Most flows are unstable...

1. Intro-definitions
2. Rayleigh-Taylor
3. Waves (phase velocity-group velocity)
4. Rayleigh Plateau (destabilization through surface tension)
5. Rayleigh-Benard
6. Taylor Couette-Centrifugal instability
7. Taylor Couette exercise
8. Kelvin-Helmholtz
9. Inflection point theorem Rayleigh+Orr-Sommerfeld equation and Tollmien Schlichting waves+spatial instability and exercise on broken line shear layer
10. Transient growth
11. Frequency response
12. Spatio-temporal stability analyis
13. Nonlinear effects
14. Chaos

SPATIALLY DEVELOPING SHEAR FLOWS

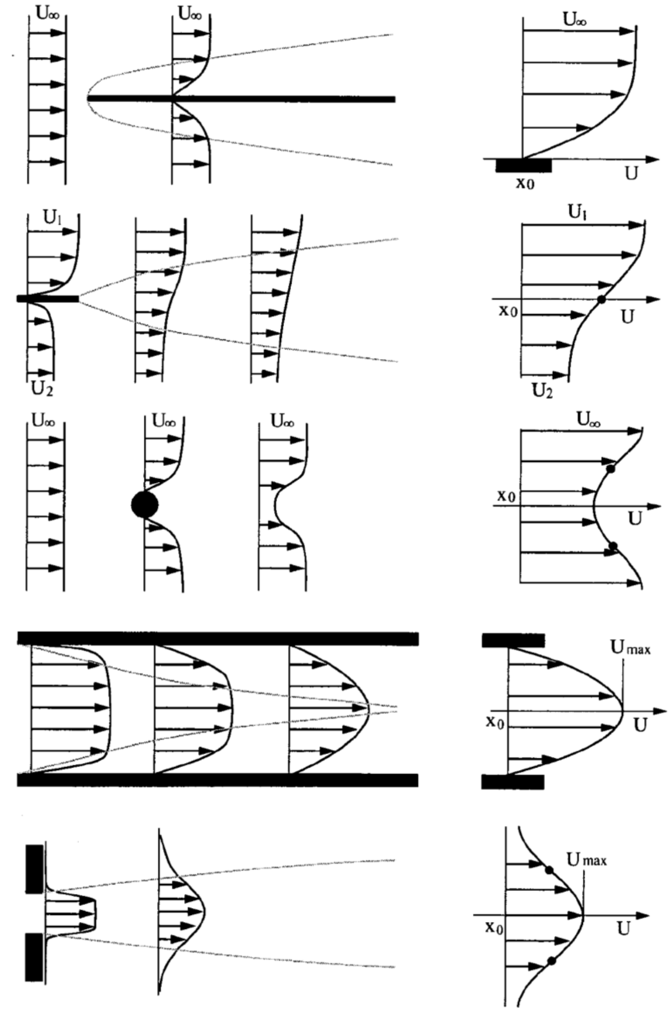
Flat plate boundary layer

Mixing layer

Cylinder wake

Plane channel flow

2D jet



2D PARALLEL FLOW CONCEPTS

Dispersion relation

2D vorticity equation

$$\left(\frac{\partial}{\partial t}+\frac{\partial\Psi}{\partial y}\frac{\partial}{\partial x}-\frac{\partial\Psi}{\partial x}\frac{\partial}{\partial y}\right)\nabla^2\Psi=\frac{1}{Re}\nabla^4\Psi$$

Basic flow + perturbation

$$\Psi(x,t)=\int U(y)dy+\psi(x,y,t)$$

Linear vorticity equation

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

Dispersion relation

$$D(k, \omega) = 0$$

Temporal approach:
k is real; ω is complex
Perturbation grow and
decay in time!

Spatial approach:
ω is real; k is complex
Perturbations grow and
decay in space!

Shear layer is inviscidly unstable!

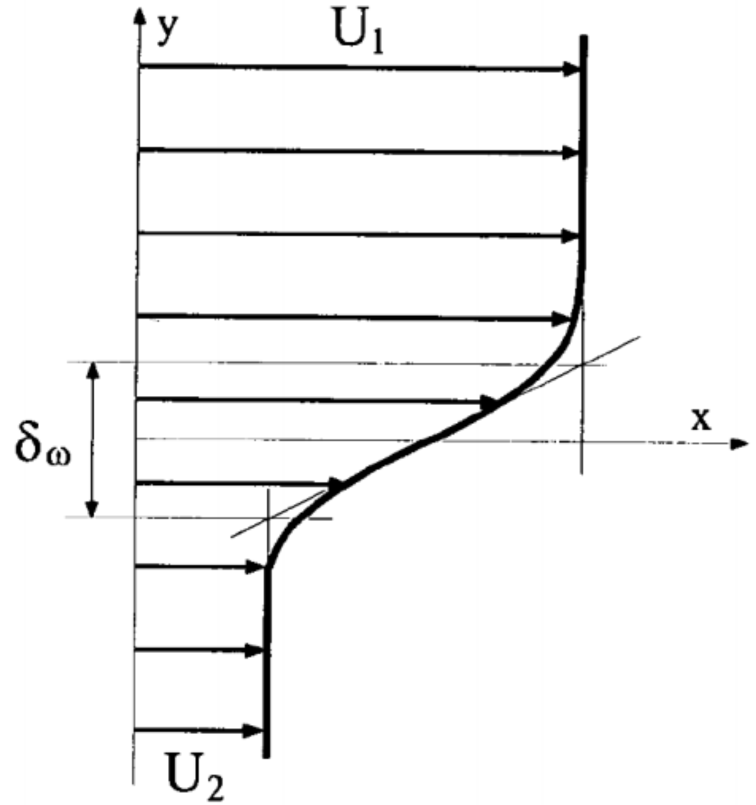
Hyperbolic tangent mixing layer

$$U(y) = \bar{U} + \frac{\Delta U}{2} \tanh\left(\frac{2y}{\delta_\omega}\right)$$

$$\delta_\omega(x) \equiv \frac{(U_1 - U_2)}{(dU/dy)_{\max}}$$

Velocity ratio

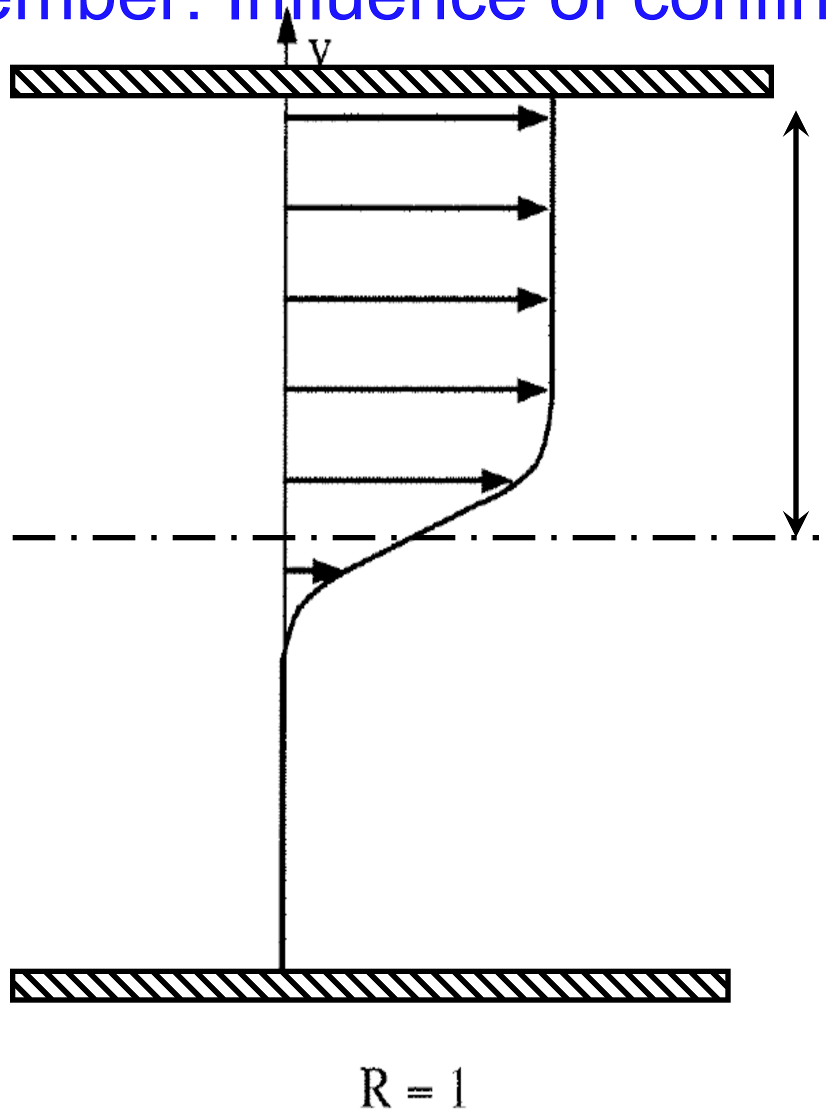
$$R \equiv \frac{U_1 - U_2}{U_1 + U_2} = \frac{\Delta U}{2\bar{U}}$$



Why?

Only a necessary condition for instability!

Remember: Influence of confinement



2D PARALLEL FLOW CONCEPTS

Hyperbolic tangent mixing layer

$$U(y;R) = 1 + R\tanh y$$

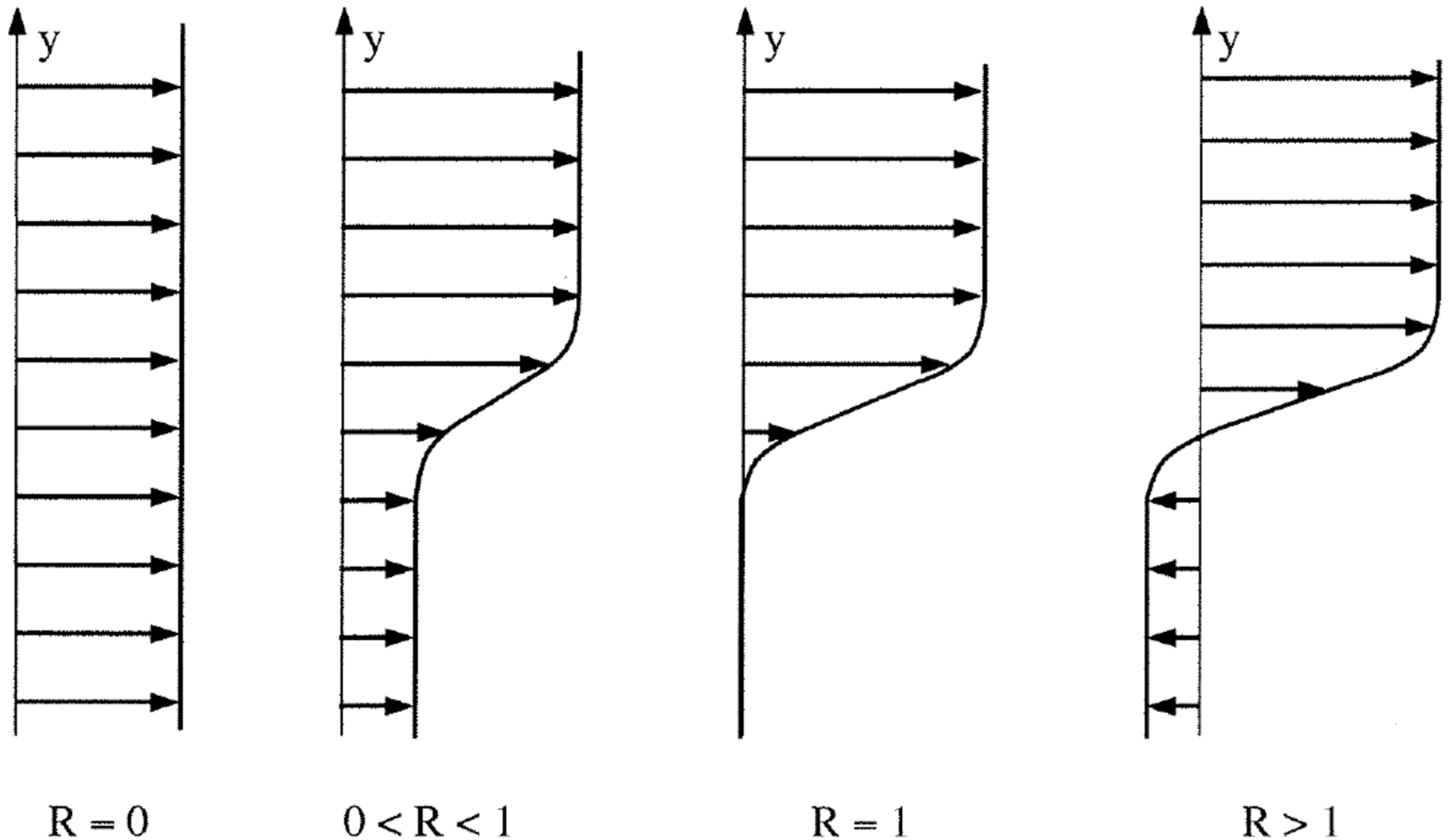
$$U_1(y) = \tanh\, y$$

Dispersion relation

$$\omega(k;R) = k + R\,\omega_1(k)$$

PARALLEL FLOW CONCEPTS

Effect of velocity ratio



2D PARALLEL FLOW CONCEPTS

Hyperbolic tangent mixing layer

Temporal approach

$$\omega_1(k) = i\,\omega_{1,i}(k)$$

$$\omega_i(k;R) = R\,\omega_{1,i}(k)$$

$$c_r = \omega_r/k = 1$$

Temporal approach: k is real; ω is complex

2D PARALLEL FLOW CONCEPTS
Hyperbolic tangent mixing layer

Spatial approach

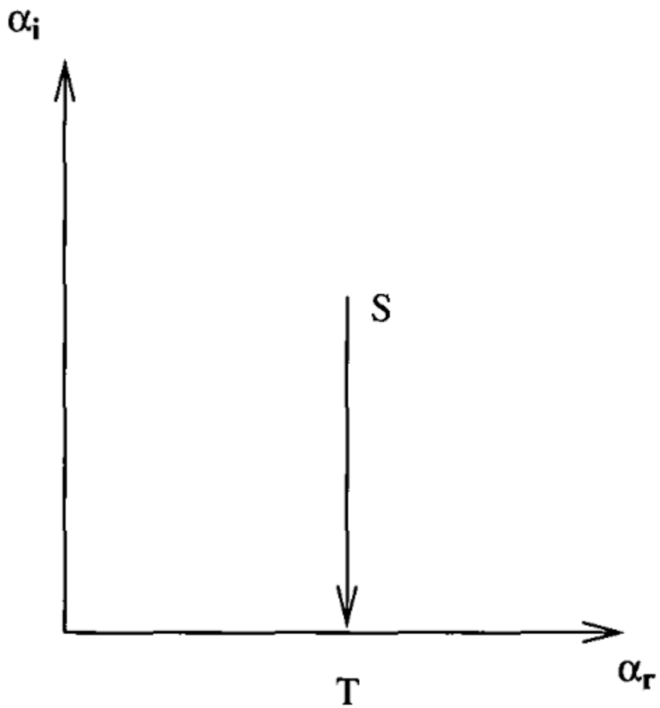
$$k + R\,\omega_1(k) = \omega$$

$$R \ll 1$$

$$\boxed{-k_i(\omega, R) \sim R\,\omega_{1,i}(\omega)}$$

Gaster transformation

Gaster transformation



$$\omega_i|_S^T = \int_S^T \frac{\partial \omega_r}{\partial \alpha_r} \mathrm{d}\alpha_i$$

$$\omega_i(T) = \int_S^0 \frac{\partial \omega_r}{\partial \alpha_r} \mathrm{d}\alpha_i \,,$$

$$\omega_i(T) = -\int_0^S \frac{\partial \omega_r}{\partial \alpha_r} \mathrm{d}\alpha_i \,,$$

$$\approx -\left.\frac{\partial \omega_r}{\partial \alpha_r}\right|_{\alpha_i^*} \alpha_i(S),$$

$$\frac{\partial \omega_r}{\partial \alpha_r} = \frac{\partial \omega_i}{\partial \alpha_i}, \quad \frac{\partial \omega_r}{\partial \alpha_i} = -\frac{\partial \omega_i}{\partial \alpha_r}.$$

