IUTAM Symposium on Unsteady Separated Flows and their Control, June 18-22, 2007, Corfu, Greece

# WAKE BEHIND A SPHERE: EXPERIMENTAL AND NUMERICAL INVESTIGATIONS

K. GUMOWSKI*, J. MIEDZIK*, S. GOUJON-DURAND,
G. BOUCHET**, P. JENFFER AND J.E. WESFREID
Ecole Supérieure de Physique et de Chimie Industrielles de la Ville de Paris, PMMH,
UMR7636 CNRS ESPCI P6-P7
*Warsaw University of Technology, Institute of Aeronautics and Applied Mechanics
** Institut de Mécanique des Fluides et des Solides, Strasbourg
gumowski@gmail.com, miedzik@gmail.com, sophie@pmmh.espci.fr, patrice@pmmh.espci.fr,
**bouchet@imfs.u-strasbg.fr, wesfreid@pmmh.espci.fr

## 1 Introduction

We study the flow behind a solid sphere in order to examine the transitional flow for Reynolds number up to 500, which shows successively stationary axisymmetric properties, stationary non-axisymmetrical instability and global temporal instability. The numerical study, with spectral methods, shows how the symmetry breaking in the recirculation bubble induces streamwise vortex. In addition we experimentally study the influence of the real conditions of holding of the sphere on the unstationary instability. Finally we perform very controlled experiments on the streamwise vortex, in order to follow the dynamics of formation of the hairpin vortex shedding.

## 2 Experimental results

The wake of the sphere has been the object of a large number of studies. Previous visualizations at low Reynolds numbers, performed by Taneda (1), Magarvey and Bishop (2), allow distinguishing different regimes. The wakes of the sphere has an axisymmetric stationary recirculating eddy with a ring structure up to Reynolds number 212. With crossing Re = 212 this eddy loose his axial symmetry and the flow became non axisymmetric. As the ring vortex shifted off axis, released from the wake in two parallel steady counter rotating vortexes. By the Re = 268 the wake becomes unsteady with peristaltic instability, which develop and causes vortex reconnection for the Re = 280 in our experiments.

We study the flow behind a sphere in the low velocity water channel built with transparent plexiglas walls of 10x10cm cross section with typical velocity 0.4 to 4 cm/sec, which corresponds to a Reynolds number from 50 up to 500. The sphere has diameter of d = 1.6cm.
The wake visualizations were performed in the three directions, using Laser Induced Flurosceine (LIF). The dye (flurosceine dye in solution) was injected in the middle of the sphere using a thin vertical or horizontal slit. The measurements of the velocity fields were performed using a standard Particle Image Velocimetry set-up (PIV).

Different types of holding were used in order to reduce the perturbations of the full three-dimensional character of the wake (Fig. 1). The symmetry plane of the two counter-rotating vortex exist is giving by the orientation angle β. The vertical velocity gradient induced by the tube support at the angle α provokes that the hairpins are detached from upper or lower side of the sphere. Effect of the support system was previously analyzed by L. Schouveiler and M. Provansal (3). We present the results about the effect of holding on the bifurcation on-set.

Two kinds of holdings were used in our experiments; the sphere was held from upstream by a rigid straight or a rigid bent tube. Breaking of the symmetries, due to the fixation provokes imperfect bifurcations. As shown in the Fig. 2 in the case of straight tube the second onset instability decrease of about 50 Reynolds.

In the Fig. 3 is shown the confirmation of the cause of the first bifurcation. The recirculation bubble remain axisymmetric up to Re = 212. With increasing Reynolds number the bubble looses his axial symmetry. The loose of axial symmetry is responsible of two counter rotating vortices apparition. The flow rests steady with planar symmetry.

