Physics of the temporal and spatial forcing in wakes, separated flows and boundary layers for flow control

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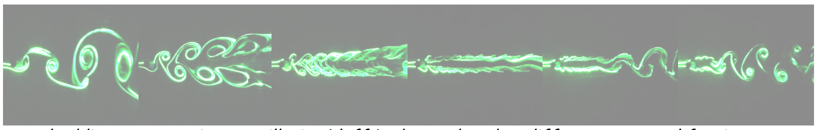
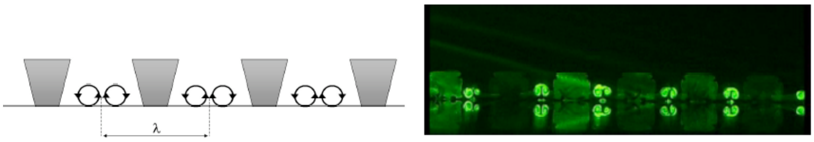


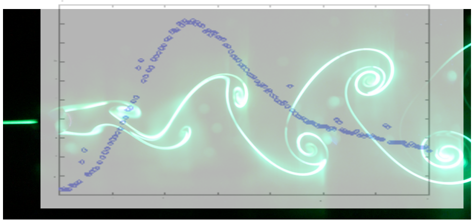
Vortex shedding patterns, in an oscillating bluff body, produced at different temporal forcing parameters (Re=150, forcing frequency = 0.5,1,2,3,4 and 5 times the natural vortex shedding frequency)



Schema of the vortex generators and flow cross-section pattern showing the downstream periodic counterrotating streamwise vortex forcing a boundary layer induced by the V.G.

Envelope of the Global Modes in *Free* Wakes: previous works

Envelope of velocity fluctuations-travelling wave-



Wesfreid et al. J. de Physique II 6,1343 (1996)
Zielinska et al. Phys. of Fluids 6,1418 (1995)
Goujon Durand et al. Phys Rev E 50, 308 (1994)

One Single Global Frequency

Strong inhomogeneity of the of velocity fluctuations

Strong dependence of the global mode shape -envelope- with Re.

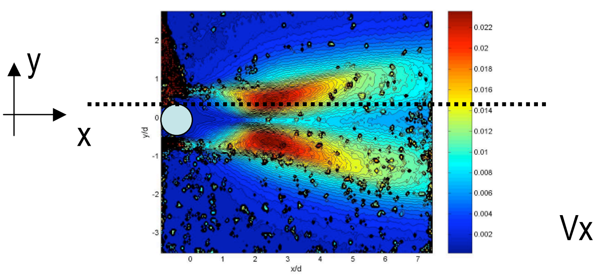
The laws for ρ_{max} and x_{max} are:

$\rho_{max} \sim (Re-Re_c)^{+1/2} \sim (\varepsilon)^{+1/2}$

and

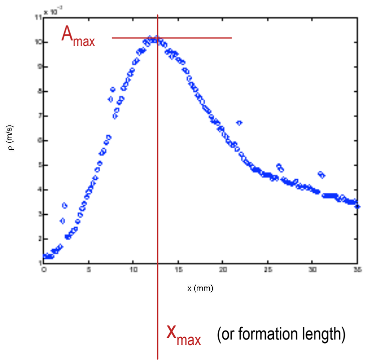
$X_{max} \sim (Re-Re_c)^{-1/2} \sim (\varepsilon)^{-1/2}$

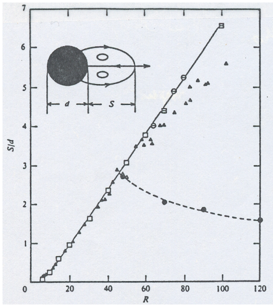
(*Landau-Ginzburg model*)