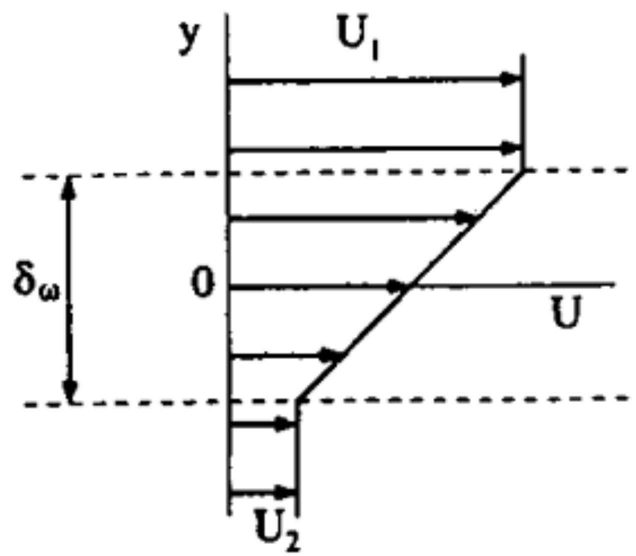
$$c_g = \frac{\partial \omega_r}{\partial \alpha_r}, \qquad \omega_i(T) = c_g \{-\alpha_i(S)\} \,.$$

2D PARALLEL FLOW CONCEPTS

Broken-line profile mixing layer

$$U(y) = \begin{cases} U_1\,, & y > \delta_\omega/2 \\ (U_1+U_2)/2 + (U_1-U_2)y/\delta_\omega\,, & |y| < \delta_\omega/2 \\ U_2\,, & y < -\delta_\omega/2 \end{cases}$$

$$\phi'' - k^2\phi = 0$$



$$\phi_1(y) = A_1\,\mathrm{e}^{-ky}, \quad y > \delta_\omega/2\,,$$
$$\phi_2(y) = B_2\,\mathrm{e}^{ky}, \quad y < -\delta_\omega/2\,,$$
$$\phi_0(y) = A_0\,\mathrm{e}^{-ky} + B_0\,\mathrm{e}^{ky}. \quad |y| < \delta_\omega/2$$

2D PARALLEL FLOW CONCEPTS

Broken-line profile mixing layer

$$
\begin{aligned}
A_1\,e^{-k\delta_\omega/2} &= A_0\,e^{-k\delta_\omega/2} + B_0\,e^{k\delta_\omega/2}\,, \\
B_2\,e^{-k\delta_\omega/2} &= A_0\,e^{k\delta_\omega/2} + B_0\,e^{-k\delta_\omega/2}\,, \\
-k(U_1 - c)A_1\,e^{-k\delta_\omega/2} &= k(U_1 - c)(-A_0\,e^{-k\delta_\omega/2} + B_0\,e^{k\delta_\omega/2}) \\
&\quad - \frac{\Delta U}{\delta_\omega}(A_0\,e^{-k\delta_\omega/2} + B_0\,e^{k\delta_\omega/2})\,, \\
k(U_2 - c)B_2\,e^{-k\delta_\omega/2} &= k(U_2 - c)(-A_0\,e^{k\delta_\omega/2} + B_0\,e^{-k\delta_\omega/2}) \\
&\quad - \frac{\Delta U}{\delta_\omega}(A_0\,e^{k\delta_\omega/2} + B_0\,e^{-k\delta_\omega/2})\,.
\end{aligned}
$$

2D PARALLEL FLOW CONCEPTS

Broken-line profile mixing layer

$$-\frac{\Delta U}{\delta_\omega} A_0\, e^{-k\delta_\omega/2} + \left[2k(U_1 - c) - \frac{\Delta U}{\delta_\omega}\right] B_0\, e^{k\delta_\omega/2} = 0$$

$$\left[2k(U_2 - c) + \frac{\Delta U}{\delta_\omega}\right] A_0\, e^{k\delta_\omega/2} + \frac{\Delta U}{\delta_\omega} B_0\, e^{-k\delta_\omega/2} = 0$$

2D PARALLEL FLOW CONCEPTS

Broken-line profile mixing layer

$$4(k\delta_\omega)^2(c-\bar{U})^2 - \left[(k\delta_\omega - 1)^2 - \mathrm{e}^{-2k\delta_\omega}\right]\Delta U^2 = 0$$

$$k\delta_\omega \mapsto 2k,\; c/\bar{U} \mapsto c$$

$$4k^2(c-1)^2 - R^2\left[(2k-1)^2 - \mathrm{e}^{-4k}\right] = 0$$

$$\boxed{c \equiv \frac{\omega}{k} = 1 \pm \frac{R}{2k}\left[(2k-1)^2 - \mathrm{e}^{-4k}\right]^{1/2}}$$

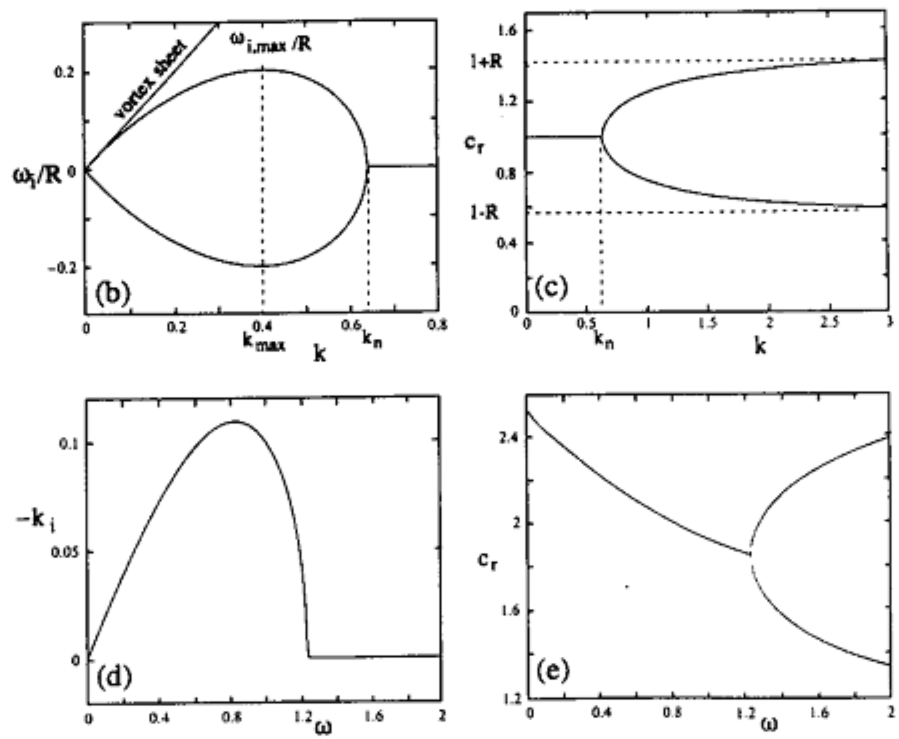
2D PARALLEL FLOW CONCEPTS

Broken-line profile mixing layer

Temporal approach

$$2k_n - 1 = e^{-2k_n}$$

Spatial approach
R = 0.5

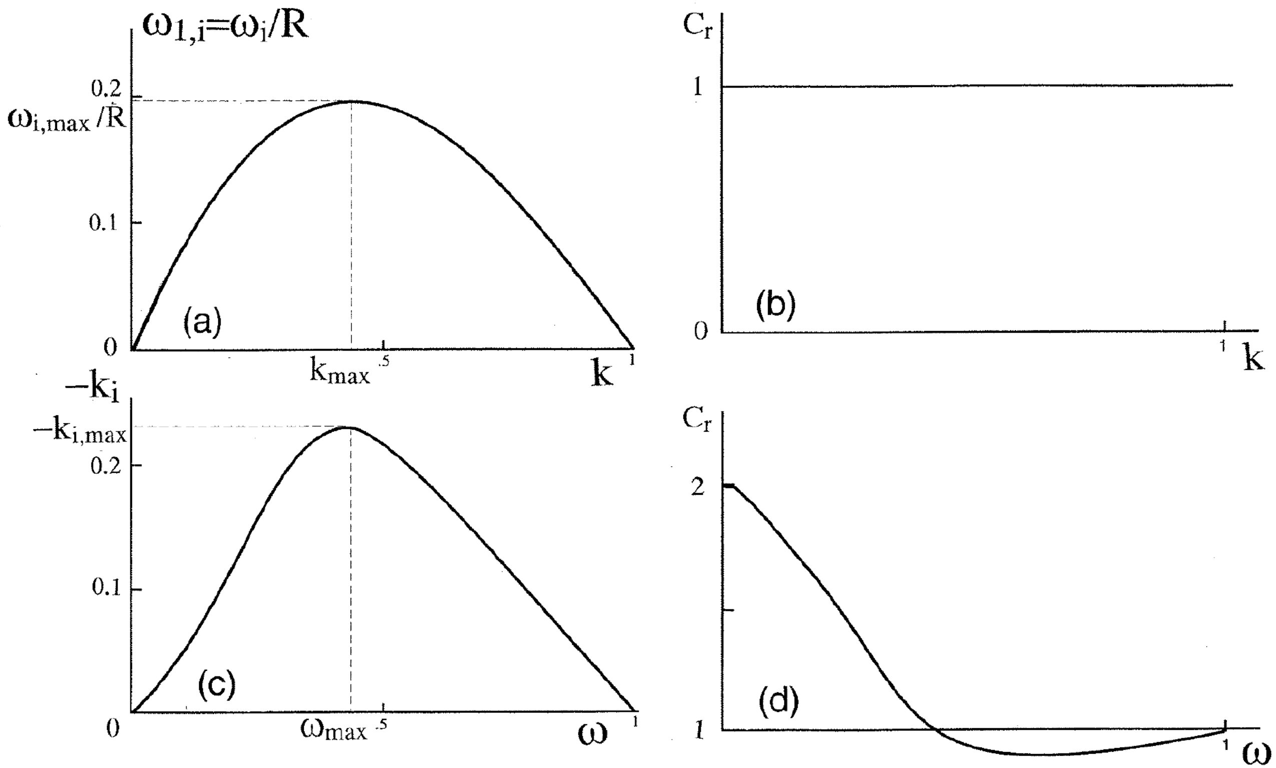


2D PARALLEL FLOW CONCEPTS

Hyperbolic tangent mixing layer

Temporal

Spatial



Michalke (1964, 65)

Solving a spatial instability problem
ex: Rayleigh equation

Back to temporal stability analysis!
How to solve Rayleigh equation for real k and complex ω?

We fix k, we need to find all ω and ψ such that

$$\boxed{\begin{gathered} k\left(U\left(\frac{d^2}{dy^2}-k^2\right)-U''(y)\right)\psi = \omega\left(\frac{d^2}{dy^2}-k^2\right)\psi \\ \psi(-L)=\psi(L)=0 \end{gathered}}$$

Formally,

$$\boxed{\mathcal{A}\psi = c\,\mathcal{E}\psi} \qquad c=\omega/k$$

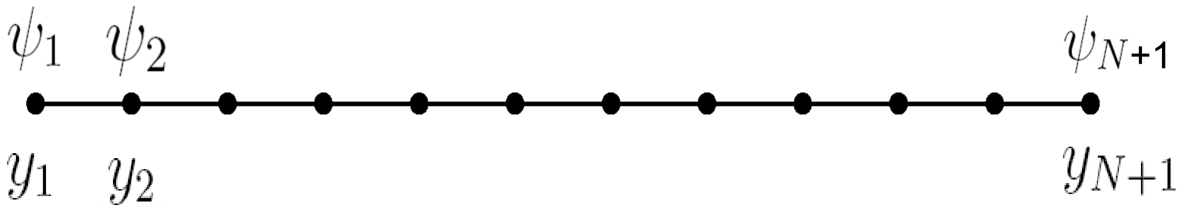
Discretize

$$\boxed{\mathbf{A}\Psi = c\mathbf{E}\Psi}$$

Generalized eigenvalue problem

How to solve Rayleigh equation for real k and complex ω?

Finite differences of order 1



$$\Psi = \begin{pmatrix} \psi(y_1) \\ \psi(y_2) \\ \vdots \\ \psi(y_N) \\ \psi(y_{N+1}) \end{pmatrix} = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \vdots \\ \psi_N \\ \psi_{N+1} \end{pmatrix} \qquad \Psi'' = \begin{pmatrix} \psi''(y_1) \\ \psi''(y_2) \\ \vdots \\ \psi''(y_N) \\ \psi''(y_{N+1}) \end{pmatrix}$$

How to solve Rayleigh equation for real k and complex ω?