Starting from Reynolds number Re = 265 it is straightforward to notice small oscillations of two vortices in the sphere wake. Oscillations are growing with Reynolds number (Fig. 4). The oscillations first appear in far wake of sphere (for Re 260, about x/d = 15) and with increasing. This flow is not anymore stationary. Still increasing Reynolds number is reached the point of observable hairpins shedding. This situation occurs with Reynolds number about 280 in our experiments. We decided to characterize this beginning of the peristaltic instability. We defined parameter delta as the difference between the biggest (b'') and smallest (b') distance between vortices cores $\Delta = (b'' - b')$. As you can see at the Fig. 5 a delta increases up to Re = 277 and for higher Reynolds number the value of the delta reach saturation what corresponds with hairpins shedding apparition. For all distances delta reach value zero for Re number about Re = 267.
These results were confirmed by PIV measurements. From rear view PIV images was obtained the frequency of vertical $V_y$ velocity component measured between two vortices. As shown in Fig. 6, for Re = 263 only noise is noticed. Starting from Re around 267 appear oscillations which are growing up to Re = 280 where hairpins developing begins. The question was if the frequency of this oscillation is a new one or is connected with hairpins shedding phenomenon.
As you can see in the Fig. 7 the frequency of peristaltic instability and of hairpins shedding are lying on the same line which implied the peristaltic undulation frequency is continuation of hairpins shedding frequency. It suggest, this both phenomenon are the same instability, which starts at Reynolds number around Re = 267. It seams that the hairpin is just the result of enough strong oscillations in the wake, more precisely in recirculation area.

## 3 Numerical results

The experimental results are compared and supplemented by a numerical study performed with an original code based on a non-linear theory of the axisymmetry breaking (three dimensional Navier-Stokes solver using spectral elements and an azimuthal decomposition in Fourier series). The exceptional effectiveness of the direct numerical method allowed to entirely describe the process of transition to turbulence of the wake of a fixed sphere involving a cascade of instabilities between neighboring states, i.e. the steady axisymmetric regime with detached flow (for Re > 20), the steady non-axisymmetric flow (for Re > 212), the unsteady periodic regime (for Re > 274) and the aperiodic regime (for Re > 300) (6).
Fig. 5 b shows a very good comparison between the experimental and the numerical determination of parameter delta. The difference between the numerical Strouhal number and the experimental one is due to the confinement of the sphere in the water channel (Fig. 8).

## 4 Conclusion

We obtained a new scenario "precursor" of the hairpin vortex shedding, with a peristaltic instability of oscillations of the two parallel counter-rotating vortices behind a sphere. These results are equally interesting to understand the dynamics of bubbles and drops, which they also shown two counter-rotating vortices induced by the lost of sphericity of the bubbles, as occur here with the loss of sphericity of the recirculation area.

## References

1 TANEDA, S.: Experimental investigation of the wake behind a sphere at low Reynolds numbers. J. Phys. Soc. Japan, 11, (1956) 1104-1108.

2 MAGARVEY, R. AND BISHOP, R.L: Transition ranges for three-dimensional wakes. Can. J. Phys., 39, (1961) 1418-1422.

3 SCHOUVEILER, L. AND PROVANSAL, M.: Self-sustained oscillations in the wake of a sphere. Phys. of Fluids, 14, (2002) 3846-3854.

4 ORMIERES, D. AND PROVANSAL, M.: Transition to Turbulence in the wake of a Sphere. Physical Review Letters, 83, (1999) 80-83.

5 JOHNSON, T.A. AND PATEL, V.C.: Flow past a sphere up to a Reynolds number of 300. J. Fluid Mech., 378, (1999) 19-71.

6 BOUCHET, G., MEBAREK, M. AND DUSEK J.: Hydrodynamic forces acting on a rigid fixed sphere in early transitional regimes. European Journal of Mechanics B/Fluids, **25**, (2006) 321-336.