Re=150, Uo = 0,03 m/s

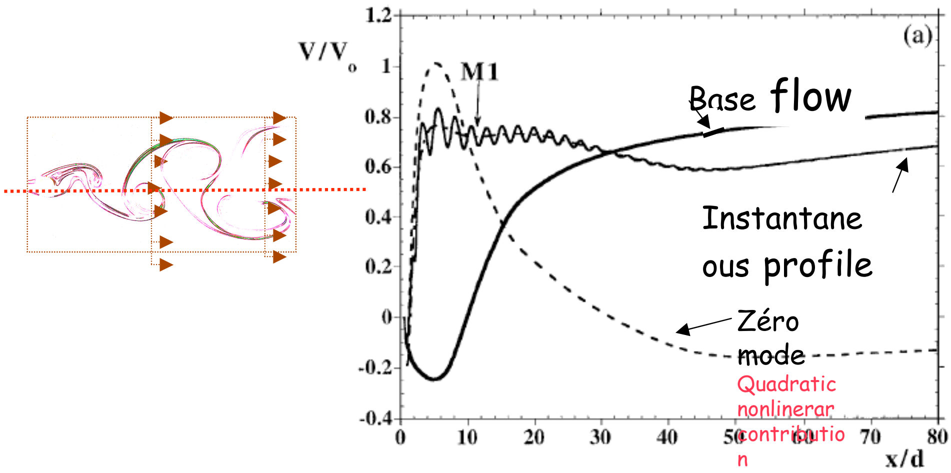
Envelope of the global mode



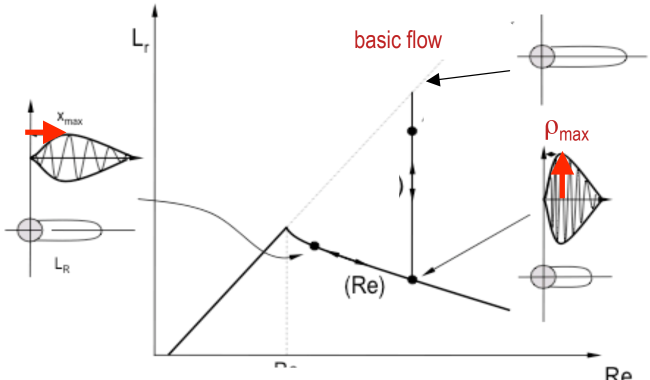


Recirculation length Lr behind the cylinder, as a function of the Reynolds number

Fluctuations develop nonlinear mean flow modification



Recirculation length L_r behind the cylinder, as function of the Reynolds number



Dependence of the global mode shape with Re.

ρ_{max}~ $(Re-Re_c)^{+1/2}$ ~ $(\varepsilon)^{+1/2}$

X_{max}~ $(Re-Re_c)^{-1/2}$ ~ $(\varepsilon)^{-1/2}$

(*Landau-Ginzburg model*)

$$\partial a/\partial t = (\epsilon + i\omega)\, a - (c_r + i c_i) \mid a^2 \mid a + (\xi_o + i\xi_i)\partial^2 a/\partial x^2$$

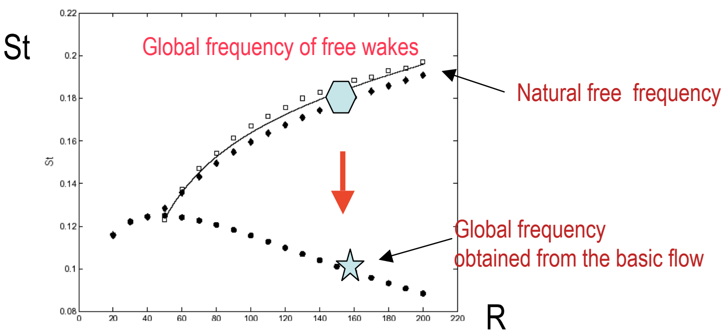


FIGURE 1. Evolution of the global selected frequency in the wake of a circular cylinder as a function of the Reynolds number. □: frequency obtained by direct numerical simulation (DNS). *solid line*: experimental results (from Williamson (1988)). Results represented by (♦), have been obtained by applying the linear criterium x_s on the time averaged mean flow. The (•) represent the same calculation (ω_s) applied on the unperturbed basic flow. From Pier (2002)

Flow control strategy

Protas and Wesfreid

812 Phys. Fluids, Vol. 14, No. 2, February 2002

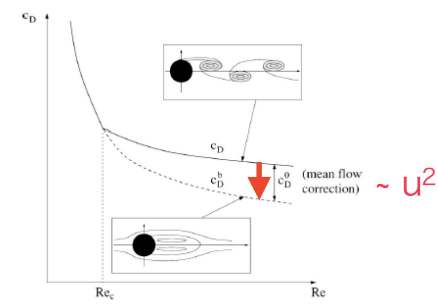
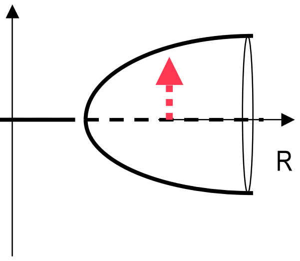
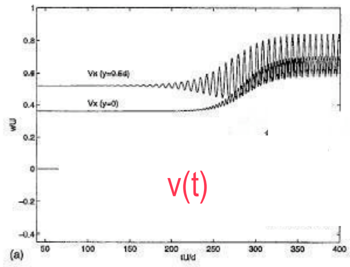


FIG. 2. Schematic showing the increase of drag due to the appearance of vortex shedding and the related mean flow correction. The insets represent the structure of the basic flow (drag indicated by the dashed line) and the unsteady flow (drag indicated by the solid line) at a given supercritical Re.