Finite differences

$$
\begin{pmatrix} \psi_2'' \\ \psi_3'' \\ \psi_4'' \\ \vdots \\ \psi_{N-3}'' \\ \psi_{N-2}'' \\ \psi_{N-1}'' \end{pmatrix} = \begin{pmatrix} -2 & 1 & 0 & \dots & \dots & \dots & 0 \\ 1 & -2 & 1 & 0 & \dots & \dots & 0 \\ 0 & 1 & -2 & 1 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & 1 & -2 & 1 & 0 \\ 0 & \dots & \dots & 0 & 1 & -2 & 1 \\ 0 & \dots & \dots & \dots & 0 & 1 & -2 \end{pmatrix} \begin{pmatrix} \psi_2 \\ \psi_3 \\ \psi_4 \\ \vdots \\ \psi_{N-3} \\ \psi_{N-2} \\ \psi_{N-1} \end{pmatrix}
$$

Sparse matrix but low order!

How to solve Rayleigh equation for complex k and real ω?

We fix ω, we need to find all k and ψ such that

$$k\left(U\left(\frac{d^2}{dy^2}-k^2\right)-U''(y)\right)\psi = \omega\left(\frac{d^2}{dy^2}-k^2\right)\psi$$

$$\psi(-L)=\psi(L)=0$$

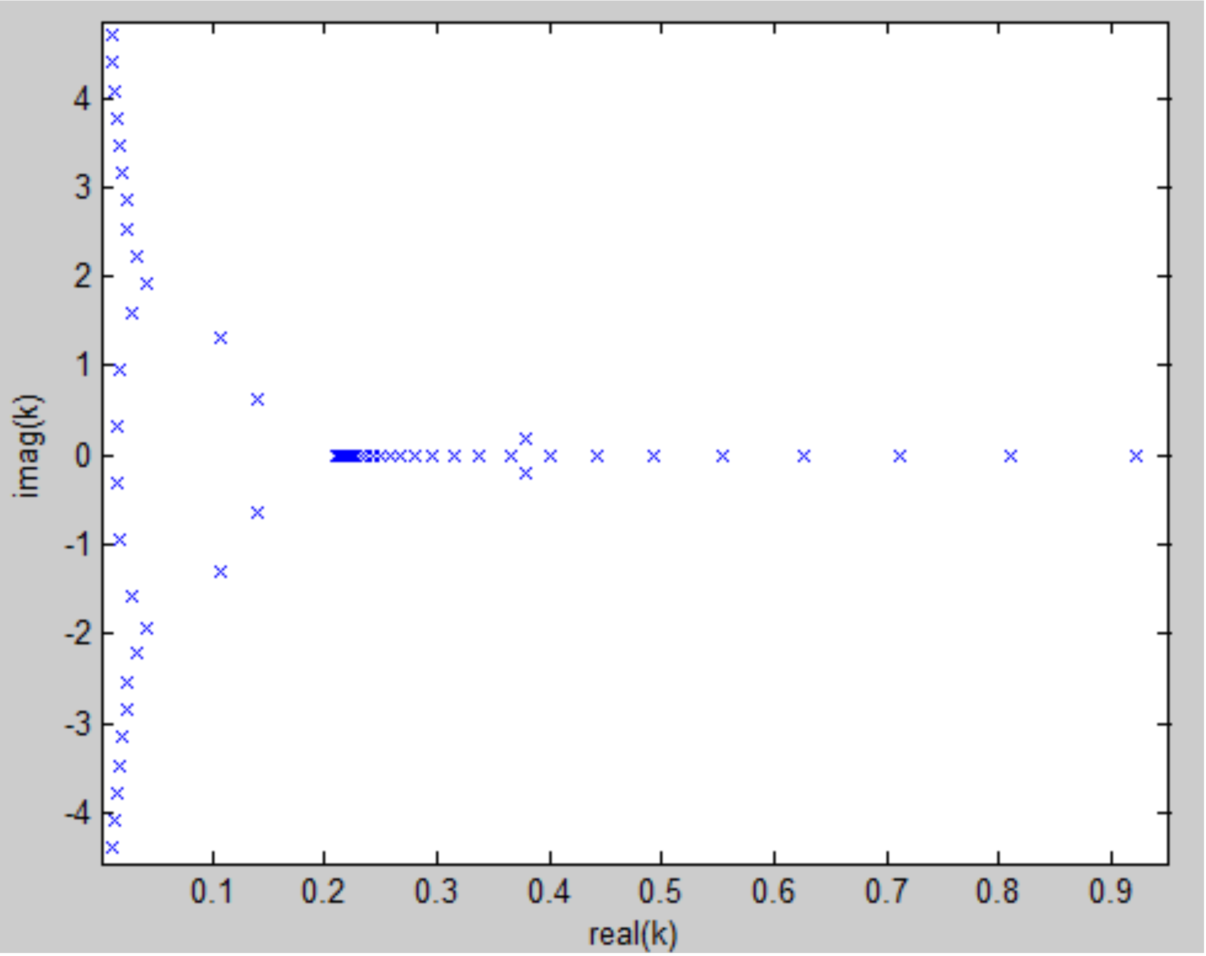
Formally,

$$\boxed{(A_0(\omega,y)+kA_1(\omega,y)+k^2A_2(\omega,y)+k^3A_3(\omega,y))\quad \psi = 0}$$

Polynomial eigenvalue problem

Many more eigenvalues (for Rayleigh equation: 3 x more!)

U=1+0.9*tanh(y); ω=0.4; L=5



Which of these waves are unstable?

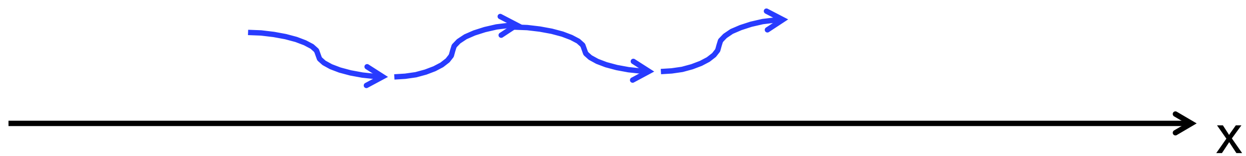
$\mathrm{Im}(k)<0$?

$\mathrm{Im}(k)>0$?

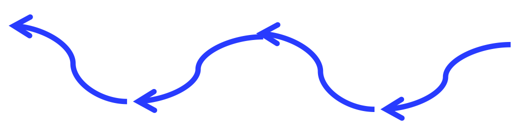
Recall : $\exp(i(kx-\omega t))$

The stability of a spatial wave can be only determined if one knows in which direction it propagates!

k^+ waves propagate towards positive x



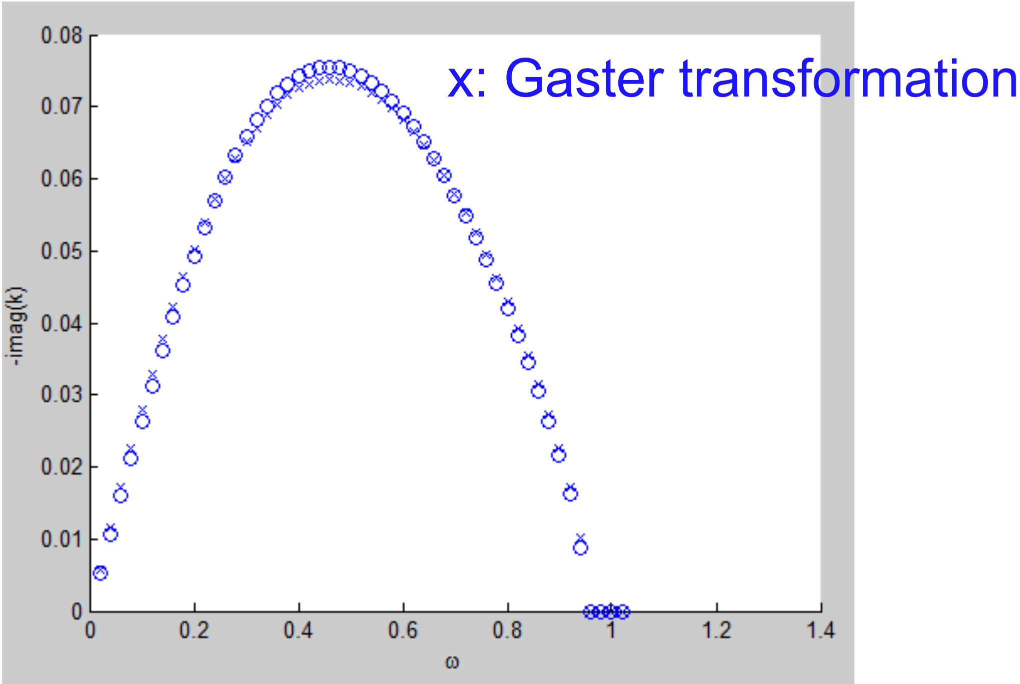
k^- waves propagate towards negative x



However, determining this direction of propagation is particularly difficult, except in the case of a temporally stable flow.

Validity of Gaster transformation?

R=0.4



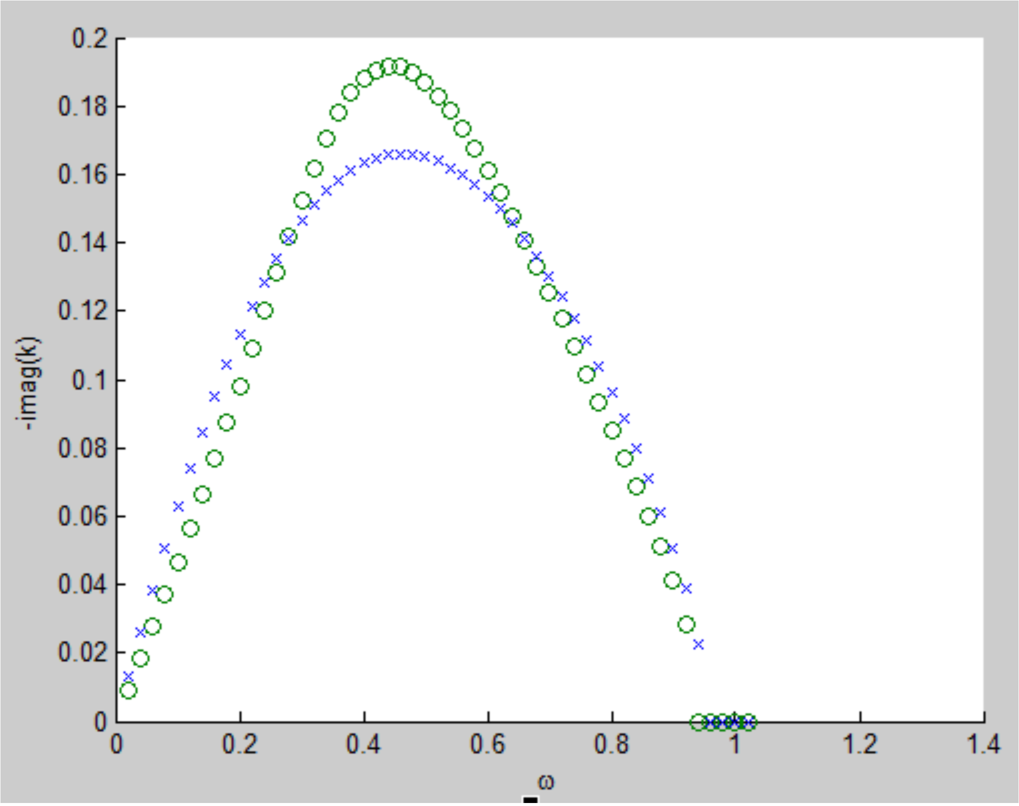
$$R \ll 1$$

$$\boxed{-k_i(\omega, R) \sim R\omega_{1,i}(\omega)}$$

Validity of Gaster transformation?

R=0.9

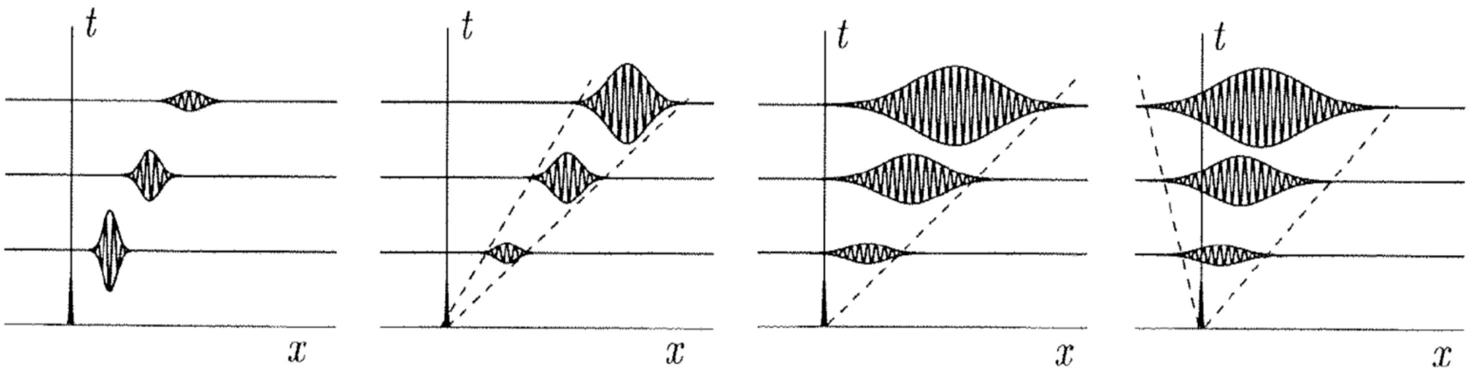
x: Gaster transformation



$$\boxed{-k_i(\omega, R) \sim R\omega_{1,i}(\omega)}$$

LINEAR IMPULSE RESPONSE: ABSOLUTE/CONVECTIVE INSTABILITY

Green's function or impulse response



Stable Unstable Unstable Unstable

Briggs (1964) Bers (1983)

Huerre and Monkewitz (1985)

LINEAR IMPULSE RESPONSE: ABSOLUTE/CONVECTIVE INSTABILITY

Linearly stable flow

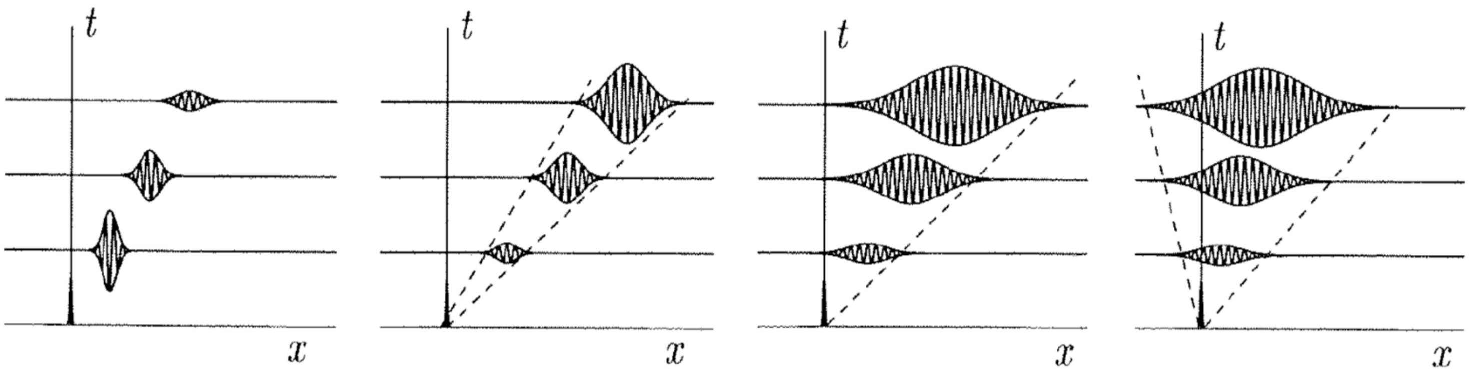
$$\lim_{t\to\infty} G(x,t) = 0$$ along all rays x/t = const.

