SEMI-CIRCULAR-SECTION CYLINDER WAKE VISUALIZATION

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Abstract
Flow visualization permits flow fields exploration, as well as physical phenomena interpretation, from fields induced by global measurement – force, moment – or from local ones – pressure, velocity. Linking that important experimental technique with image processing, this work investigates the vortex-shedding wake from semi-circular section prismatic bluff-body. Experiments were performed out in a pilot vertical low turbulence hydrodynamic tunnel, with 146×146×500 mm of test section. The emission of liquid dye tracers through very small holes on the body surface has been used to create the flow image. Video images have been captured using a 3 CCD high-resolution video camera, and still photographic images using a S.L.R. 35 mm camera. Strouhal number is determinate by image processing for Reynolds numbers up to 600. The knowledge of the Strouhal number behavior in function of Reynolds number for several rigid body shapes is much important as aid to vortex meter projects.

Keywords: Flow visualization, Image processing, Vortex shedding, Bluff body

1. INTRODUCTION

Studies of vortex wakes generated by different geometries of rigid prismatic bluff-bodies applied to several engineering fields as well as to the Nature. Many numerical or experimental tools have been developed intending to understand this complex phenomenon.

Numerical research works on several prismatic bluff-body wakes, circular and square sections mostly, are frequently found, as in Meneghini *et al*. (1998), employing large eddy simulation for an oscillating circular cylinder, or in Pereira *et al*. (1999), using vortex method simulation to arbitrary bodies.

Many experimental techniques have also been proposed in the technical literature to von Kármán-vortex wake research. In scientific laboratory environment, vortex-shedding frequency is generally measured by a number of different ways. Modi & Dikshit (1975) employed successfully a highly sensitive pressure transducer positioned at the centerline of the vortex wake, and Sarpkaya & Kline (1982) measured the lift force actuating directly on the body surface using very small pressure sensors. Many researchers prefer to determine a spectral analysis of the flow velocity in a fixed point on the wake. In those cases, the velocity signal are obtained by several ways, hot-wire anemometers (HWA) – Okajima (1982) and Kawakita & Silvares (1993) – laser Doppler Anemometers (LDA) – Ferreira & Santos (1998) and Durão *et al* (1991), at last, using particle image velocimetry (PIV) – Agüi & Jiménez (1987) and Lourenço *et al*. (1997).

On the other hand, experimental flow visualization represents a very powerful tool for bluff-body wake analysis. Several beautiful images have been obtained out of different prismatic non-aerodynamic body wakes in hydrodynamic medium for relatively low Reynolds (up to 4000). Examples are the the images obtained by: Gonçalves & Vieira, (1999) utilizing four different regular polygon section cylinders (Re less than 600); Lindquist *et al*. (1999), for circular cylinder (showing the vortex street and re-circulating bubble) and Lindquist *et al*. (1998) for rectangular cylinder.

However, just few works explore the semi-circular section geometry, one exception could be given up to the papers by Luo & Chew (1989) and by Boisaubert *et al*. (1996). Additionally it is well known to the bluff-body aerodynamicist that the wakes of different prismatic bluff-bodies are not identical and moreover, there is a great influence of the after-body shape on their aerodynamics.

The main goal of the present work is, therefore, to study the wake generated by semi-circular cylinders positioned orthogonally according two different arrangements – the flat side facing upstream and downstream respectively, as in Figure 1.

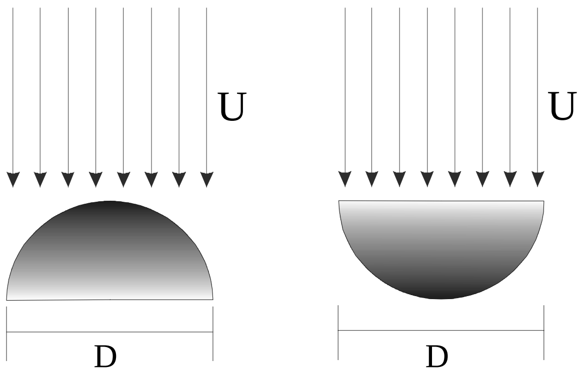

Figure 1. Semi-circular section bluff-body cylinder tested in two different arrangements

2. EXPERIMENTAL SET-UP

Qualitative and quantitative experimental results from flow visualization have been obtained in a vertical low turbulence hydrodynamic pilot tunnel, operated by gravitational effect in blow-down mode, with a 146x146x500 mm test section and 0,1 % of turbulence. More details about that water tunnel facility and its operation are available in Gonçalves & Vieira (1999).