Mean flow as a function of time

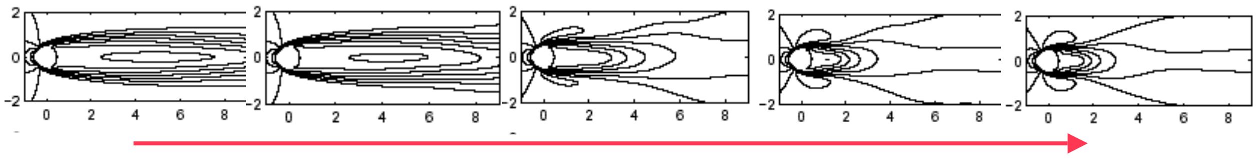
Thiria,Bouchet and Wesfreid (preprint 2007))
D. Barkley Europhysics Lett 75,750 (2006)
Noack,Tadmor, Morzynski AIAA (2006)





Fluctuations develop nonlinear mean flow modification

$$\partial a/\partial t = (\epsilon - |a^2|)\, a$$



Time

Fully 2D linear stability analysis of the **mean** flow, by D. Barkley (Europhys Lett. 2006)

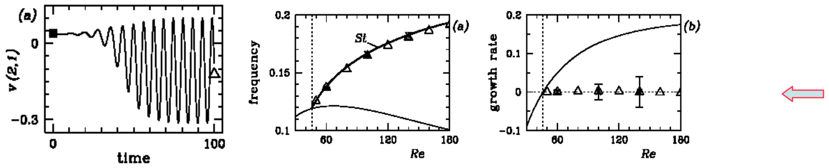
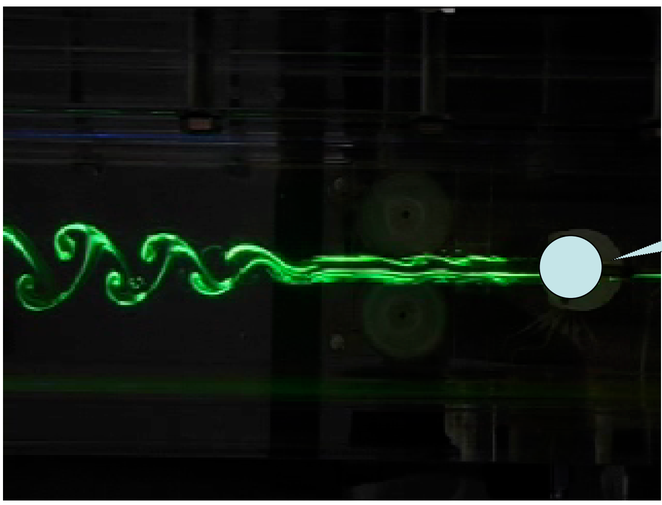
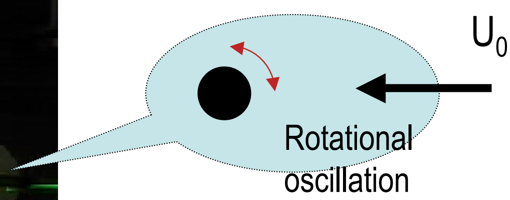


Fig. 2 – (a) Frequencies and (b) growth rates as a function of Reynolds number. In (a) the bold curve

The mean flow evolves to a state of marginal stability and the amplitude saturates
(…as Malkus marginal stability criterion for fully developed turbulent flows !)

Forcing the wake, with cylinder oscillation



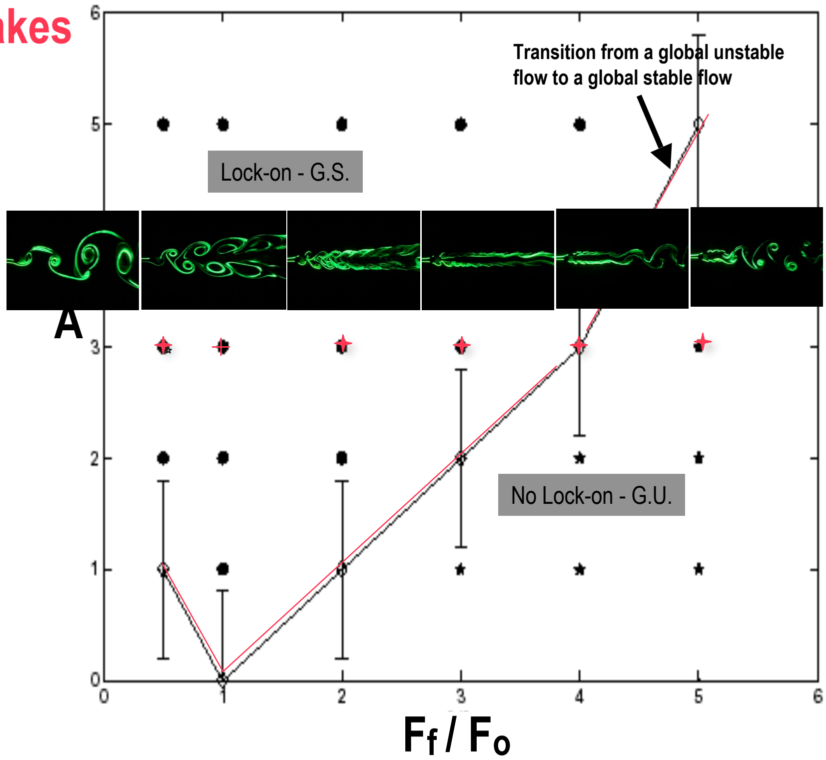


$$A = V_{max} / U_0$$

$$F = f_f / f_0$$

Thiria, B.; Goujon-Durand, S.: Wesfreid, J.E., Wake of a cylinder performing rotary oscillations. *Journal Of Fluid Mechanics* **2006,** 560, 123-148

Forced wakes



Movies of all the states can be downloaded on ftp://ftp.espci.fr/shadow/

FIGURE 19. Predicted global stability properties of forced wakes in the $A - f_f/f_0$ plane. The symbols ($\bullet$) denote a globally stable flow, while the symbols ($\star$) denote a globally unstable flow. The lozenges ($\Diamond$) indicate the transition between these two states, corresponding to a critical value of the forcing amplitude A_c, for each forcing frequency.

