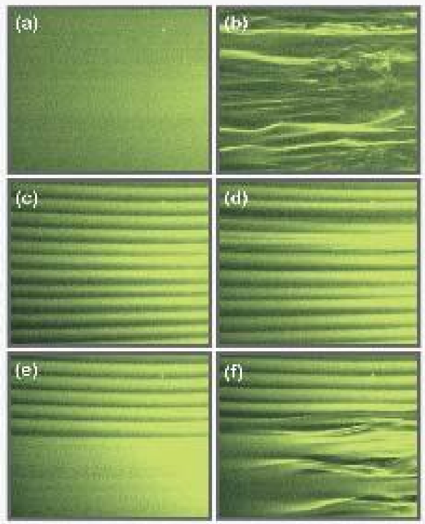
Flow visualization of streak control
(Fransson et al. 2006, Phys Rev Lett.)
without dist. with dist.

No streaks

Streaks

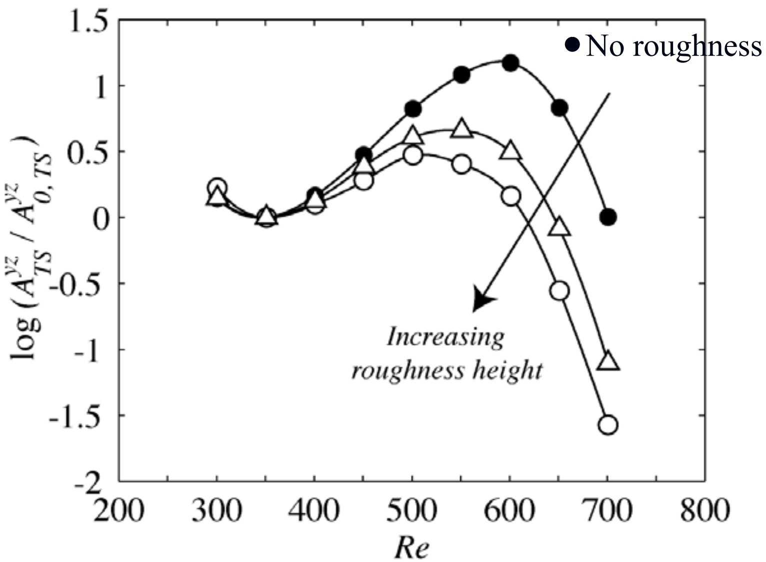
Streaks

No streaks



flow direction

Decrease of TS-wave growth



Conclusion and questions

- Transition in boundary layers can follow different routes an we have a fairly good understanding of the routes but still not the transitional Reynolds number !

- We do not know how the transition route affect the turbulent boundary layer ?

This is important for both experiments and simulations of boundary layer flows !