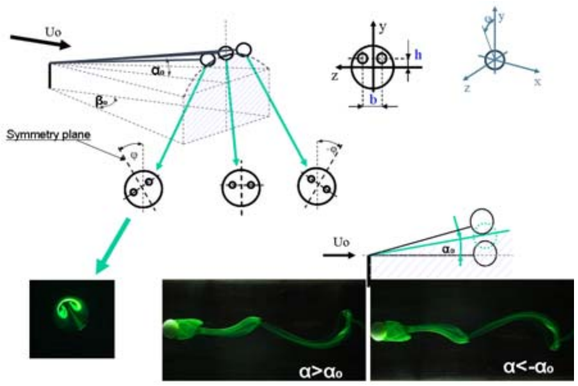


Fig. 1 Holding influence

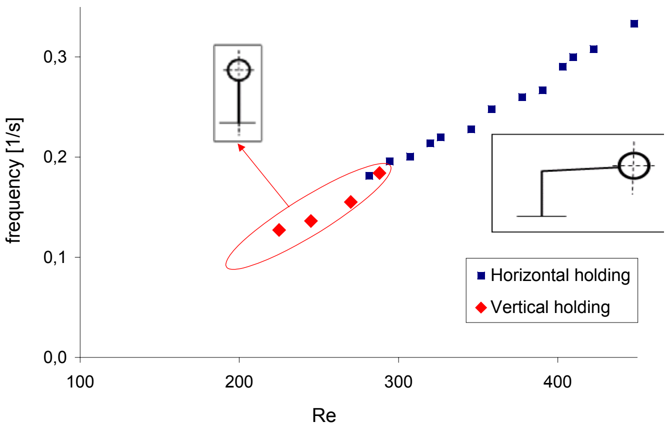


Fig. 2 Imperfect bifurcation

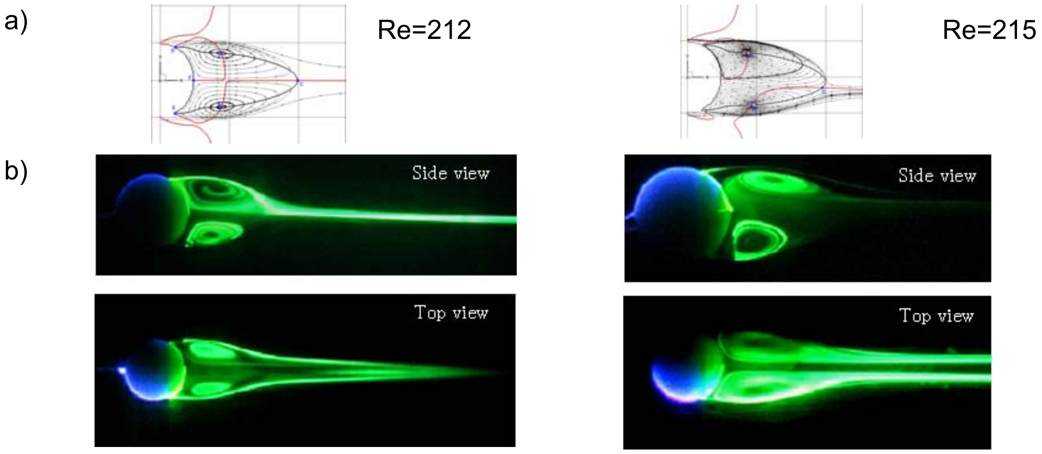


Fig. 3 Recirculation area, numerical simulation (a) and visualization (b) results before and after bifurcation