Stability properties of forced wakes

Thiria & Wesfreid, *J. Fluid Mech.* **579**, 137-161, 2007

Linear stability analysis of the forced *mean* flow *U(y)*, obtained experimentally by PIV

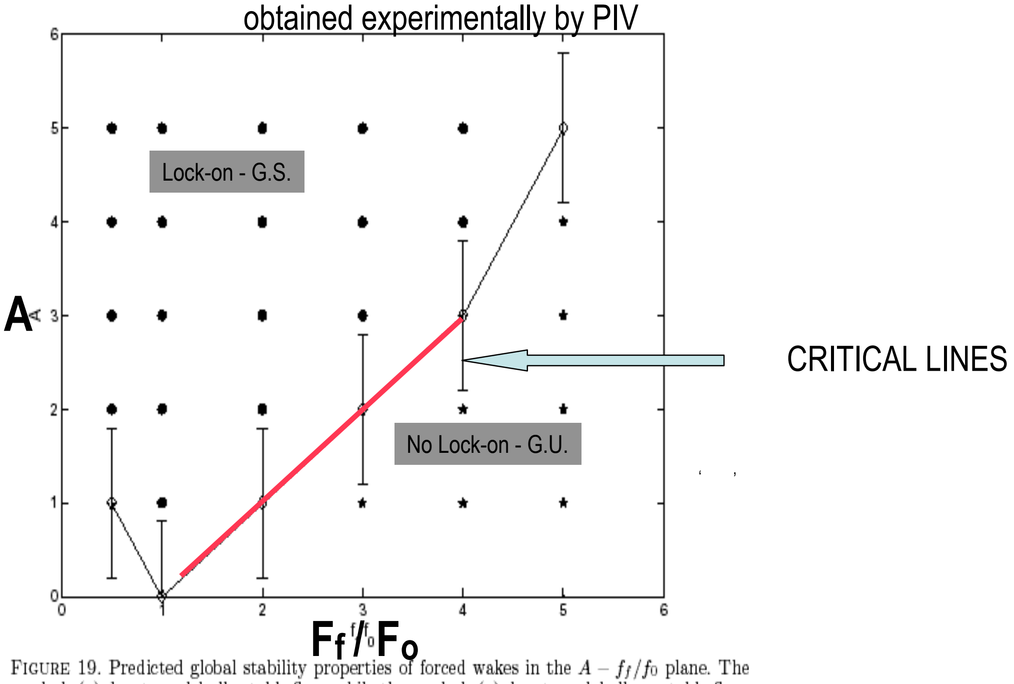
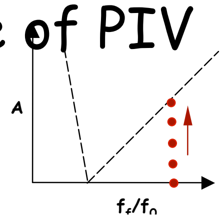


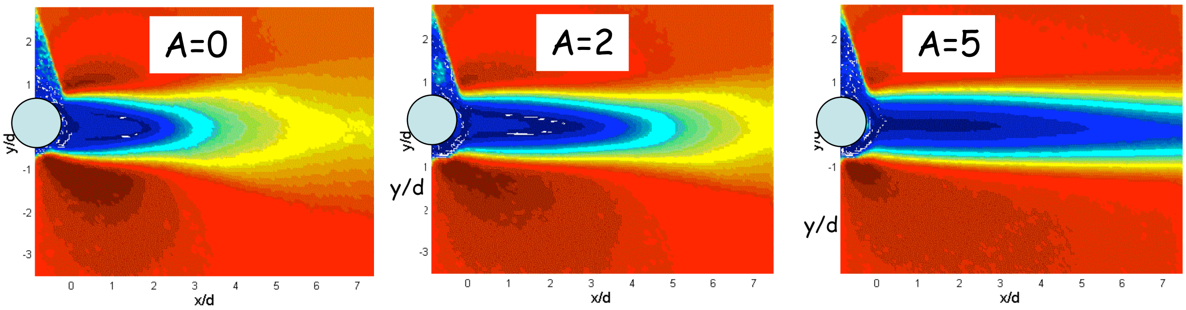
FIGURE 19. Predicted global stability properties of forced wakes in the $A - f_f/f_0$ plane. The symbols ($\bullet$) denote a globally stable flow, while the symbols ($\star$) denote a globally unstable flow. The lozenges ($\Diamond$) indicate the transition between these two states, corresponding to a critical value of the forcing amplitude A_c, for each forcing frequency.