Linearly unstable flow

$$\lim_{t\to\infty} G(x,t) = \infty$$ along at least one ray x/t = const.

LINEAR IMPULSE RESPONSE: ABSOLUTE/CONVECTIVE INSTABILITY

Green's function or impulse response



Stable Unstable Unstable Unstable

Briggs (1964) Bers (1983)

Huerre and Monkewitz (1985)

LINEAR IMPULSE RESPONSE: ABSOLUTE/CONVECTIVE INSTABILITY

Convectively unstable flow

$$\lim_{t \to \infty} G(x,t) = 0$$ along the ray x/t = 0

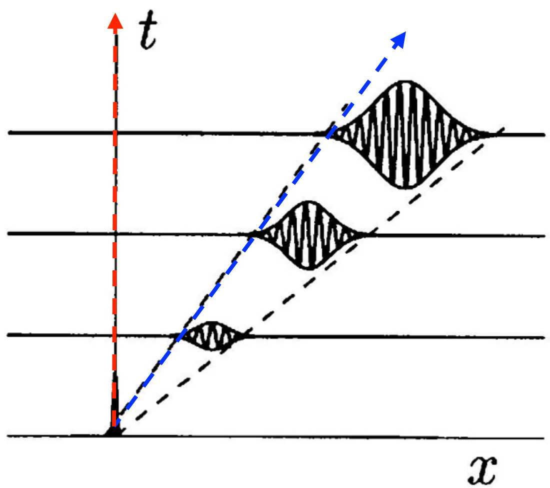
Absolutely unstable flow

$$\lim_{t \to \infty} G(x,t) = \infty$$ along the ray x/t = 0

Théorie de la stabilité linéaire spatio-temporelle

☞ Instabilité convective

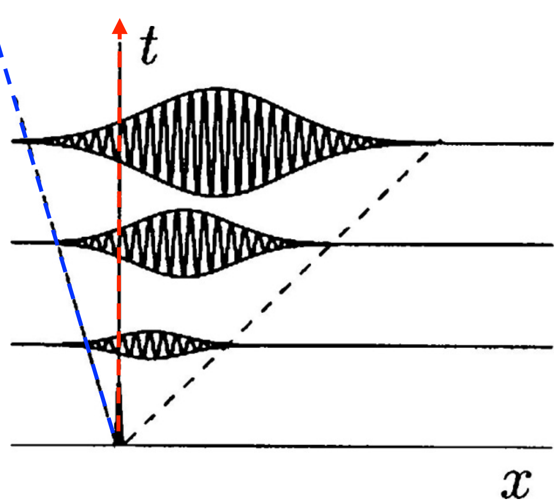
$\Rightarrow$ Amplificateur



Im(ω_0)<0

✦ Instabilité absolue

$\Rightarrow$ Oscillateur

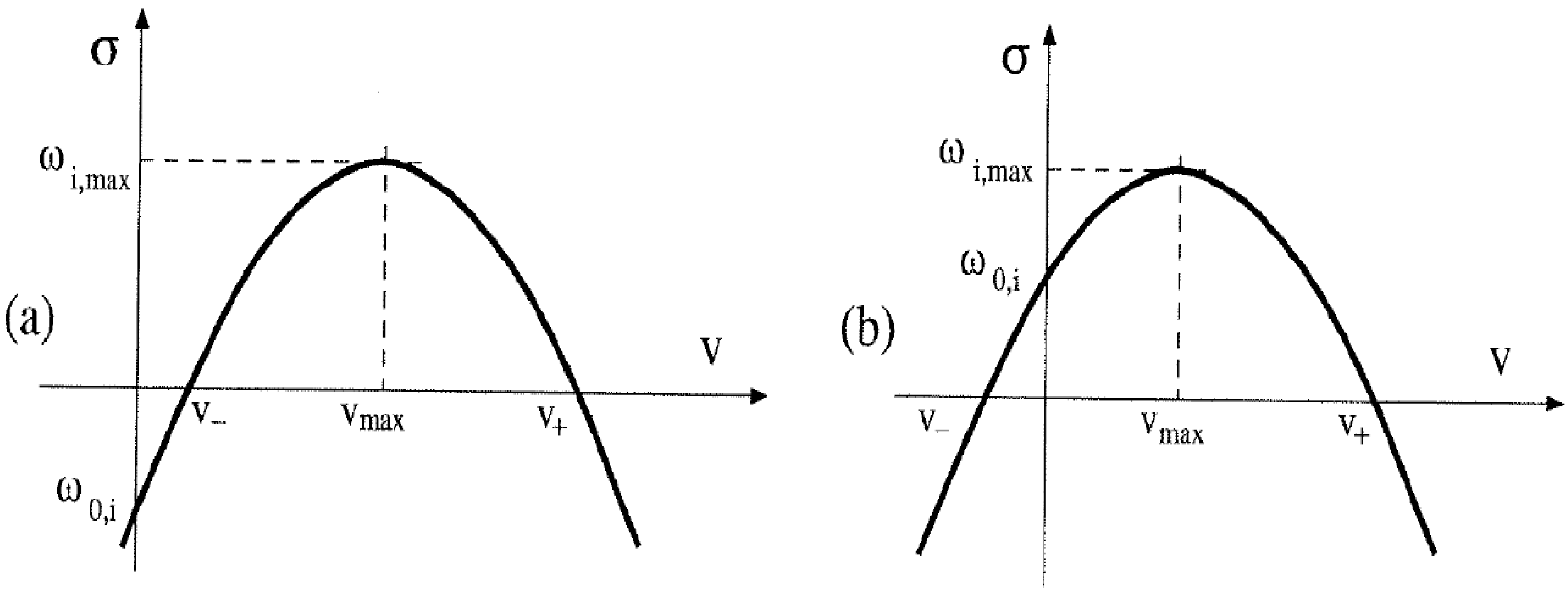


Im(ω_0)>0

Onde de vitesse de groupe nulle : $d\omega/dk=0 \Rightarrow (k_0,\omega_0)$

ANALYSIS IN COMPLEX FOURIER SPACE: AU/CU CRITERION

Temporal growth rate « at velocity v »



Convective instability

Absolute instability

Go into Fourier space !

$$\psi(x,t,y) = \frac{1}{(2\pi)^2}\int_{L_\omega}\int_{F_k}\psi(k,\omega,y)e^{i(kx-\omega t)}\,dk\,d\omega$$

$$\psi(k,\omega,y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\psi(x,t,y)e^{-i(kx-\omega t)}\,dx\,dt$$

Manipulate these integrals….

ANALYSIS IN COMPLEX FOURIER SPACE: AU/CU CRITERION

Important notions

Leading and trailing edge velocities of wavepacket

$$x/t = v^+ \qquad x/t = v^-$$

defined by

$$\sigma(v^+) = \sigma(v^-) = 0$$

Maximum temporal growth rate

$$\omega_{i,max} = \omega_i(k_{max})$$

such that

$$\frac{\partial \omega_i}{\partial k}(k_{max}) = 0$$

observed along ray

$$\partial\omega/\partial k(k_{max}) = v_{max}$$

ANALYSIS IN COMPLEX FOURIER SPACE: AU/CU CRITERION

Important notions

Absolute wavenumber k_0 and frequency $\omega_0 = \omega(k_0)$ observed along ray v = 0, i.e. for a stationary observer, defined by

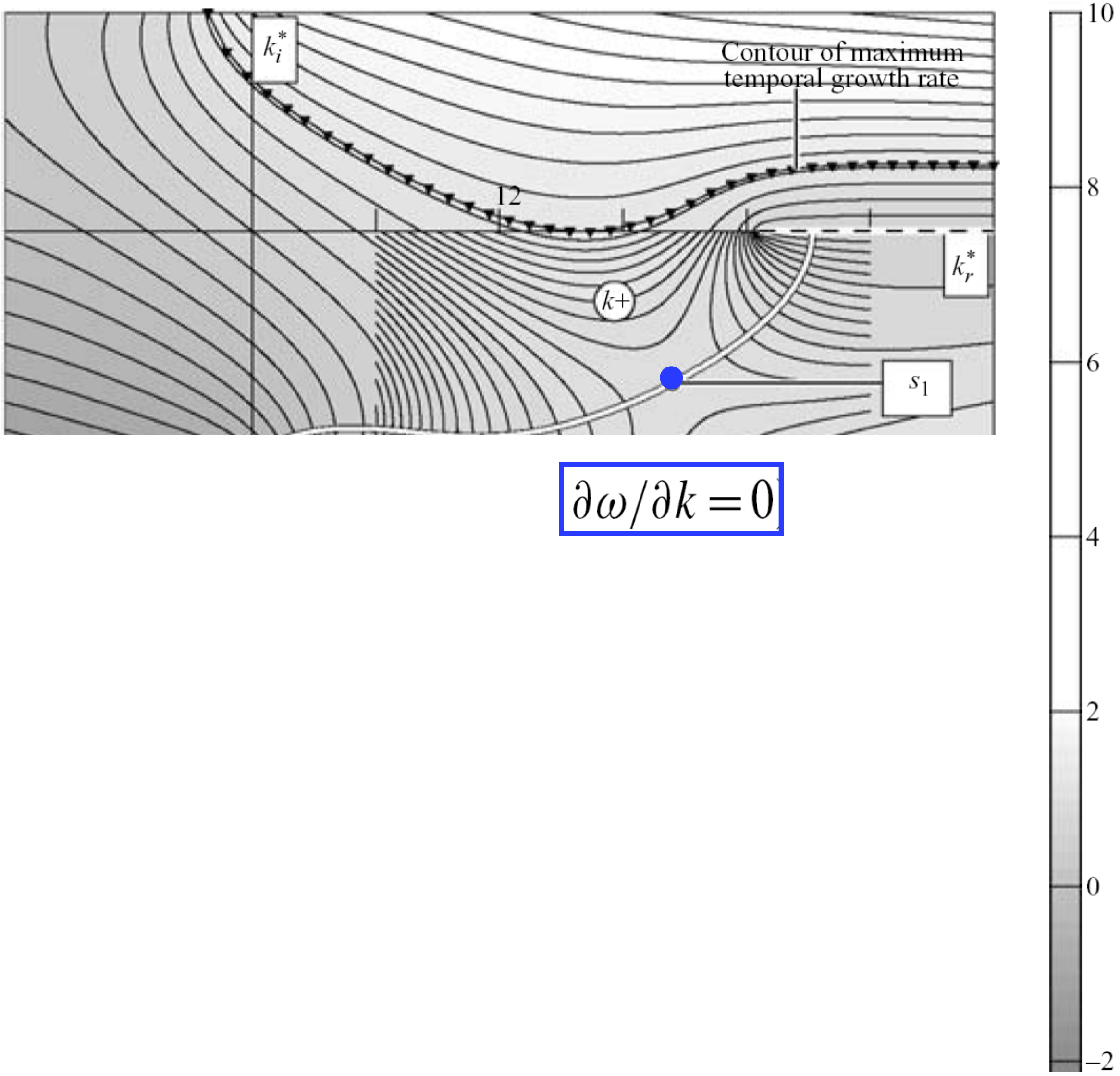
$$\frac{\partial \omega}{\partial k}(k_0) = 0$$

Absolute growth rate is

$$\sigma(0) = \omega_{0,i}$$

Isovaleurs de ω_i

Absolute frequency ω_0: Saddle point condition



$$\boxed{\partial\omega/\partial k = 0}$$

ANALYSIS IN COMPLEX FOURIER SPACE: AU/CU CRITERION

Instability criteria

$\omega_{i,max} < 0$	linearly stable
$\omega_{i,max} > 0$	linearly unstable
$\omega_{0,i} < 0$	convectively unstable
$\omega_{0,i} > 0$	absolutely unstable