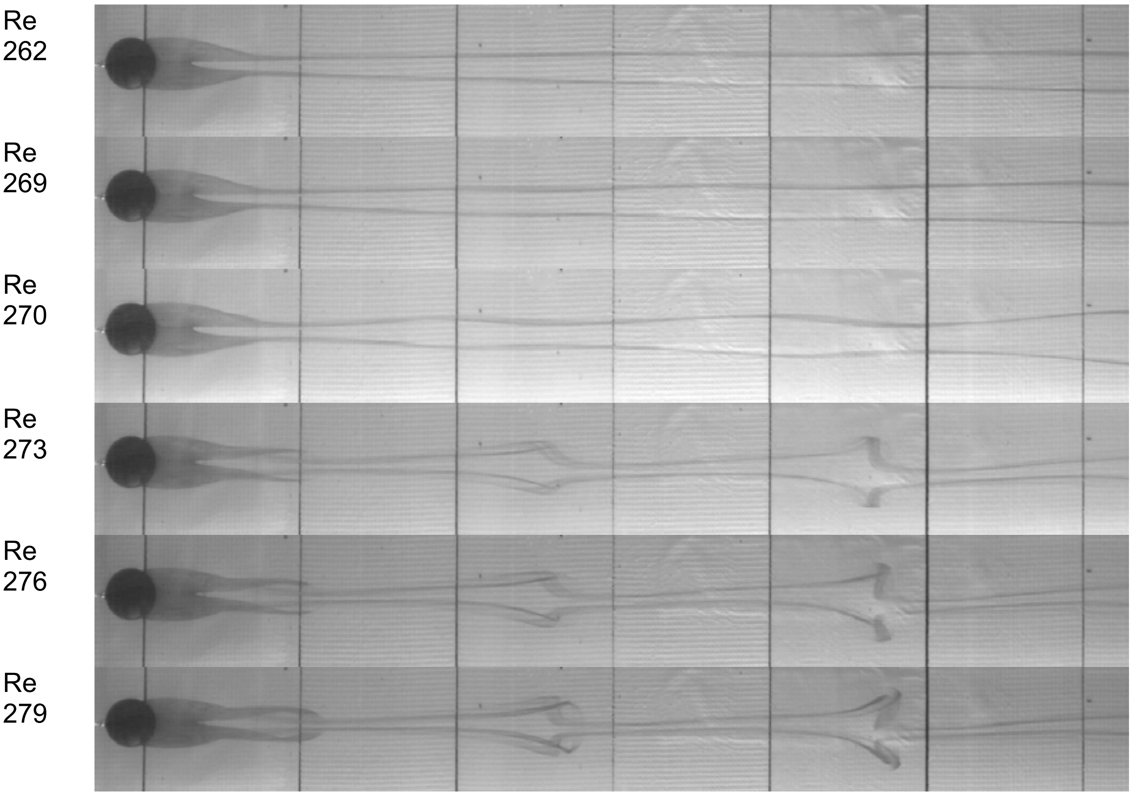


Fig. 4 From peristaltic instability to hairpins shedding

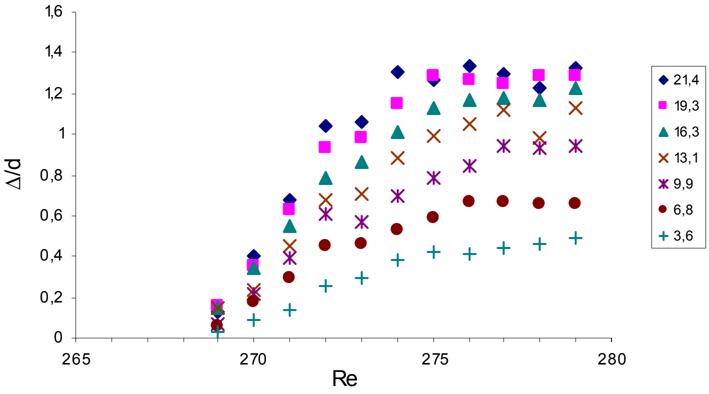


Fig. 5 a Delta as a function of Reynolds number (experimental results)