The flow visualization technique applied in this work is the injection of opaque liquid dye through small holes (I.D. 0,7 mm) on the body surface. The dye utilized is a solution of black PVA pigments, water and ethyl alcohol. The flow image has intensively been illuminated by twelve photoflood tungsten (150 W) lamps, shielded by white velvet-like translucent paper in order to provide a uniformly diffuse bright background against which the dye patterns were photographed.

A JVC KY-27C high-resolution video camera and a BR-S822U JVC videocassette recording (VCR) equipped with a TC (time counter) board have been used to capture video images. TC board permits the recording of a precise temporal identification of each frame. Observing in a highly controlled slow motion, the images recorded in video, it is possible to identify the precise moment of the beginning of the vortex shedding process. Once a complete vortex-shedding period identified, the time counter board allows the determination of the time associated with the process and consequently the vortex frequency. An estimate of errors associated to vortex-shedding frequency is about ±5%. More details about the technique to determine the vortex-shedding frequency using a VCR are found in the work of Gonçalves & Vieira (1999). Additionally, vortex street still images have been captured utilizing a Nikon F4s (SLR) single lens reflex 35 mm camera and black & white negative film - Kodak Tmax 400.

The non-perturbed velocity upstream the test model has been obtained using a *Yokogawa* electromagnetic flow meter mounted downstream the test section. An estimation of the errors associated to free stream velocity has shown less than about 5%, when compared with data obtained by hot film anemometer (*Dantec CTA Streamline*).

3. RESULTS

Flow images captured to the normal flat face turned downstream are showed in figure 2, and the opposite arrangements, the flat face turned upstream, are showed in Figure 3.

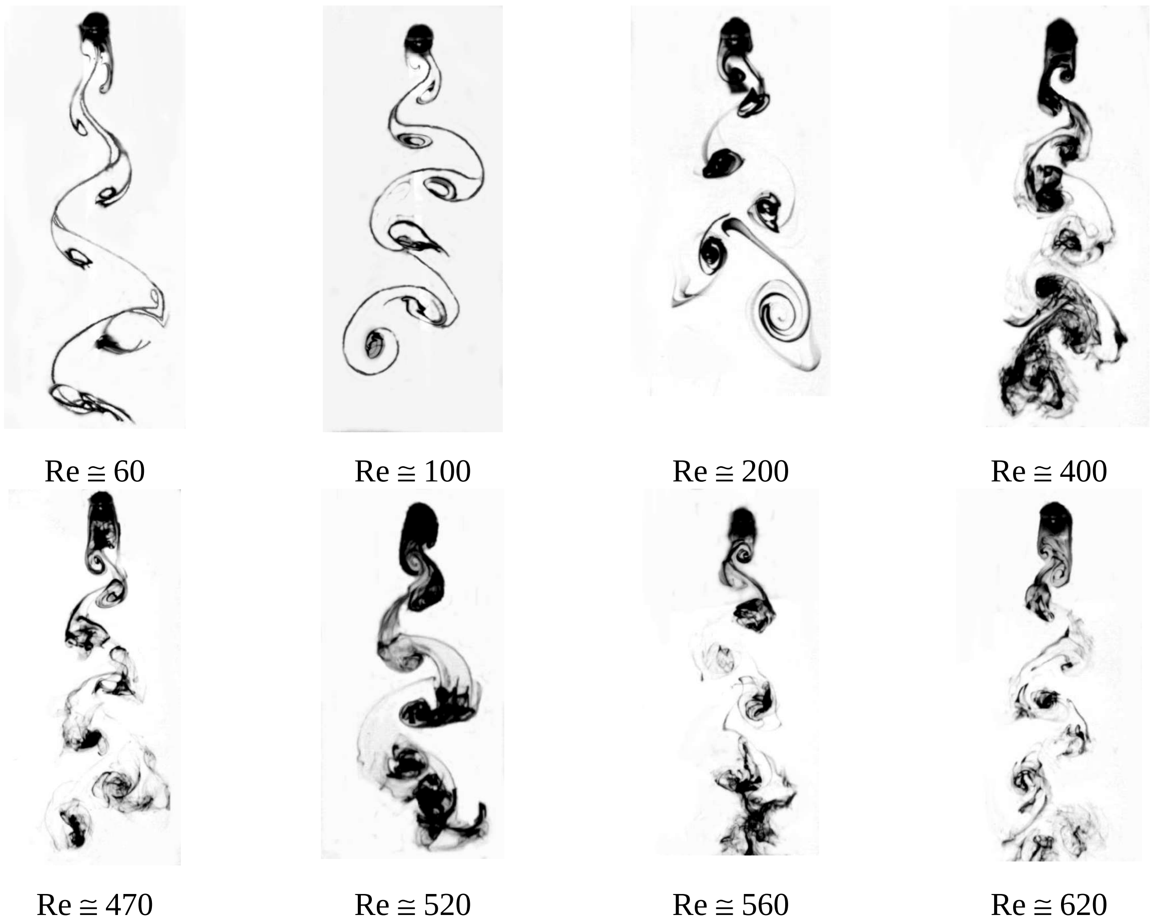

Figure 2. Wakes generated by a semi-circular cylinder (flat face turned downstream).