Hyperbolic tangent mixing layer

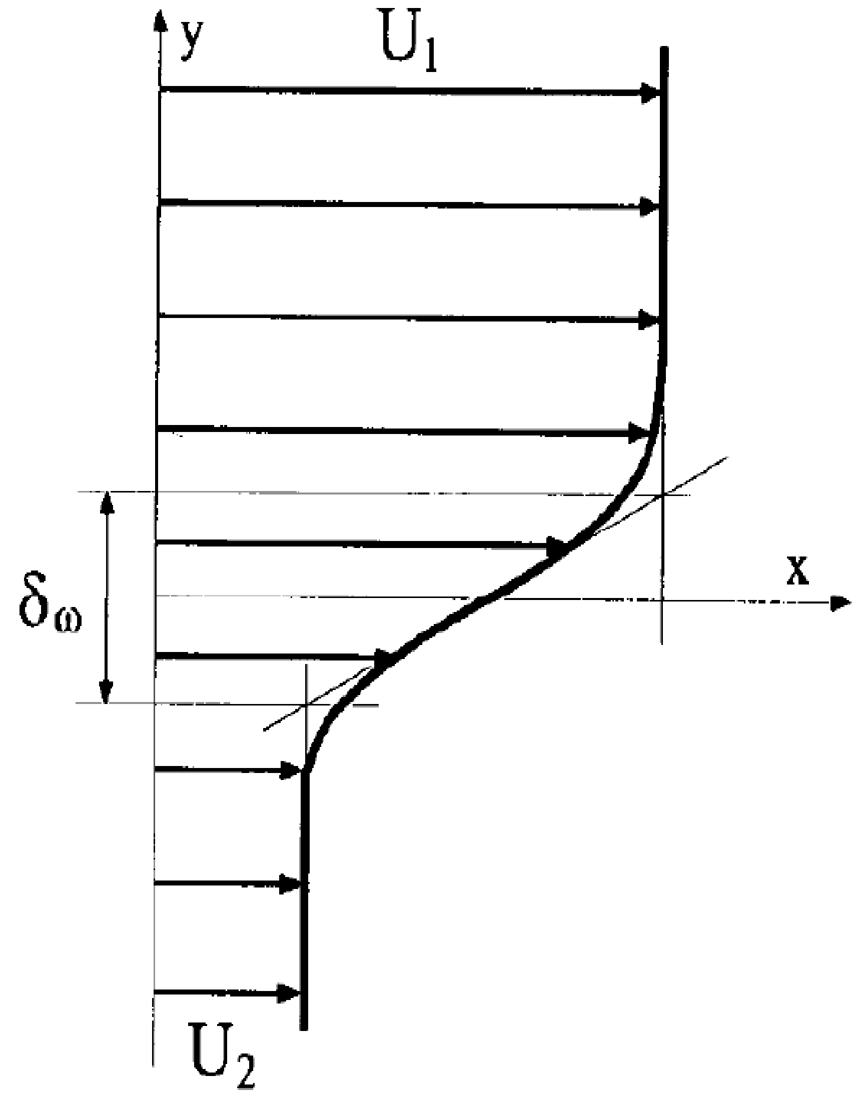
$$U(y) = \bar{U} + \frac{\Delta U}{2} \tanh\left(\frac{2y}{\delta_\omega}\right)$$

$$\delta_\omega(x) \equiv \frac{(U_1 - U_2)}{(dU/dy)_{\max}}$$

Velocity ratio

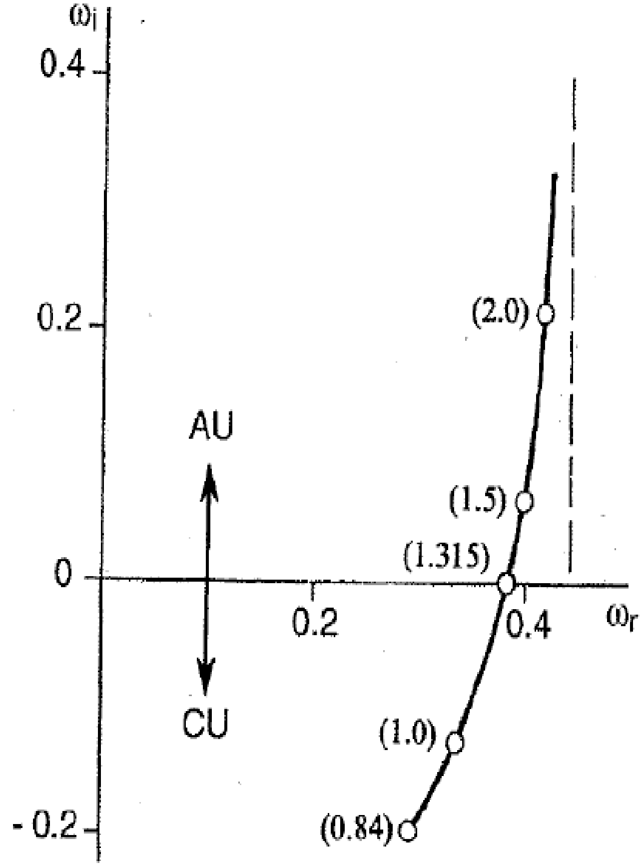
$$R \equiv \frac{U_1 - U_2}{U_1 + U_2} = \frac{\Delta U}{2\bar{U}}$$

$$\boxed{U(y;R) = 1 + R\tanh y}$$

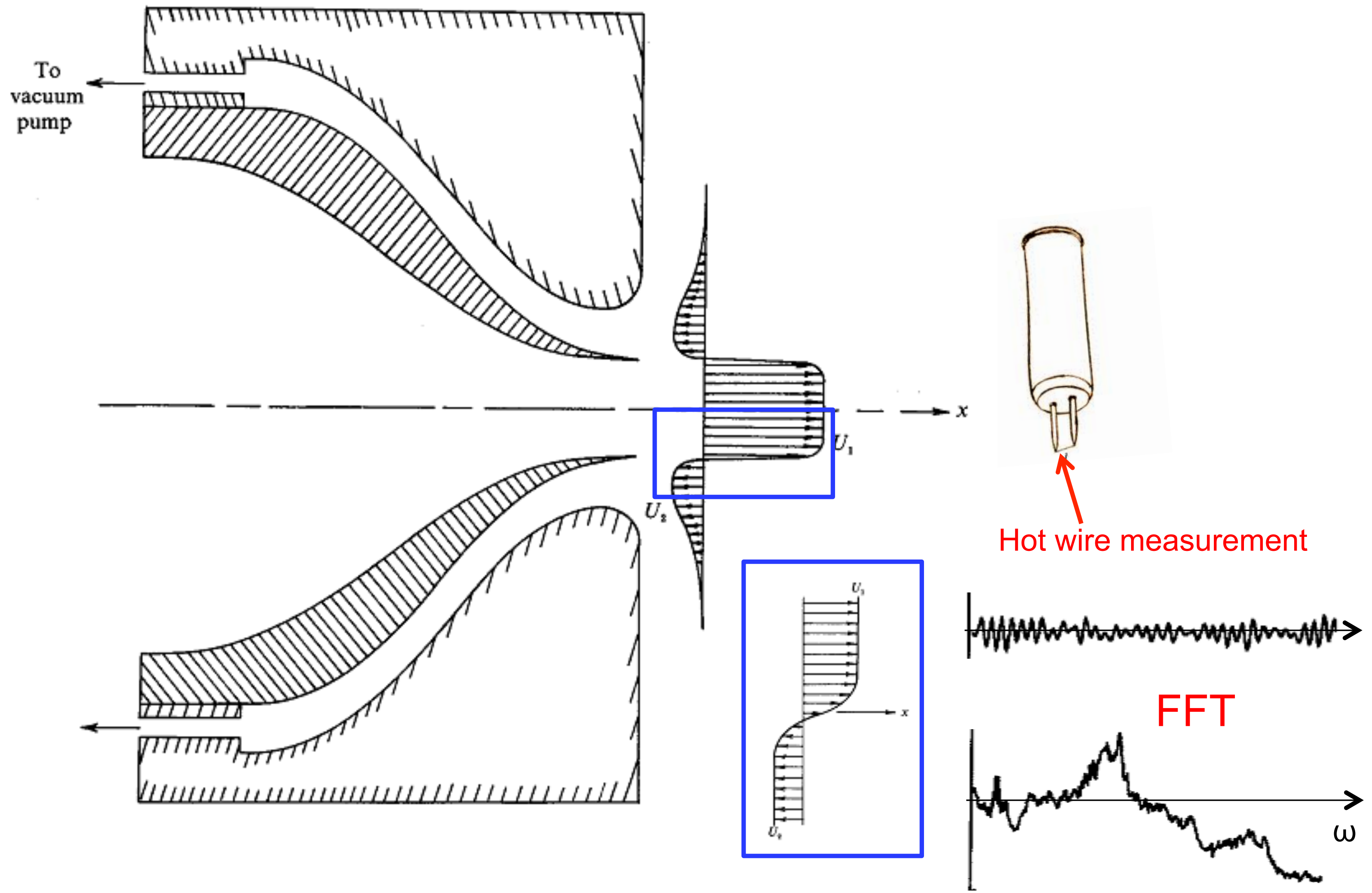


APPLICATION TO MIXING LAYERS

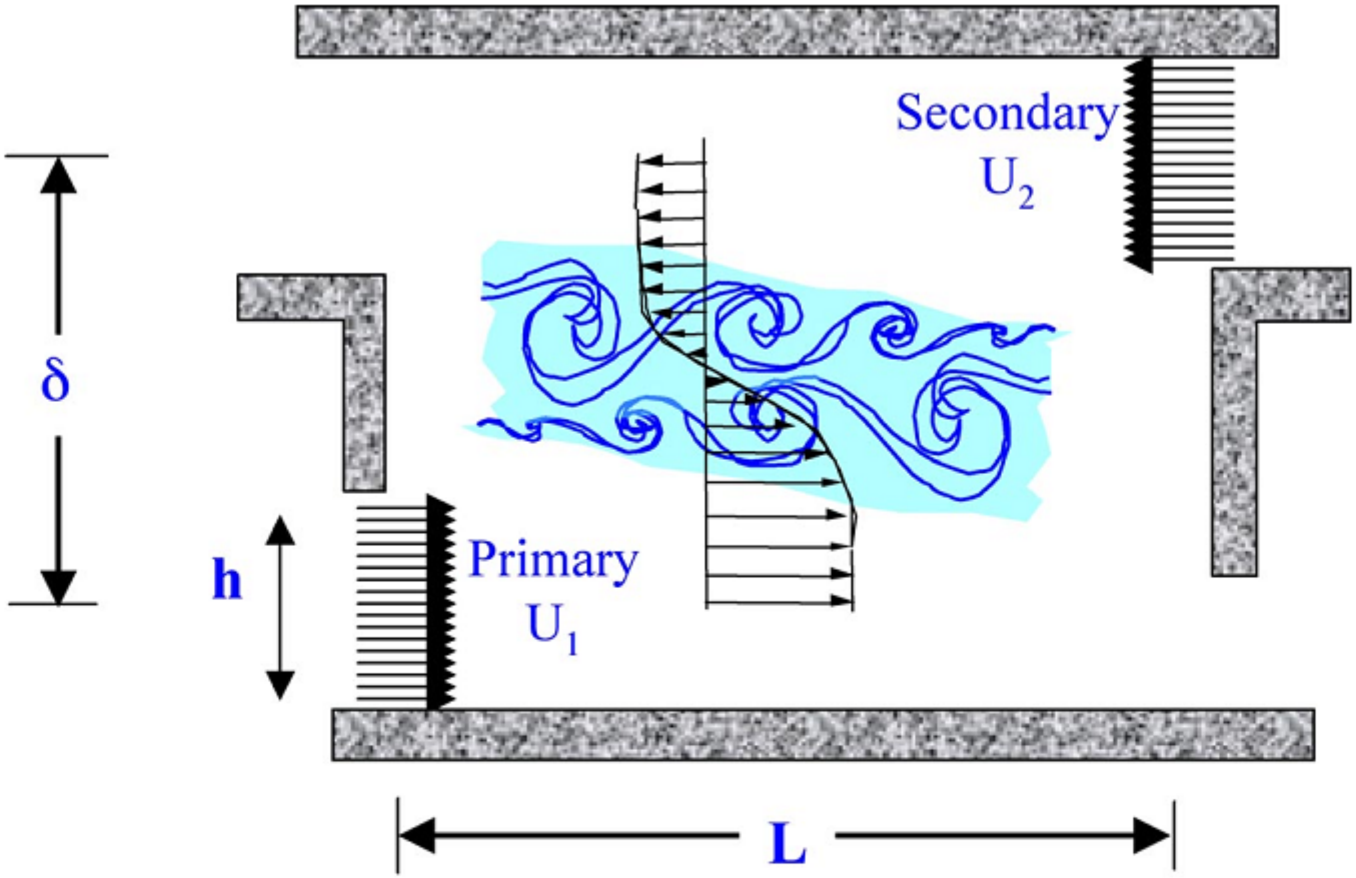
Locus of complex absolute frequency



H.&Monkewitz (1985)