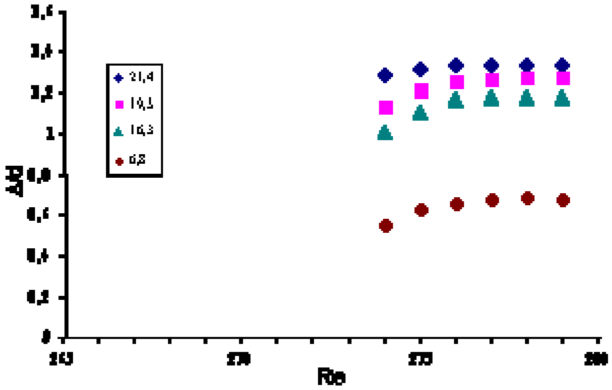
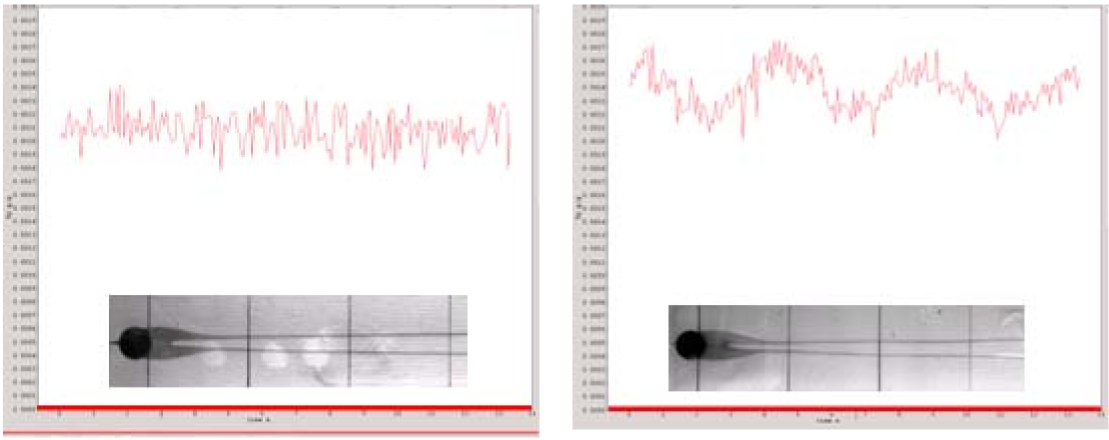
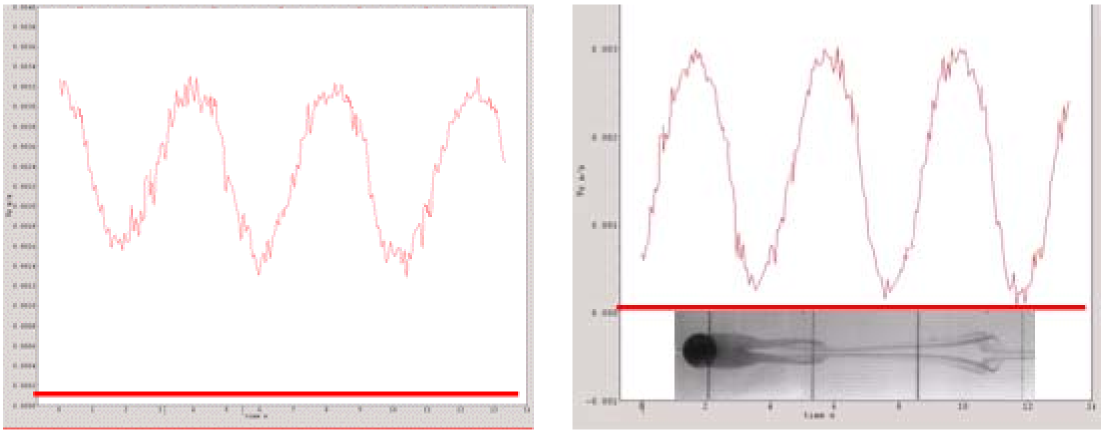


Fig. 5 b Delta as a function of Reynolds number (numerical results)



Stable (Re 263)

First oscillations (Re = 269)



Re 276

Hairpins shedding (Re = 280)