Mean flows obtained by time average of PIV measurements, at $f_f/f_0 = 5$



Strong mean flow modification by the fluctuating vortex

The recirculation growing with *A*

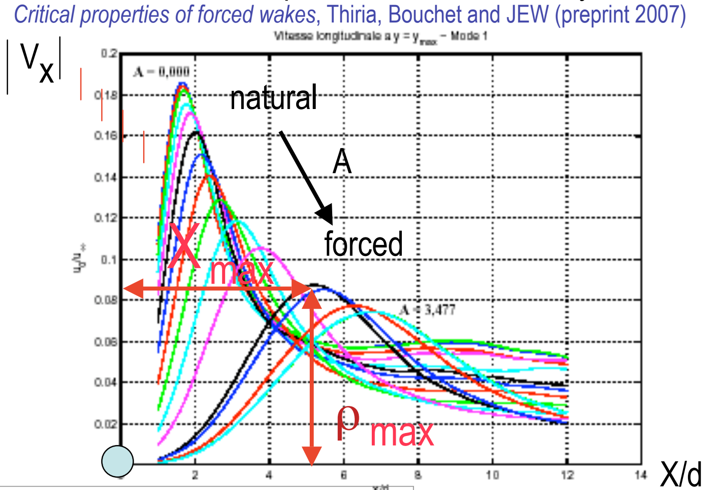


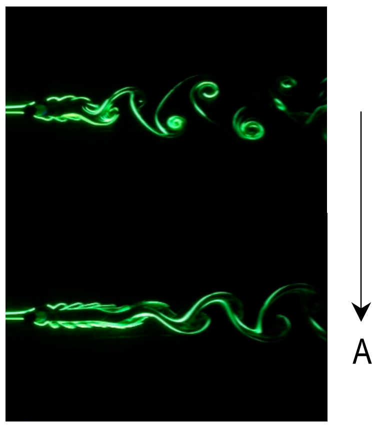
What happens with the global modes in forced wakes ?

There are scaling laws?

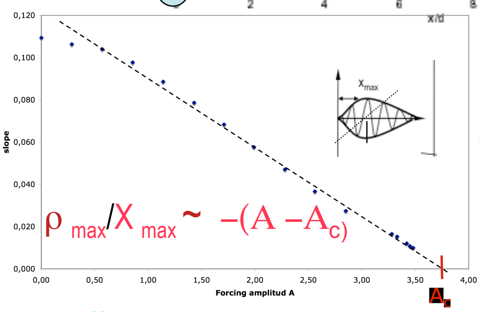
Envelope of the filtered velocity

Critical properties of forced wakes, Thiria, Bouchet and JEW (preprint 2007)





Experiments of Thiria, Goujon-Durand and Wesfreid (JFM 2006), when A grows at fixed forcing frequency



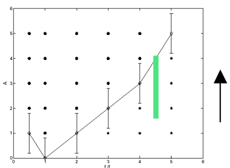
$\rho_{max} \sim (A_c\text{-}A)^{+1/2} \sim (\underline{\varepsilon})^{+1/2}$

and

$X_{max} \sim (A_c\text{-}A)^{-1/2} \sim (\underline{\varepsilon})^{-1/2}$,

so

$\rho_{max} \,/\, X_{max} \sim (A_c\text{-}A)^{+1} \sim (\underline{\varepsilon})^{+1}$



$\underline{\varepsilon}$: effective distance at onset;Growth rate tends to zero on this critical line

$$\partial a/\partial t = (\epsilon + i\omega)\, a - (c_r + ic_i) \mid a^2 \mid a - (\beta_r + i\beta_i) b\, a$$

$$\partial b/\partial t = -b + \kappa \mid a^2 \mid$$

Thiria, B.: Wesfreid, J.E., Stability properties of forced wakes. *Journal Of Fluid Mechanics* **2007,** 579, 137-161

