

Sudden transition in frequency for travelling waves

S. Scarsoglio F. De Santi, D. Tordella

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Travelling perturbations in sheared flows: sudden transition in frequency and phase speed asymptotics

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 Temporal evolution of the wave frequency in two archetypical shear flows, the plane channel flow and the bluff-body wake;



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- Temporal evolution of the wave frequency in two archetypical shear flows, the plane channel flow and the bluff-body wake;
- Frequency transient poorly investigated
 - ⇒ Attention mainly devoted to the frequency of vortex shedding for the most unstable spatial scales (Williamson, 1989; Strykowski & Sreenivasan, 1990);



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 - ⇒ Attention mainly devoted to the frequency of vortex shedding for the most unstable spatial scales (Williamson, 1989; Strykowski & Sreenivasan, 1990);
- The linear transient dynamics offers a great variety of very different behaviors (Scarsoglio et al., 2009, 2010, 2011):
 - High maxima of energy followed by asymptotic damping;



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 - ⇒ How does the frequency of these travelling waves behave?
- Nonlinear terms limit the amplitude of the wave packet leaving unaffected its frequency (Delbende & Chomaz, 1998).



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• Steady base flow excited with small 3D perturbations;



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- Steady base flow excited with small 3D perturbations;
- Linearized 3D Navier-Stokes equations (velocity-vorticity);
- Laplace-Fourier (wake) and Fourier-Fourier (channel) transform in the x and z directions.



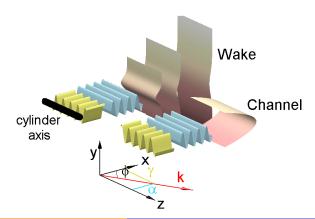
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Measure of the growth

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• Kinetic energy density *e*:

$$e(t; \alpha, \gamma) = \frac{1}{2} \int_{-y_d}^{+y_d} (|\hat{u}|^2 + |\hat{v}|^2 + |\hat{w}|^2) dy$$



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• Amplification factor G:

$$G(t; \alpha, \gamma) = \frac{e(t; \alpha, \gamma)}{e(t = 0; \alpha, \gamma)}$$



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$$G(t; \alpha, \gamma) = \frac{e(t; \alpha, \gamma)}{e(t = 0; \alpha, \gamma)}$$

• Temporal growth rate r:

$$r(t; \alpha, \gamma) = \frac{log[e(t; \alpha, \gamma)]}{2t}$$



Characteristics of the perturbation

Initial-value problem



• Phase θ_w :

$$\theta_w(y, t; \alpha, \gamma) = arg(\hat{v}(y, t; \alpha, \gamma))$$



Characteristics of the perturbation

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• Phase θ_w :

$$\theta_w(y, t; \alpha, \gamma) = arg(\hat{v}(y, t; \alpha, \gamma))$$

• Angular frequency ω :

$$\omega(t; y_0, \alpha, \gamma) = \frac{|d\theta(t; y_0, \alpha, \gamma)|}{dt}$$



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$$\theta_w(y, t; \alpha, \gamma) = arg(\hat{v}(y, t; \alpha, \gamma))$$

• Angular frequency ω :

$$\omega(t; y_0, \alpha, \gamma) = \frac{|d\theta(t; y_0, \alpha, \gamma)|}{dt}$$

• Phase velocity C:

$$\mathbf{C} = (\omega/k)\hat{\mathbf{k}}$$

 $\hat{\mathbf{k}} = (\cos(\phi), \sin(\phi))$ is the unitary vector in the k direction.



Channel flow (Re = 10000, k = 15, $y_0 = 0.5$)

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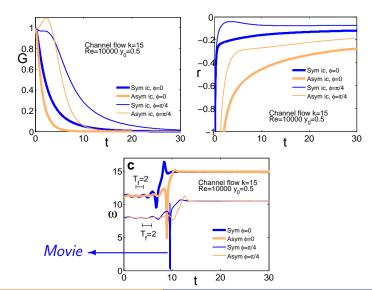
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Wake flow (Re = 100, k = 0.7, $x_0 = 50$, $y_0 = 1$)

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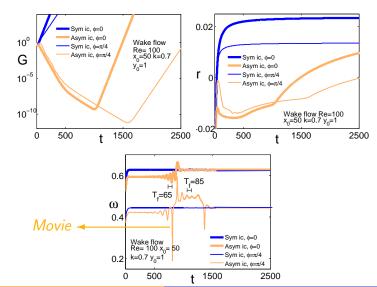
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Typical transient time scales

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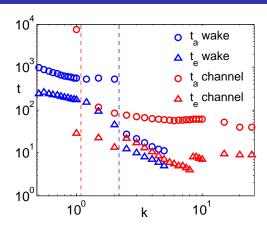
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 t_a (o): the asymptotic limit is reached. t_e (Δ): the early transient ends and the frequency discontinuities occur. Blue symbols: wake flow, Re=100, antisymmetric input, $\phi=\pi/4$, $x_0=10$, $y_0=1$. Red symbols: channel flow Re=10000, symmetric input, $\phi=\pi/4$, $y_0=0.5$.



Spectra of the frequency and phase velocity

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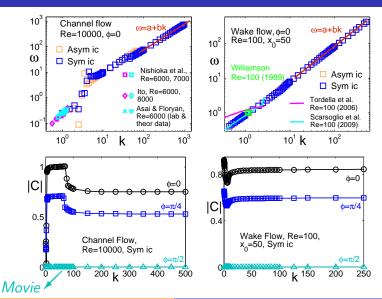
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Discontinuities in frequency never observed before (loss of information with the spectral analysis of signals);



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- Discontinuities in frequency never observed before (loss of information with the spectral analysis of signals);
- Jumps observed for different (stable and unstable) Reynolds numbers and for different shear flows;



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- Discontinuities in frequency never observed before (loss of information with the spectral analysis of signals);
- Jumps observed for different (stable and unstable) Reynolds numbers and for different shear flows;
- Emergence of different temporal scales in a linear system regardless the symmetry, the wavelength and the obliquity of perturbations;



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- Emergence of different temporal scales in a linear system regardless the symmetry, the wavelength and the obliquity of perturbations;
- Intermediate transient;



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- Jumps observed for different (stable and unstable) Reynolds numbers and for different shear flows;
- Emergence of different temporal scales in a linear system regardless the symmetry, the wavelength and the obliquity of perturbations;
- Intermediate transient:
- Orthogonal standing waves ⇒ How does a spot form?



Coming next...Spot formation

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• Single wave: k = 0.6;



Coming next...Spot formation

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• Single wave: k = 0.6;

• Different wavelengths: $k \sim 10^{-1} - 10^{0}$:



Coming next...Spot formation

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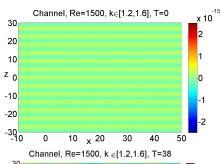
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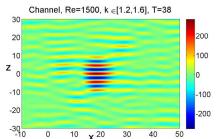
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• Single wave: k = 0.6;

• Different wavelengths: $k \sim 10^{-1} - 10^{0}$:

• Wave packet: $k \sim 1.4$.







Influence of the Reynolds number

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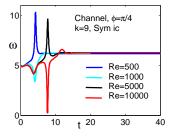
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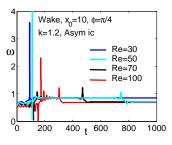
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Different transversal observation points y_0

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