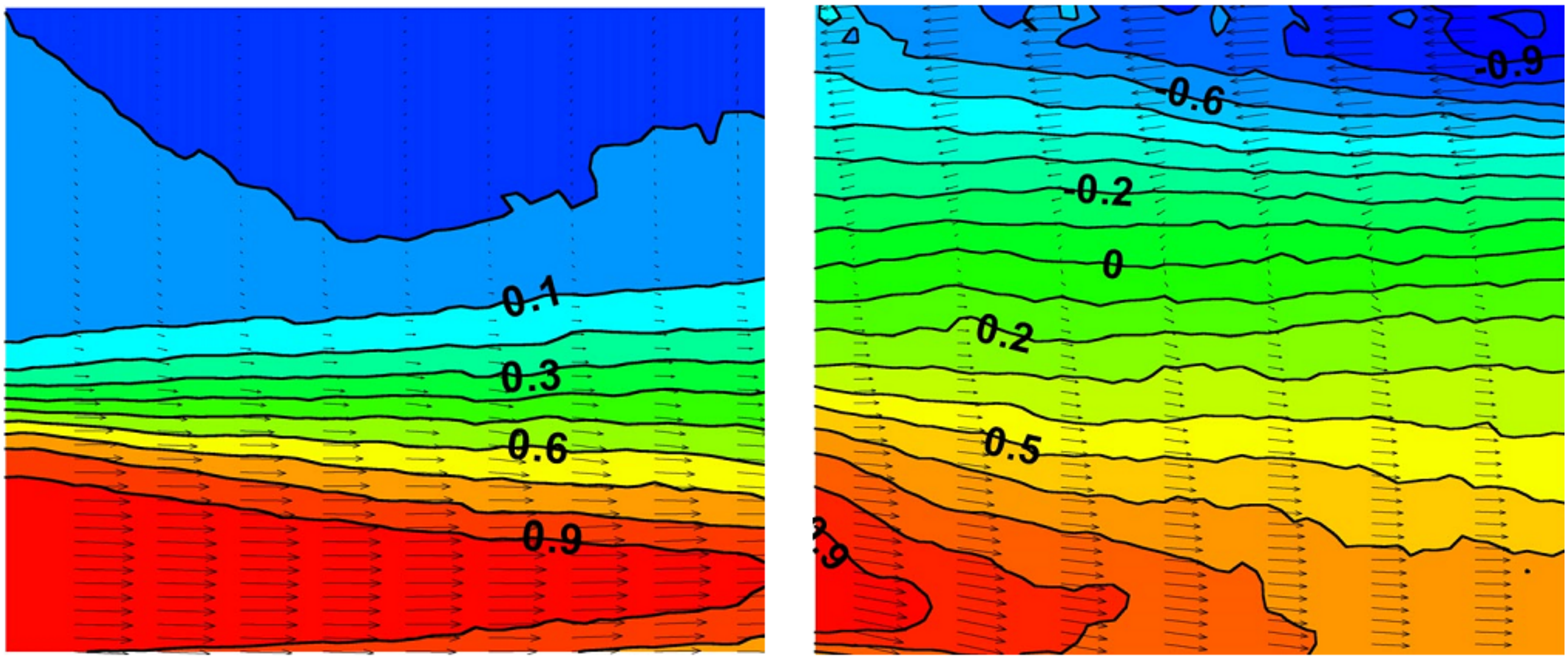

To vacuum pump
x
U_1
U_2
Hot wire measurement
t
FFT
ω

Influence of coutercurrent shear on turbulence level



Influence of coutercurrent shear on turbulence level

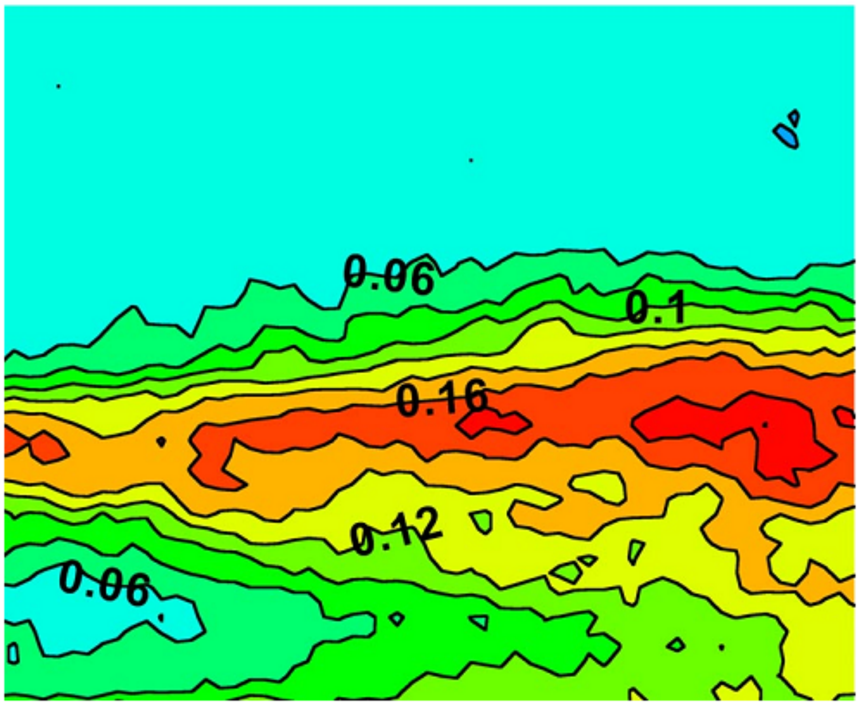
Base flow



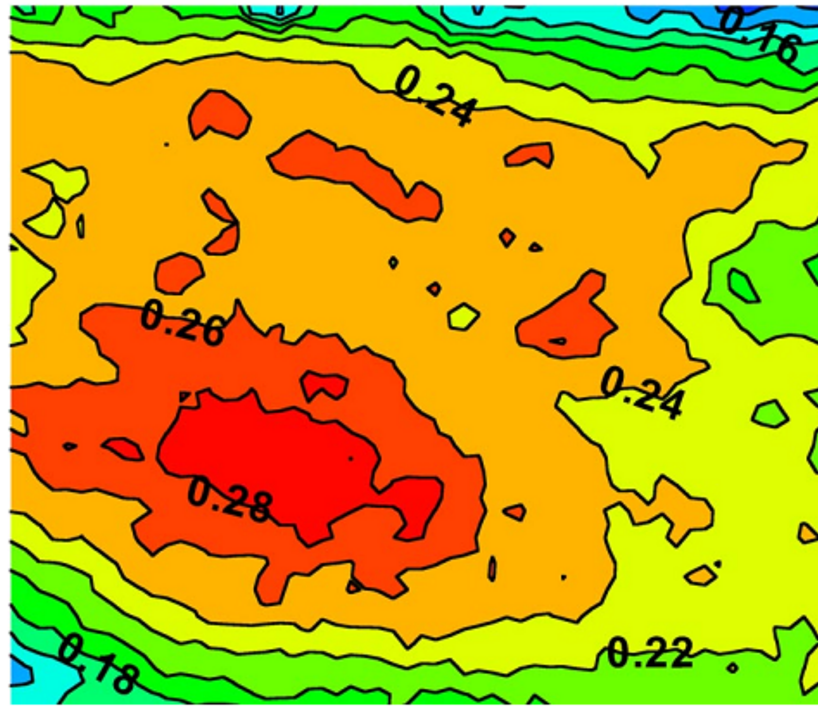
a) Single stream shear layer   b) Countercurrent shear layer

Influence of coutercurrent shear on turbulence level

Turbulence intensity

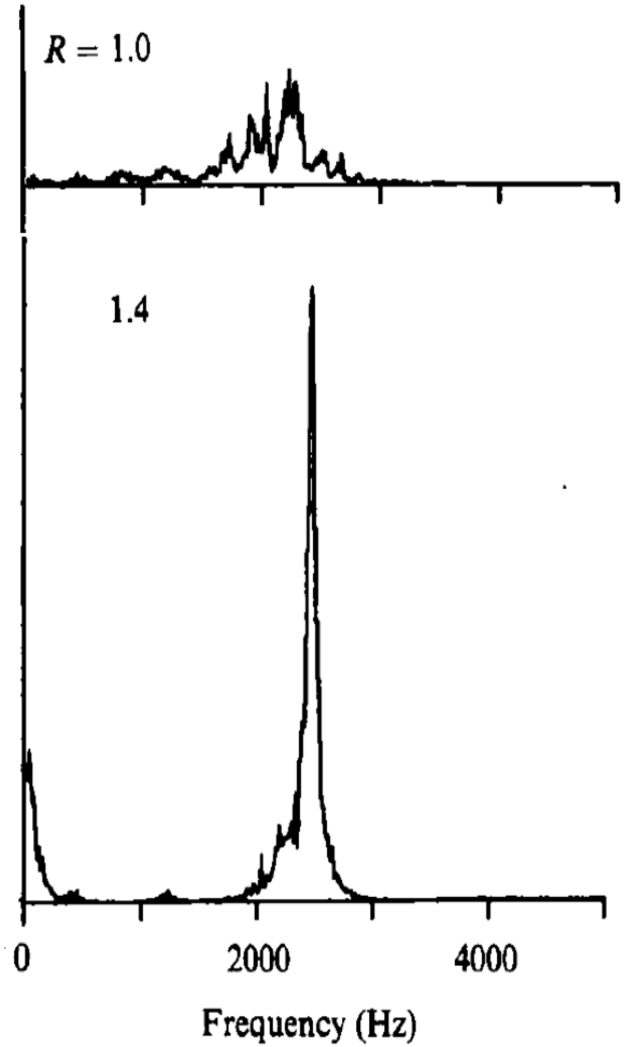


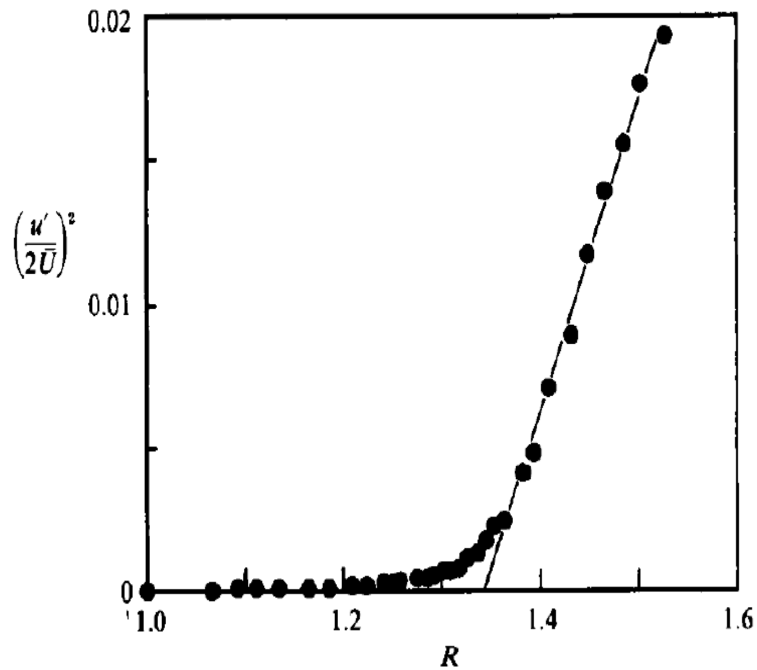
a) Single-stream shear layer



b) Countercurrent shear layer

THE MIXING LAYER: SHIFT TO OSCILLATOR !



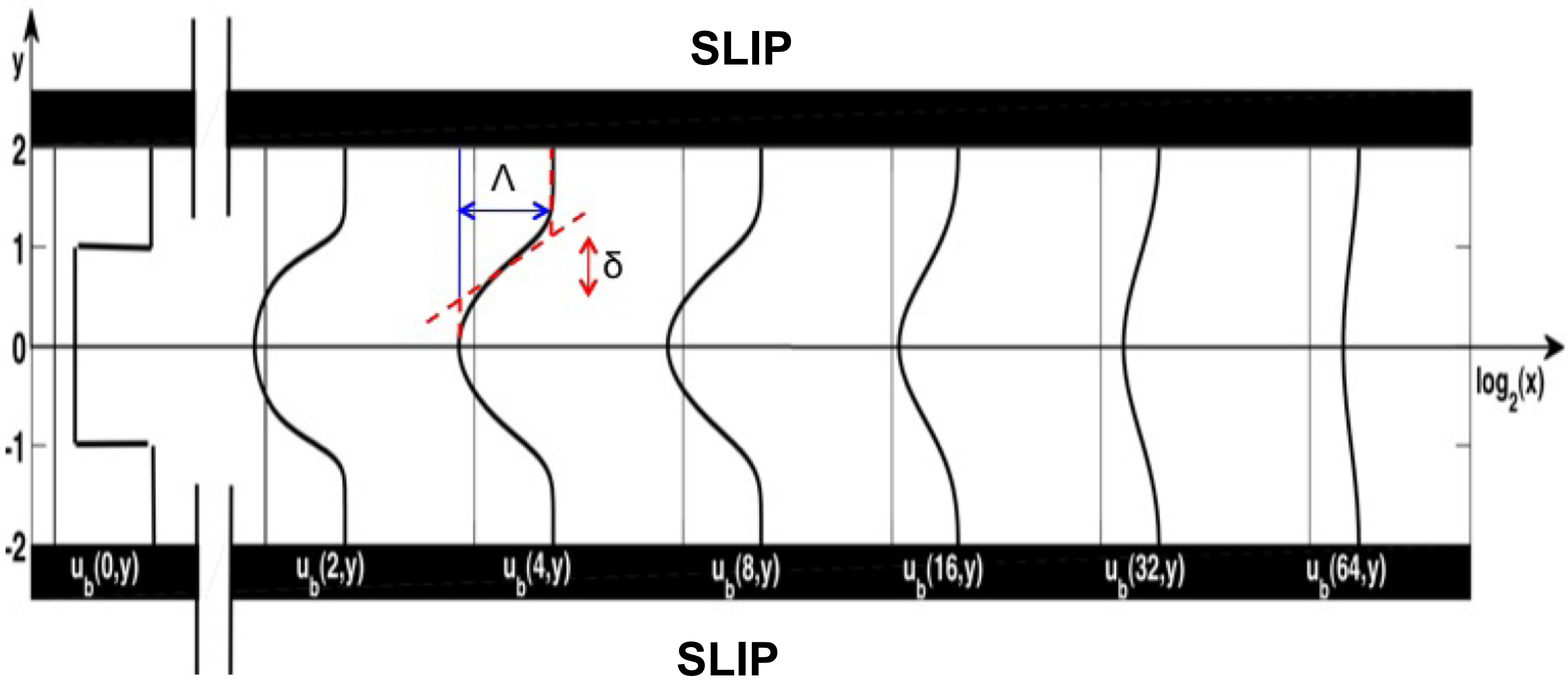


Strykowski & Niccum (1991)

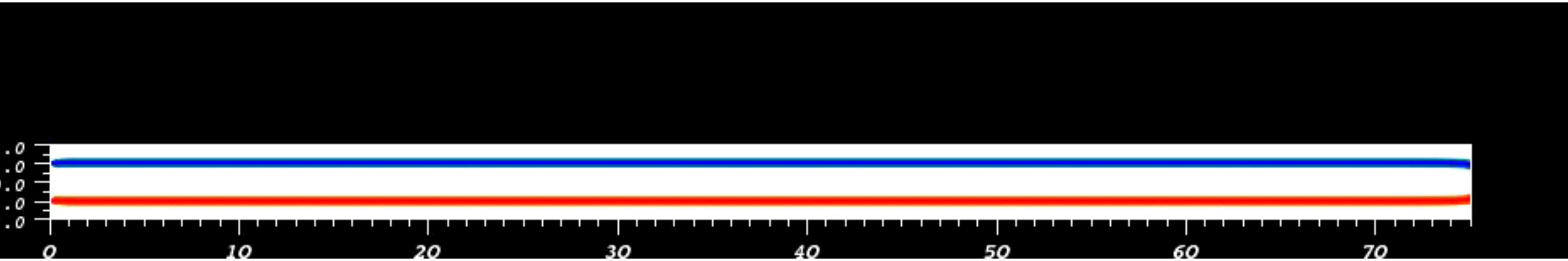
Direct Numerical Simulations with top-hat profile at inlet

Viscous diffusion $\longrightarrow$ Non-parallel flow

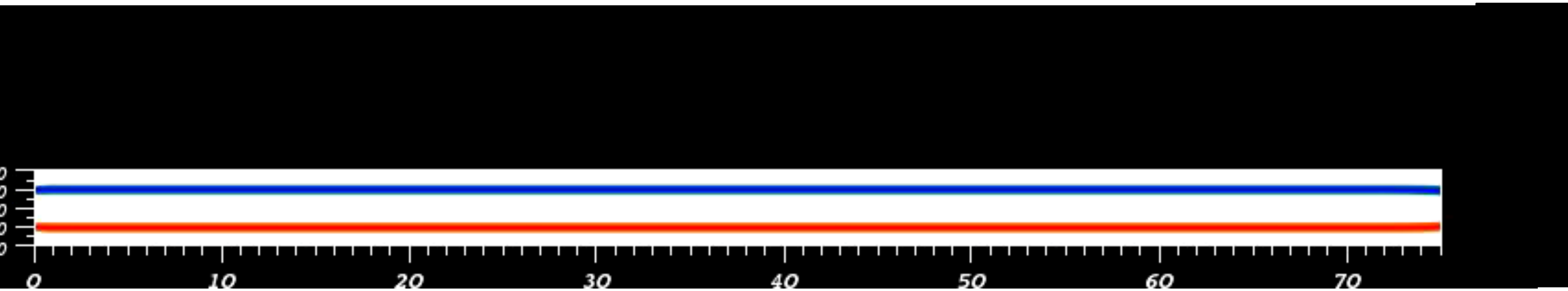
- $\Lambda_{loc} = (U_{max} - U_{min})/(U_{max} + U_{min})$
- $\delta = (U_{max} - U_{min})/(|dU/dy|_{max})$



