Instabilities of a cylinder wake in a stratified fluid

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Although the dynamics of a cylinder wake is well known and extremely rich for a homogeneous fluid, very few studies have focused on stratified wakes despite their obvious applications to geophysical flows and submarine wakes. The goal of this study is to analyze experimentally, numerically and theoretically how a linearly stratified fluid modifies the dynamics of a tilted cylinder towed horizontally in a linearly stratified fluid.
The 2D dynamics of the wake shows that the von Karman vortex street is stabilized by a moderate stratification for tilted and horizontal cylinders in agreement with the stabilization of shear flows at large Richardson numbers. However, the von Karman vortices surprisingly reappear for large stratification for a tilted cylinder. The 3D instabilities are characterized by the classical mode A for a vertical cylinder, but reveal a new critical-layer structure for large tilt angles.

MOTIVATIONS AND PRESENTATION OF THE PROBLEM

Bluff body wakes have been a main subject of interest in engineering where drag reduction and mechanical robustness have been a major issue for trains, boats, bridges and buildings. The vortex street was firstly explained as an intrinsic phenomenon by Karman (1912). It is also well known that for homogeneous fluid, a 3D instability appears at Re > 189 for a cylinder wake (Williamson 1996).
In geophysical flows and submarine wakes, the presence of the stratification may largely modify the dynamics of the wake. However, very few studies have focused on stratification wakes and have been mostly devoted to turbulent wakes at large Reynolds number. We wish here to address the transition to turbulence in a stratified cylinder wake.
Our experiment consists in towing horizontally a circular cylinder of diameter D in a stratified fluid at a velocity U. The cylinder axis is tilted relative to the vertical at an angle α in the cross-stream plane. The continuous profile of density ρ is established by the two tank method and characterized by the Brunt Vaisala frequency $N = \sqrt{-(g/\rho)(\partial\rho/\partial z)}$. The two non-dimensional parameters are the Reynolds number Re = UL/ν (varying from 60 to 250) and the Froude number F=UN/D (varying from 0.5 to 8).

2D INSTABILITY

In a homogeneous fluid, it is well known that the von Karman vortex street appears for a critical Reynolds number (Rec=50). In a stratified fluid and at low stratification, the von Karman street can also be observed at Re=100. The vortices are shed alternatively from each side of the cylinder and roll-up while they are advected downstream. When the stratification increases, the vortex street disappears and is replaced by a stationary recirculation bubble at the same Reynolds number. The stratification can thus restabilize the wake, even for a Reynolds number close to twice the initial Reynolds number in a homogeneous fluid. Surprisingly when the stratification increases further, the wake becomes unstable once again (Figure 1) and leads to a von Karman vortex street as for a homogeneous fluid. This new unstable mode can be understood by the presence of tilted vortices with no vertical velocity, i.e with horizontal streamlines.

3D INSTABILITY

In a second part, we focus on the 3D instability of the cylinder wake which appears at large Reynolds number.
For weak stratification, the classical mode A which is well known in homogeneous cylinder wakes is observed, as shown on shadowgraph visualizations (Figure 2a). This mode is made of counter-rotating longitudinal vortex pairs

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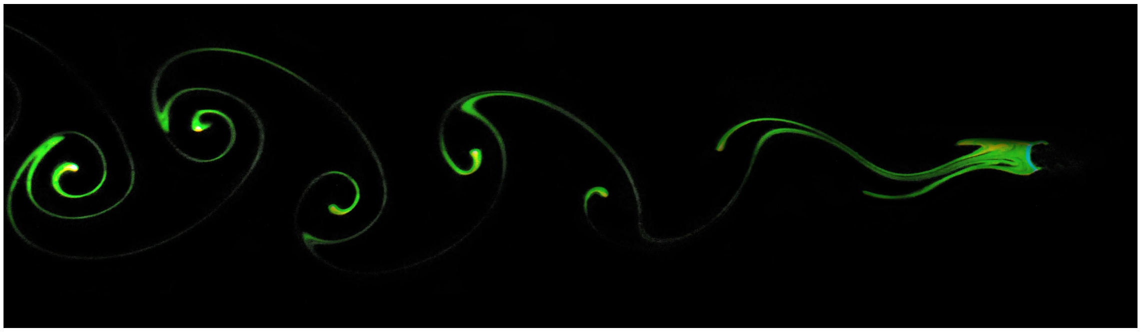