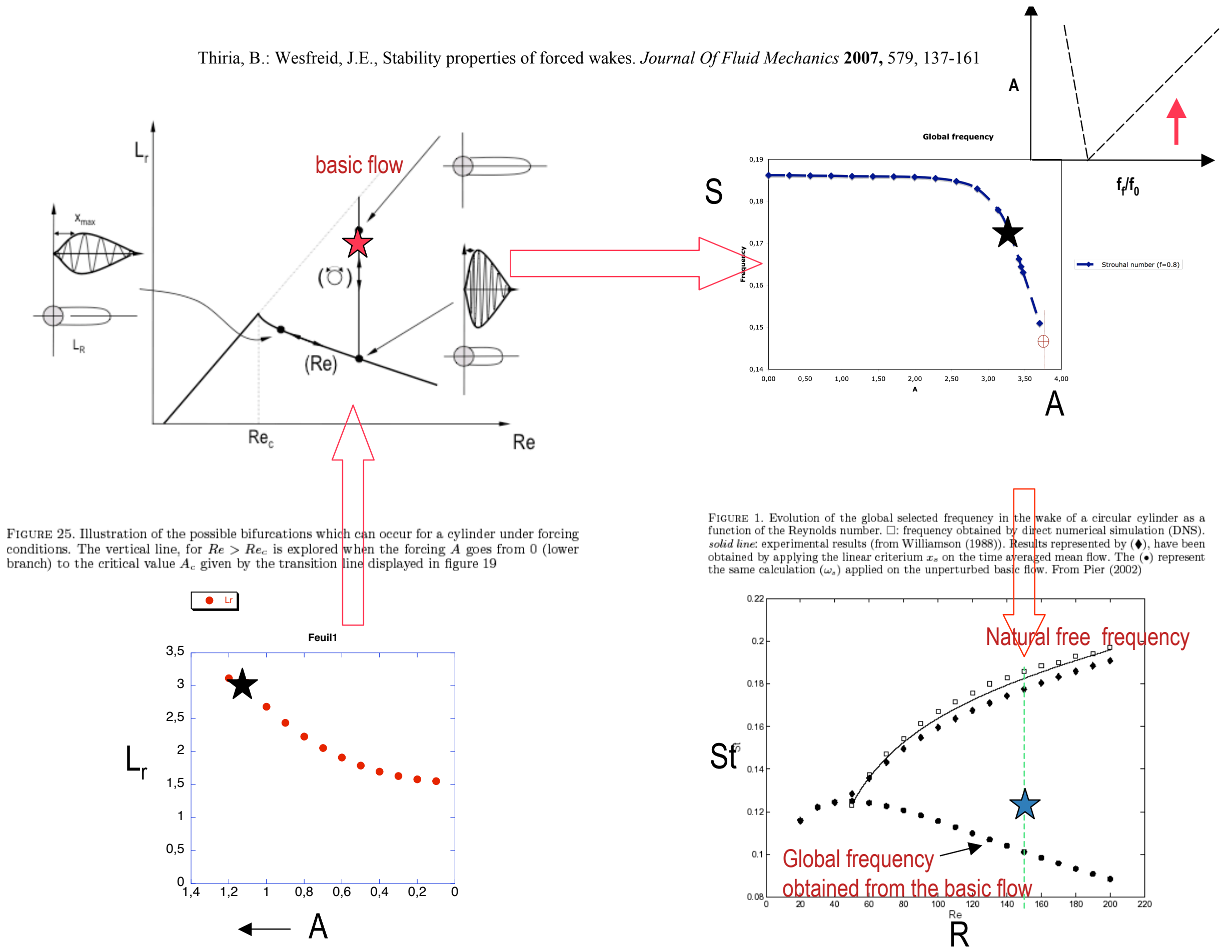


FIGURE 25. Illustration of the possible bifurcations which can occur for a cylinder under forcing conditions. The vertical line, for $Re > Re_c$ is explored when the forcing A goes from 0 (lower branch) to the critical value A_c given by the transition line displayed in figure 19

FIGURE 1. Evolution of the global selected frequency in the wake of a circular cylinder as a function of the Reynolds number. □: frequency obtained by direct numerical simulation (DNS). *solid line*: experimental results (from Williamson (1988)). Results represented by (♦), have been obtained by applying the linear criterium x_s on the time averaged mean flow. The (•) represent the same calculation (ω_s) applied on the unperturbed basic flow. From Pier (2002)

Model with mean flow coupling

In the forced non-locked state, the maximum amplitude and the typical length scales with the intensity of the forcing, as occurs in natural wakes with distance at the onset (R-Rc).

The effective control parameter changes R, but also with forcing which modifies the effective growth rate

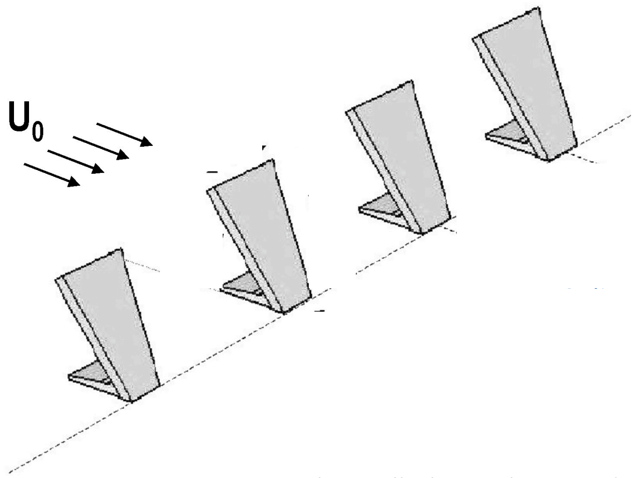
A model for these dynamics can be described by coupled amplitude equations as :

$$\partial a/\partial t = (\epsilon + i\omega)\, a - (c_r + ic_i) \mid a^2 \mid a - (\beta_r + i\beta_i) b\, a$$
$$\partial b/\partial t = -b + \kappa \mid a^2 \mid$$

where b is related to the mean flow modification (zero mode) and the effective growth rate increases with $(\beta_r + i\beta_i)B$