Vorticity field: Re = 100, h = 1



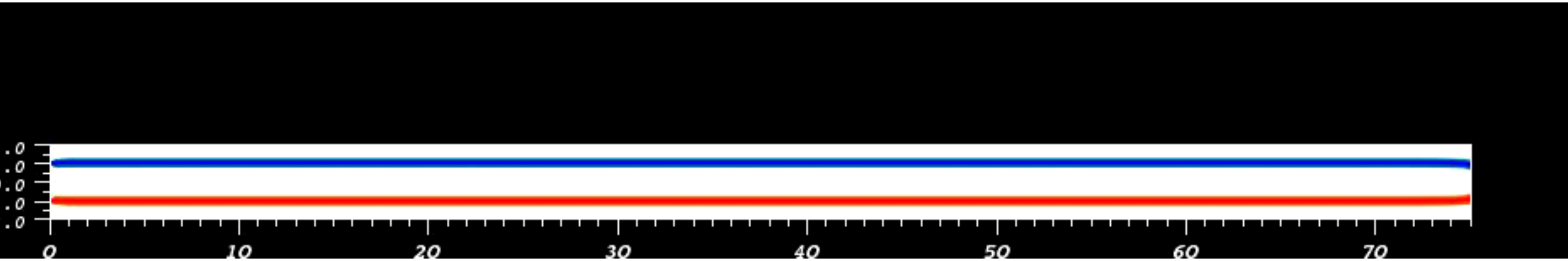
Λ = -0.739



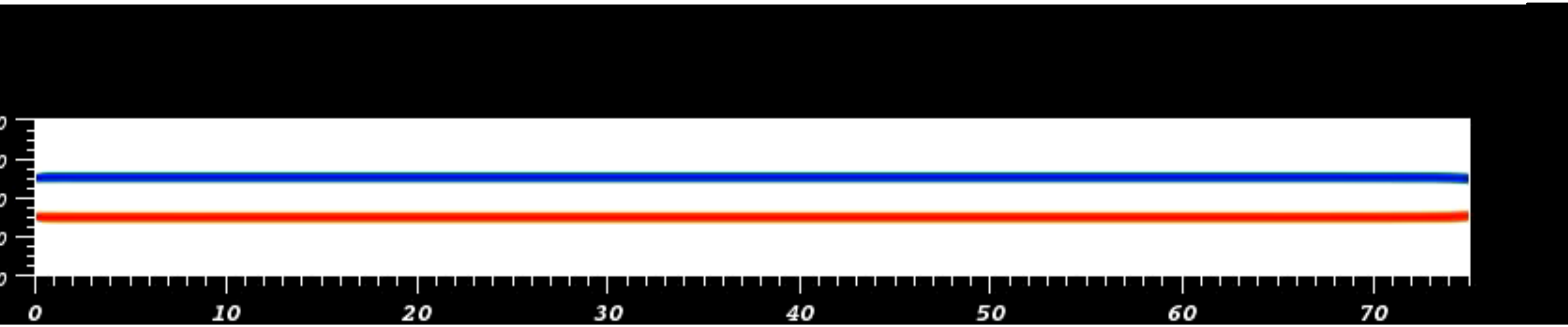
Λ = -0.667

An increase in Λ (more coflow) advects the perturbation

Vorticity field: Re = 100, Λ = -0.739



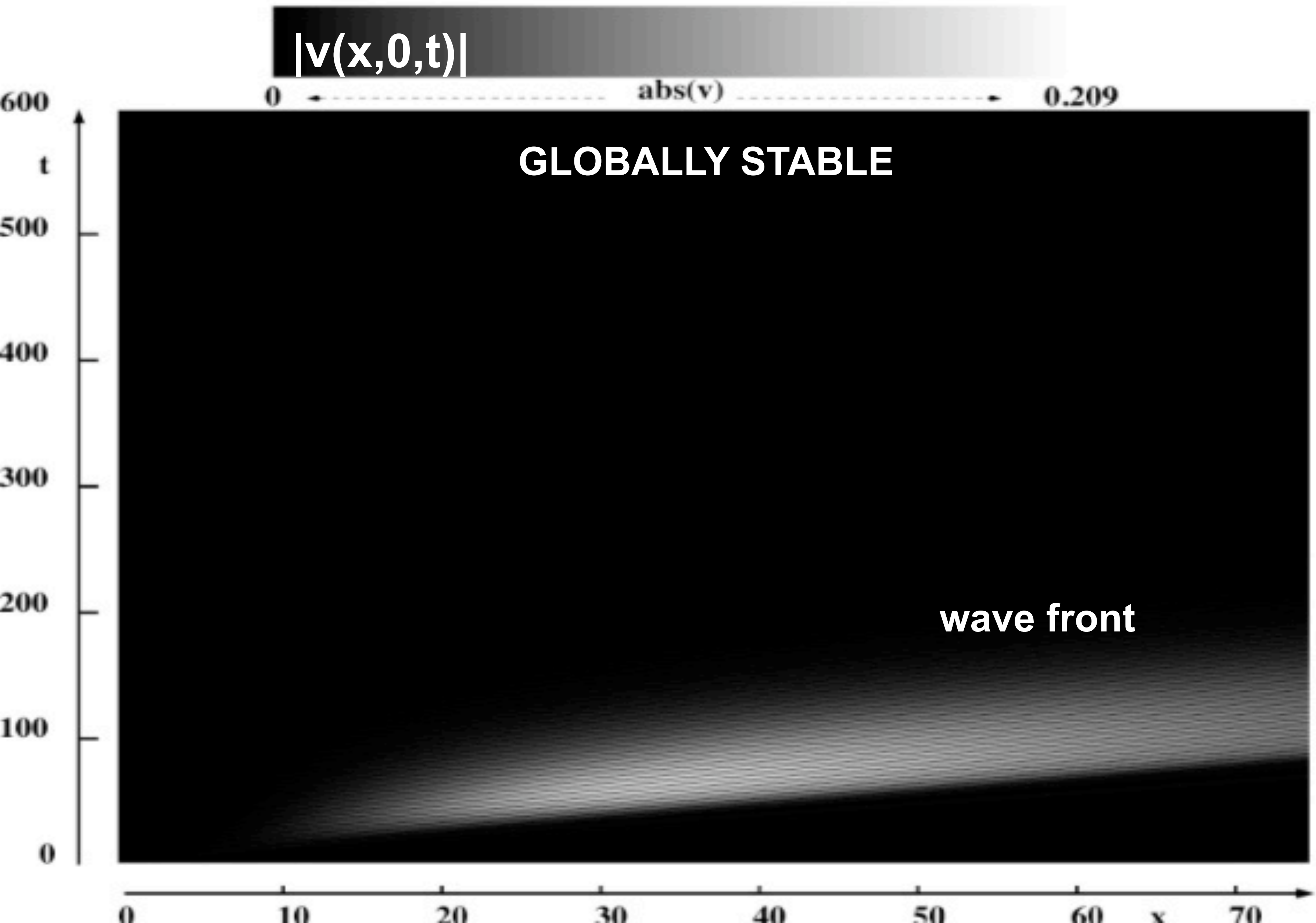
h=1



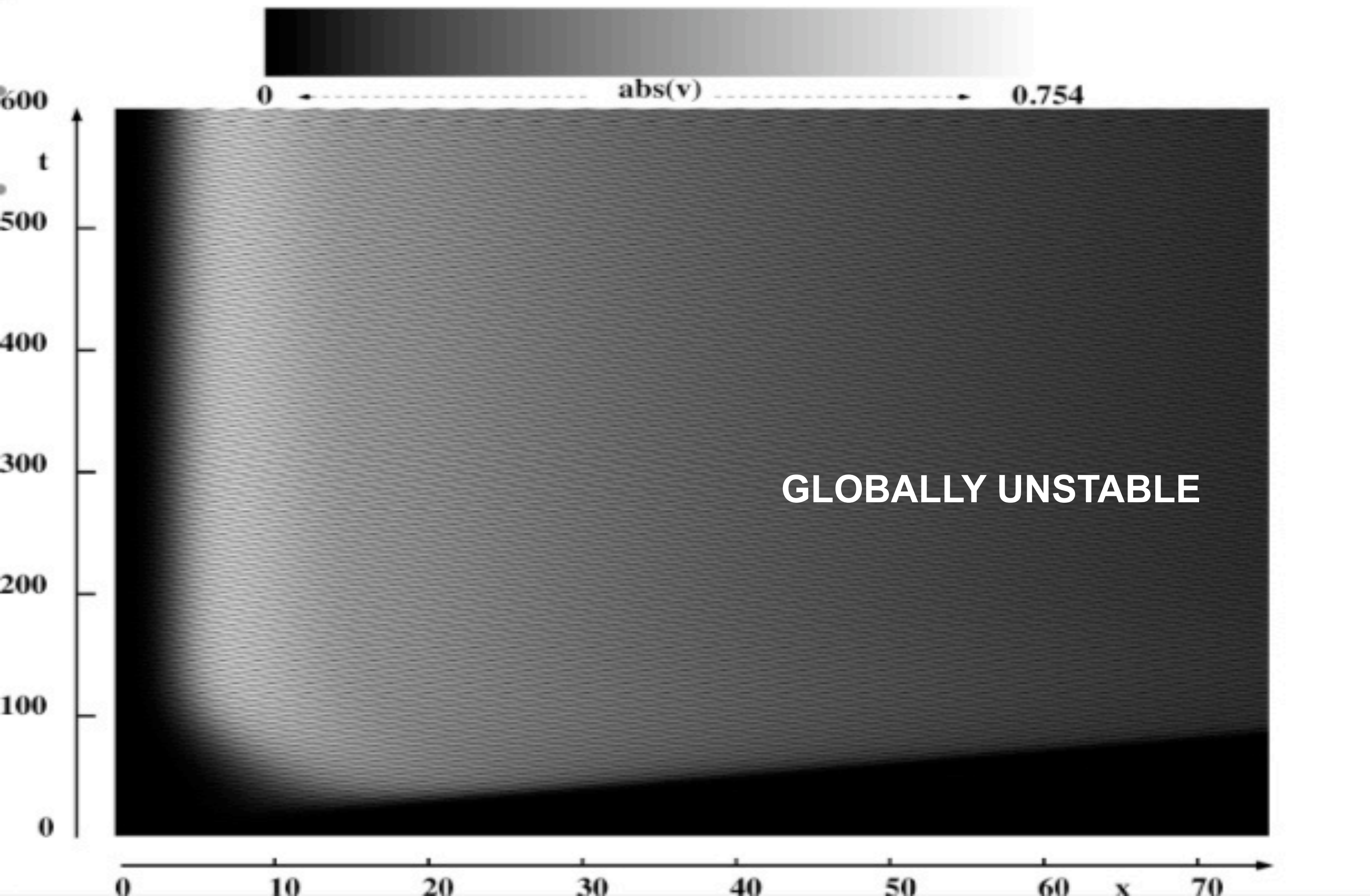
h=3

Destabilizing influence of confinement!

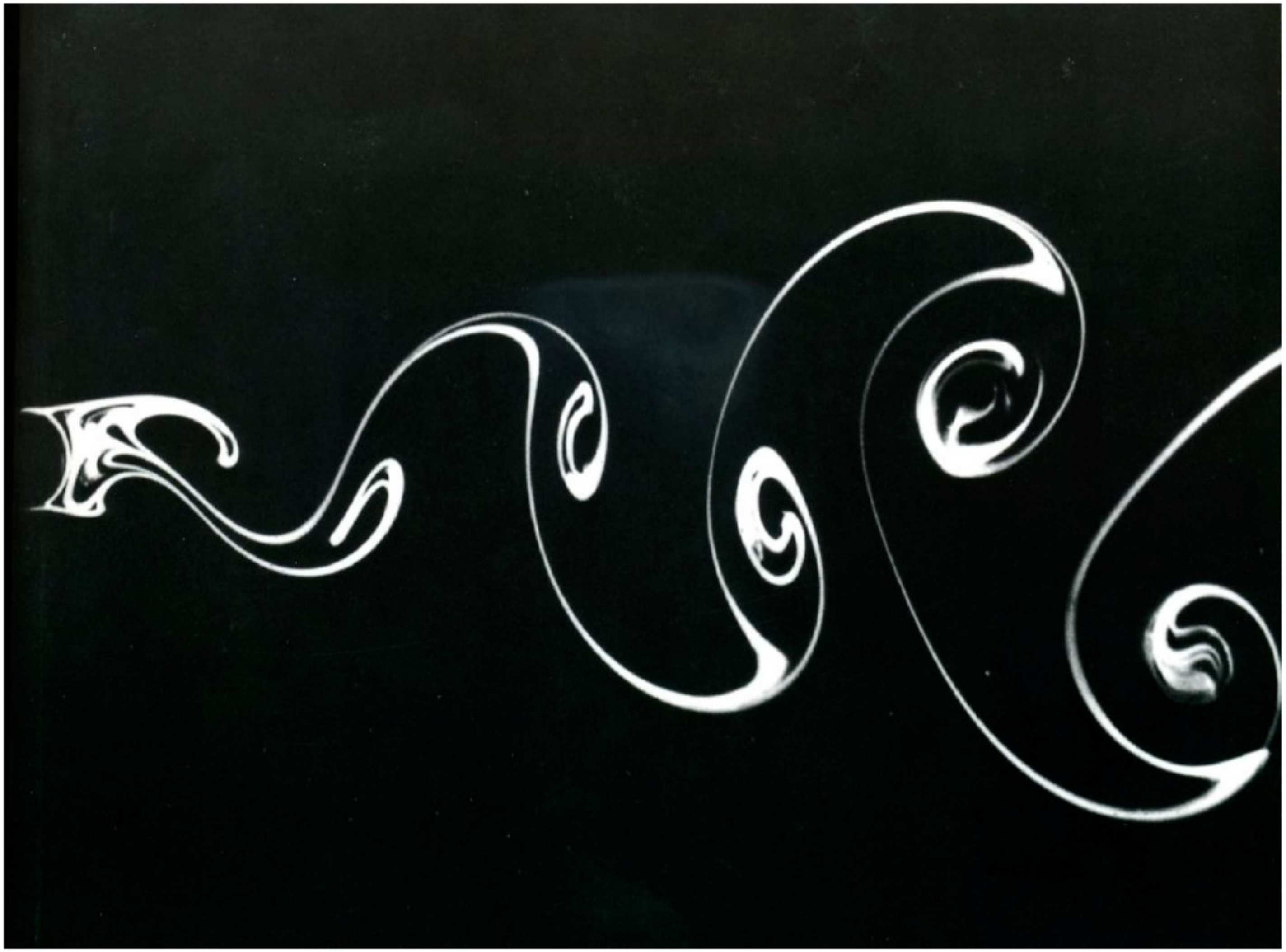
Spatio-temporal diagram, h=1 and Λ = -0.667