Fig. 6 Vertical velocity component time

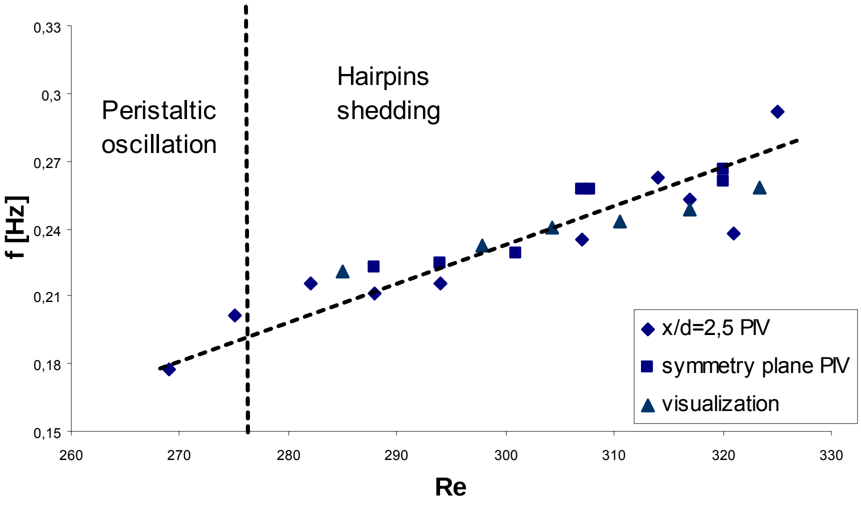


Fig. 7 Frequency of instability

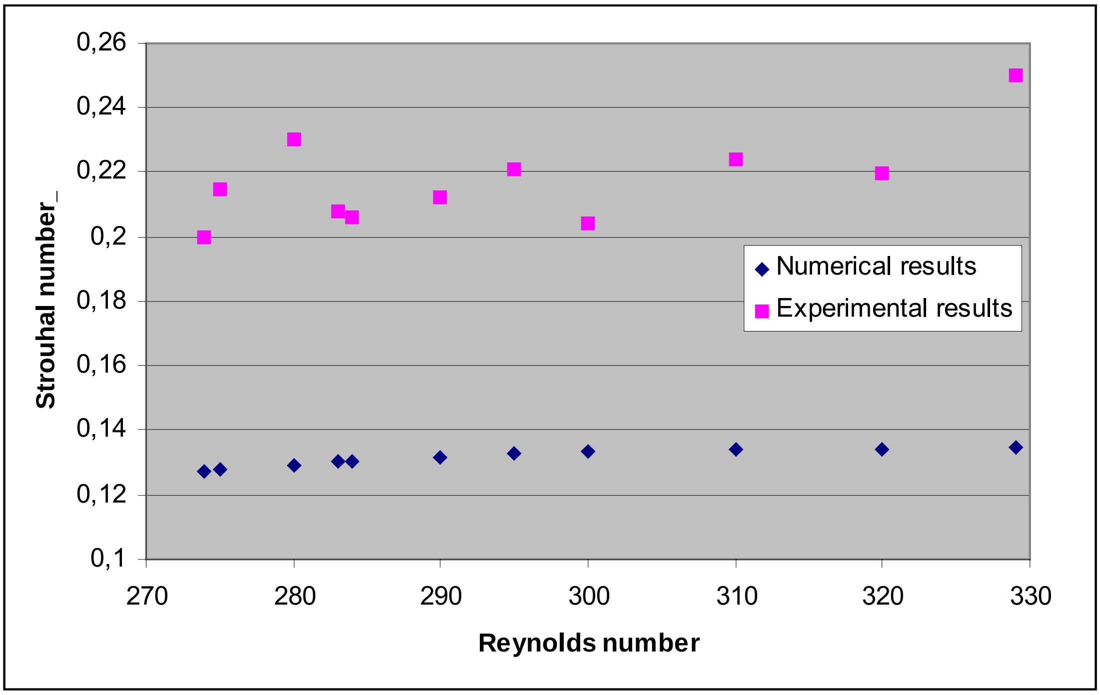


Fig. 8 Strouhal number