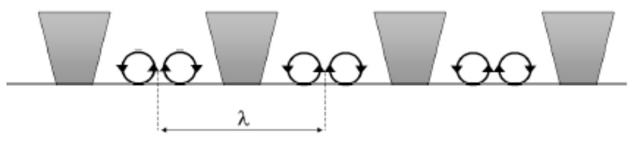
Periodically spatial forcing

Vortex Generators

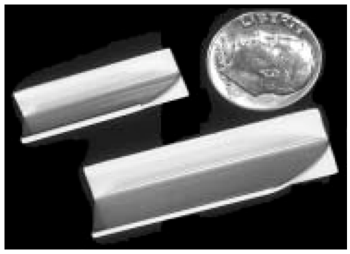


λVortex generators are simply small plates that sit above the wall. They look like tiny little wings sitting up perpendicular to the plate itself.

λ"As fluid moves past them, vortices are created off the **tips** of the generators". These vortices interact with the rest of the fluid moving over the wall and help generally, to prevent separation.



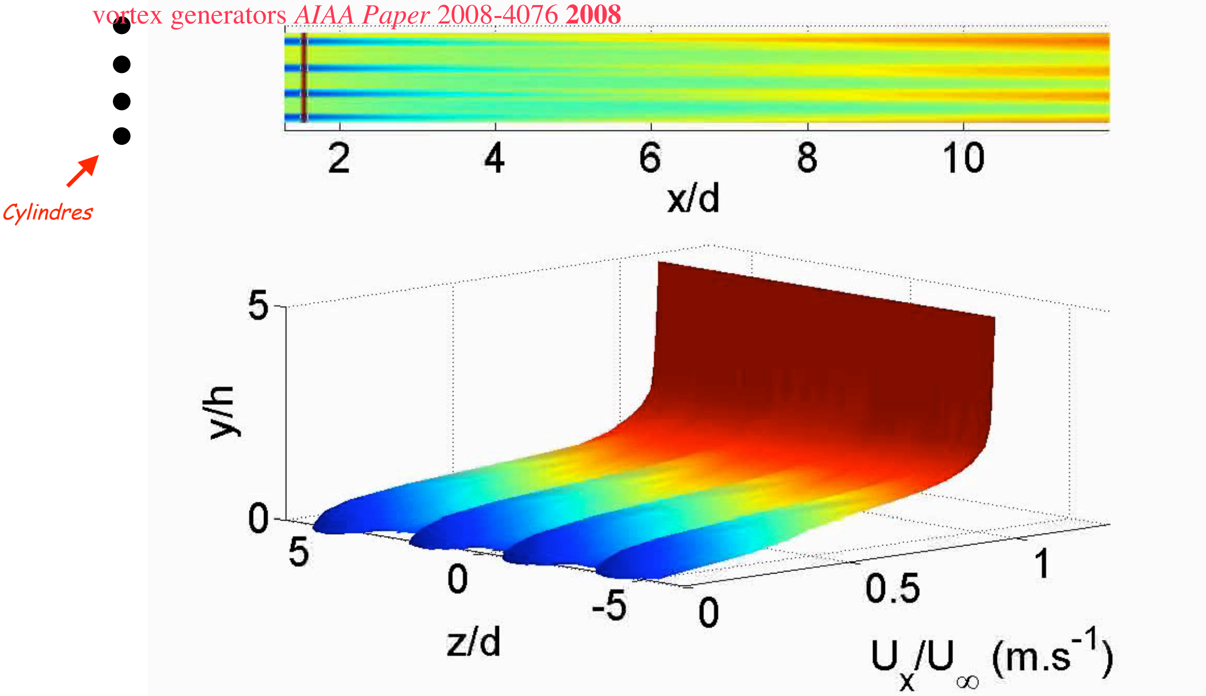
Applications:



The C-Airlounge has a drag coefficient of 0.26.

Modulation of the boundary layer profiles, induced by the V.G.

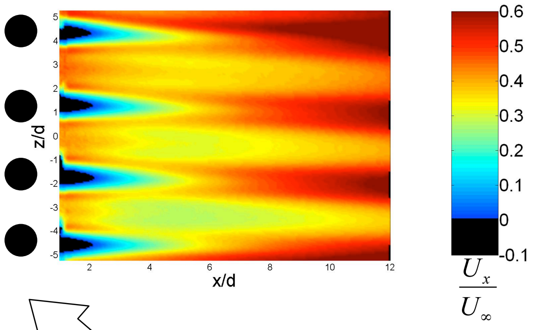
Duriez, T., Aider, J.-L.; Wesfreid, J.E., Non-linear modulation of a boundary layer induced by vortex generators *AIAA Paper* 2008-4076 **2008**