Spatio-temporal diagram, h=1 and Λ = -0.739



THE BLUFF BODY WAKE: A TYPICAL FLOW OSCILLATOR



Re = 140
Periodic
flow

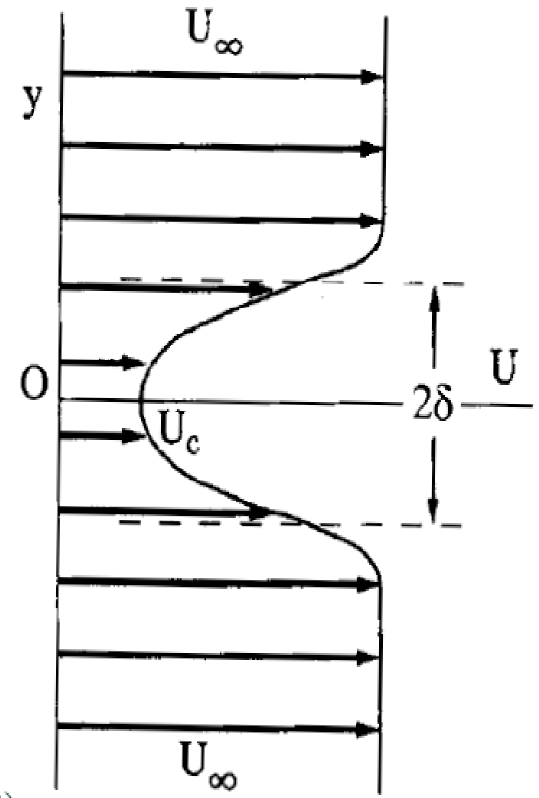
Taneda (1982)

ABSOLUTE/CONVECTIVE INSTABILITY IN PARALLEL WAKES

Family of wake profiles

$$U(y) = U_\infty + (U_c - U_\infty)\, U_1\left(\frac{y}{\delta}; N\right)$$

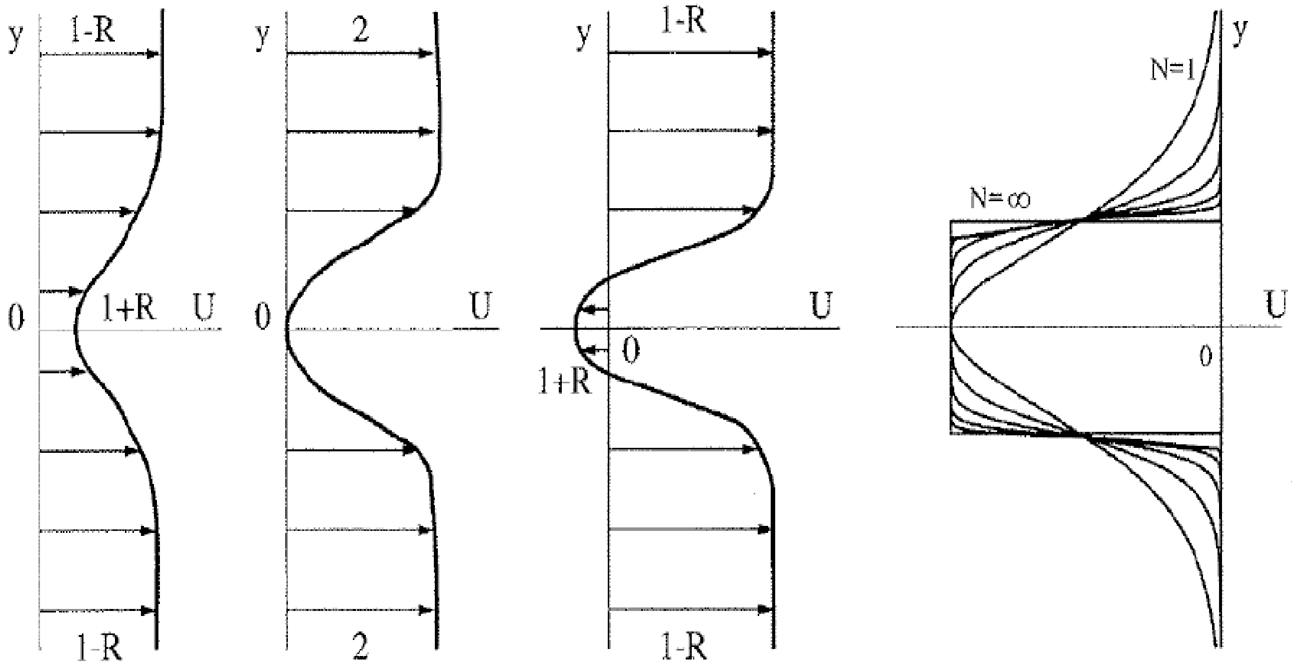
$$U_1(\xi; N) = [1 + \sinh^{2N}\{\xi \sinh^{-1}(1)\}]^{-1}$$



Monkewitz (1988)

ABSOLUTE/CONVECTIVE INSTABILITY IN PARALLEL WAKES

Family of wake profiles



(a) **-1 < R < 0**

(b) **R = -1**

(c) **R < -1**

(d)

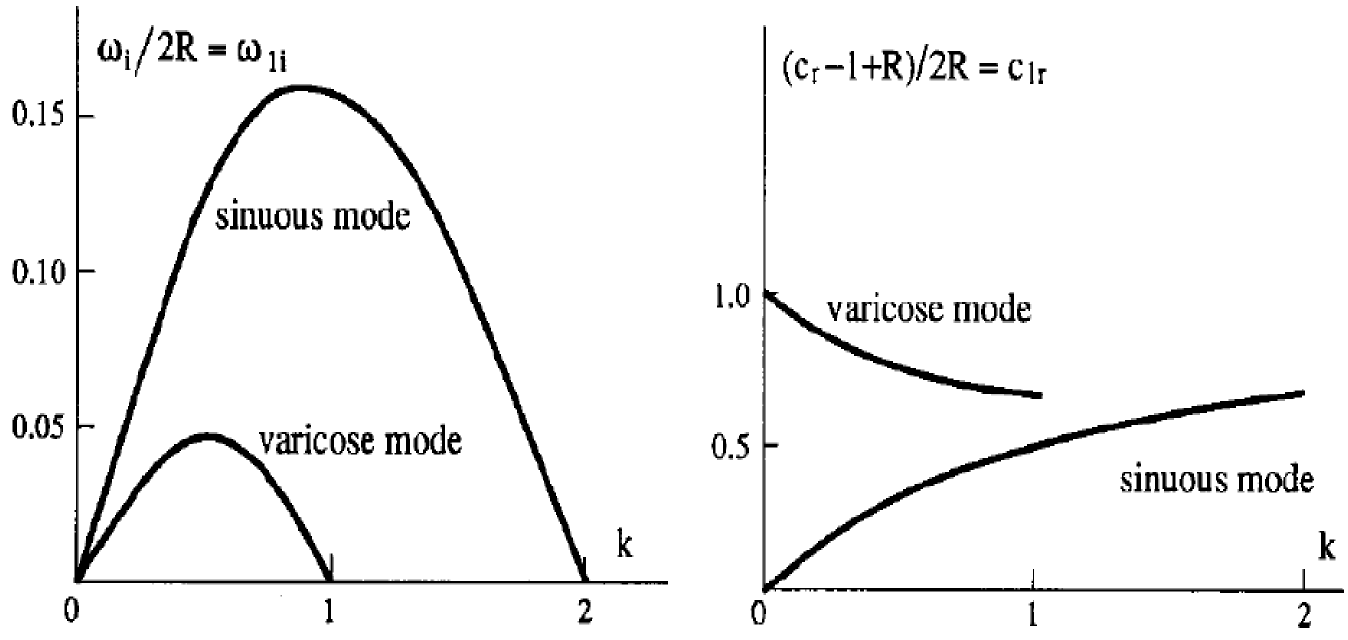
Effect of velocity ratio R

Effect of N

ABSOLUTE/CONVECTIVE INSTABILITY IN PARALLEL 2D PARALLEL FLOW CONCEPTS

$\mathrm{sech}^2\, y$ wake

Temporal approach

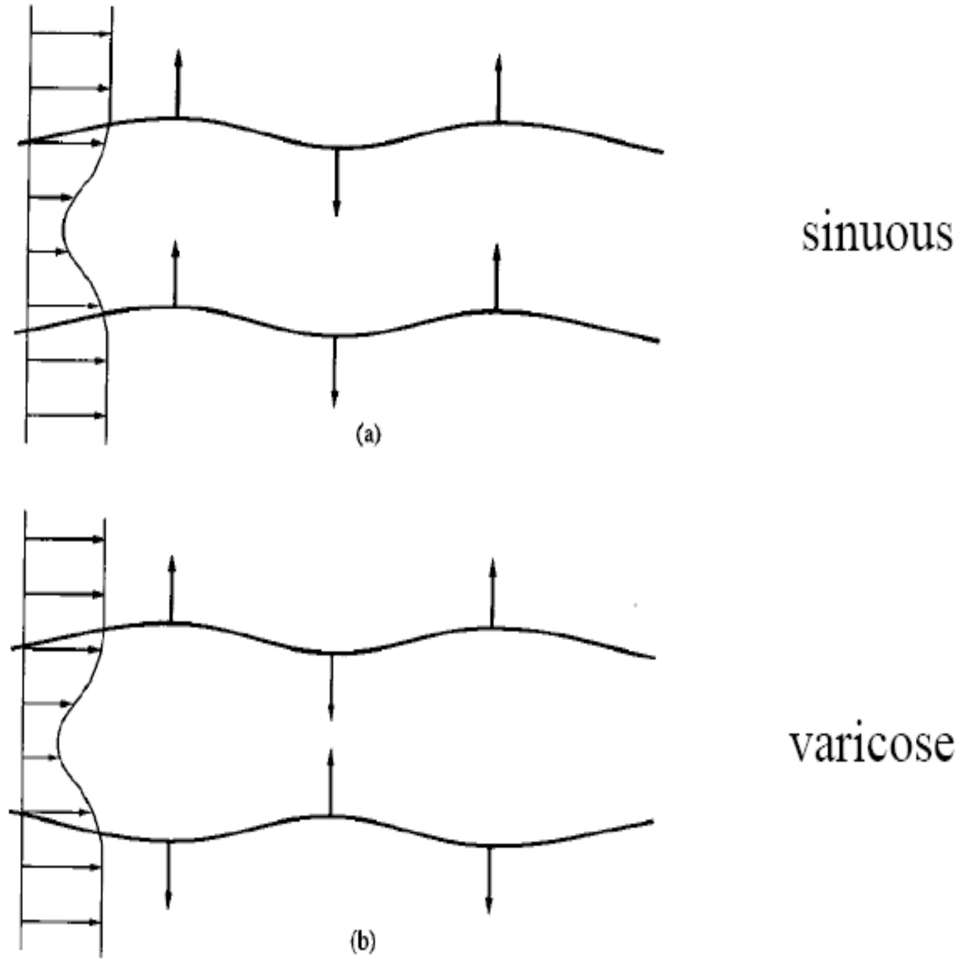


Betchov & Criminale (1966)

2D PARALLEL FLOW CONCEPTS

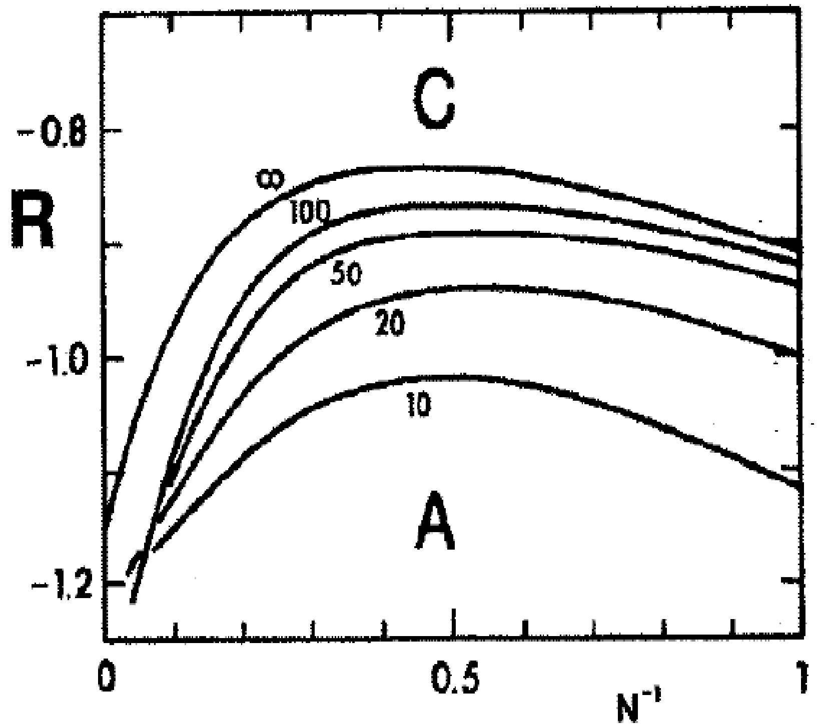
$\mathrm{sech}^2\, y$ wake

Sinuous and varicose modes



ABSOLUTE/CONVECTIVE INSTABILITY IN PARALLEL WAKES

Effect of steepness, velocity ratio and Reynolds number



Monkewitz (1988)

LOCAL INSTABILITY BEHAVIOR OF CYLINDER WAKE

$5 < Re < 25$ **Convective instability**

$25 < Re < 48.5$ **Absolute instability**