Figure 1: Dye visualization of the reappearance of von Karman street obtained at Re=100, F=0.8 and α=30°

whose tails seem to be entrained to the left by the cylinder. The vortex pairs close to the cylinder are fairly visible whereas the vortex pairs far from the cylinder are very contrasted which reflects the temporal growth of these structures. The axial wavelength is close to 4 diameters, corresponding to the wavelength for the well known mode A. The 3D stability diagrams have been established for different tilt angles and show that the mode A is enhanced at 1.5<F<4 and suppressed for F<1.5. The behaviour is strongly modified for large tilt angles (from 45° to 60°) with the presence of a new unstable mode (Figure 2b) characterized by dark and bright undulated layers probably corresponding to critical layers. The structure is similar to the Kelvin-Helmholtz billows which have been observed in the critical layer of a tilted stratified vortex.

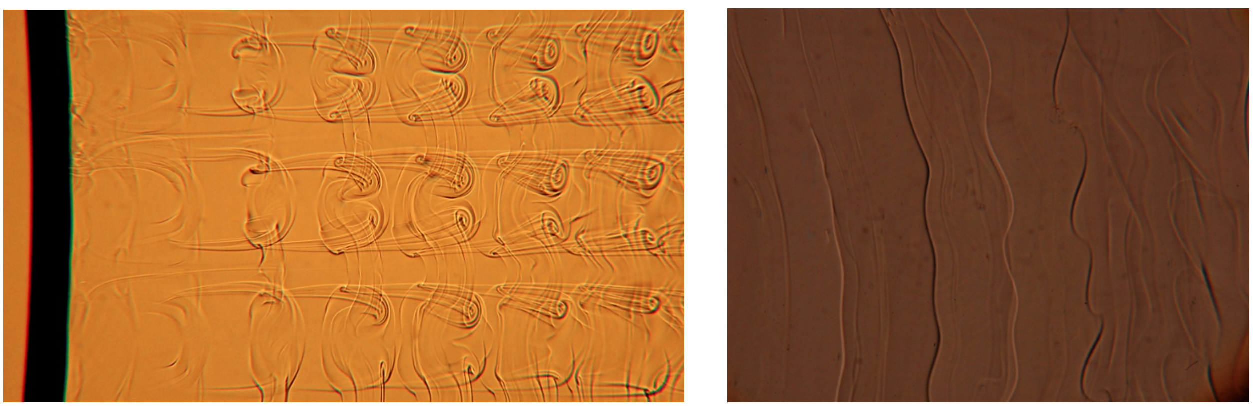

Figure 2: Shadowgraph visualization of 3D unstable modes in a vertical cylinder (2a, left) and in a cylinder tilted at 45° (2b, right). (a): Re=185, F=3.5. (b): Re=170, F=2.

CONCLUSIONS

This study has shown that the dynamics of a cylinder wake is largely modified by the presence of a stratification, with the stabilization of the von Karman wake at moderate stratification and with a new 3D unstable mode for tilted cylinders. In the future, this instability will be studied for very strong stratification and large tilt angles. The bluff body will be replaced by a half cylinder on a tilted bottom in order to be closer to geophysical applications.

References

[1] J.T. Lin and Y.H. Pao: Wakes in stratified fluids: a review. *Ann. Rev. Fluid Mech.* Vol **11** p 317, 1979.
[2] C.H.K. Williamson: Three-dimensional wake transition. *J. Fluid Mech.* Vol **328** p 345-407, 1996.
[3] N. Boulanger, P. Meunier and S. Le Dizes: Tilt-induced instability of a stratified vortex. *J. Fluid Mech.* Vol **596** p 1-20, 2008.
[4] P. Meunier: Stratified wake of a tilted cylinder. Part 1: Suppression of von-Karman vortex street. Subm to *J. Fluid Mech.* 2011.
[5] Boyer D. and al. : Linearly stratified flow past a horizontal circular cylinder. *Philos. Trans. R. Soc. London Ser.* **328**, 501 1989.