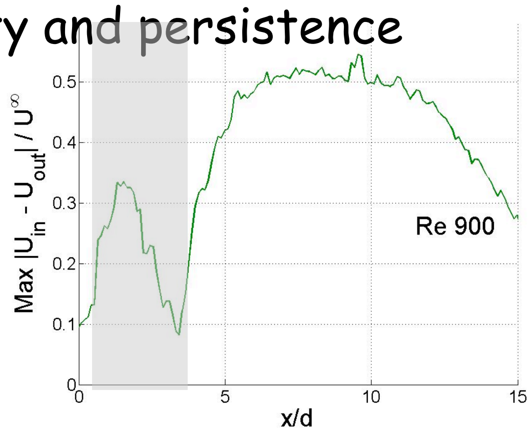


PIV reconstruction of the full velocity U_x field

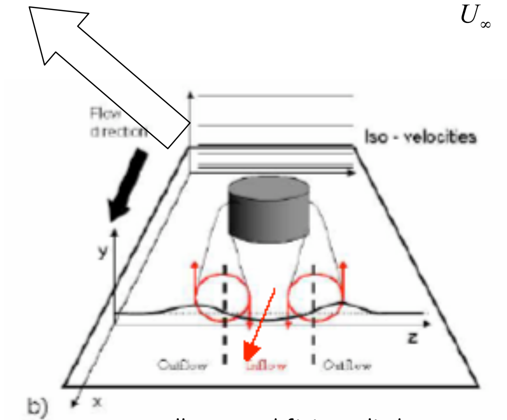
Spatial inhomogeneity and persistence

λ=3d

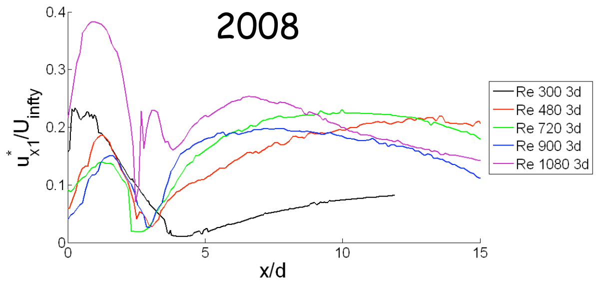


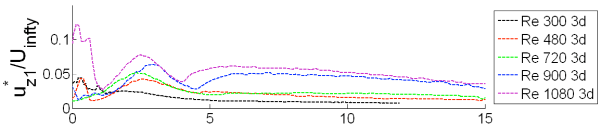


T.Duriez Ph.D. 2008



wall-mounted finite cylinder
produces horseshoes structures





Evolution of the flow depending also on the spacing

Non linear mean flow modification

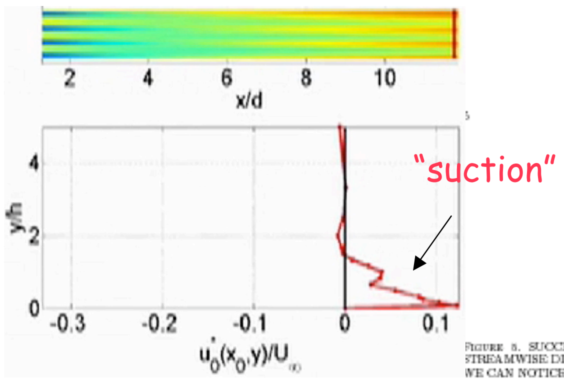
$$U(x,y,z) = U_{base}(x,y) + u_L(x,y,z) + u_{nL}(x,y,z)$$

$$u_{L(x,y,z)} = u_1^*(x,y)\exp(i\frac{2\pi}{\lambda}z) \quad u_{nL} = \sum_{k\geq 0, k\neq 1} u_i^*(x,y)\exp(ik\frac{2\pi}{\lambda}z)$$

Zeroth mode: $\boxed{u_0^*(x,y) = \langle U(x,y)\rangle_z - U_{base}(x,y)}$

Obtained from
measurements without
the V.G.

So, mean flow modulation !
BASE FLOW MODIFICATION
BY STREAMWISE VORTICES



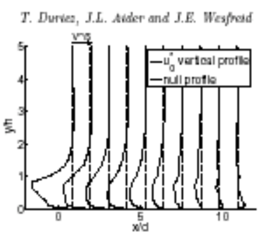


FIGURE 5. SUCCESSIVE VERTICAL PROFILES OF ZERO MODE u_0^* ALONG THE STREAMWISE DIRECTION IN THE CASE SPACING 3d AND REYOLDS NUMBER 300. WE CAN NOTICE THE SIGN CHANGE OF THE PROFILE PAST $x/d = 10$

Define a global mean
flow perturbation

$$G(x) = \int u_o(x,y)dy$$

Mean flow correction as non-linear saturation. Maurel, Pagneux, Wesfreid. Europhysics Letters (1995), 32 (3) 217—222
Spatial evolution of Gortler instability in a curved duct of high curvature. Petitjeans, Wesfreid. AIAA Journal, (1996) 34 (9) 1793—1800
Duriez, T.,Aider, J.-L.; Wesfreid, J.E., Base flow modification by streamwise vortices.Application to the control of separated flows Proceedings of FEDSM2006 (2006) and AIAA Paper 2008