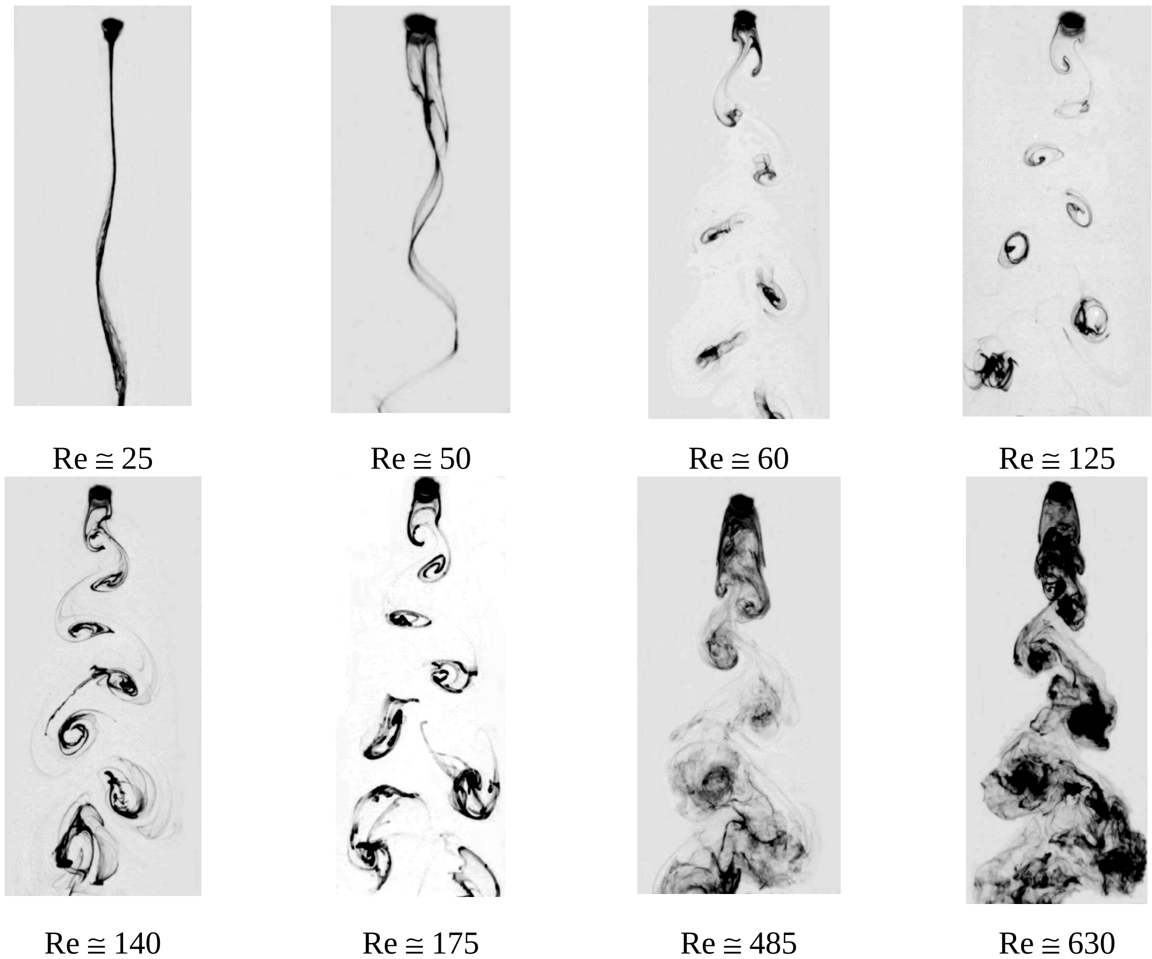

Figure 3. Wakes generated by a semi-circular cylinder (flat face turned upstream)

The non-dimensional vortex shedding frequency or Strouhal number (*Sr*), is based in the characteristic length (*D*) and non-perturbed flow velocity (*U*) − see Figure 1 − and the vortex shedding frequency (*f*), in accord to Equation 1.

$$Sr = \frac{f\ D}{U} \tag{1}$$

Strouhal number behavior in function of Reynolds number for two arrangements proposed is depicted in the Figures 4 and 5.

All experiments have been performed out using a test model made from aeronautical polished aluminum of D = 6 mm. In this situation, the blockage ratio is less than 5 % and aspect ratio (length to characteristic dimension (*D*) ratio) more than 24.

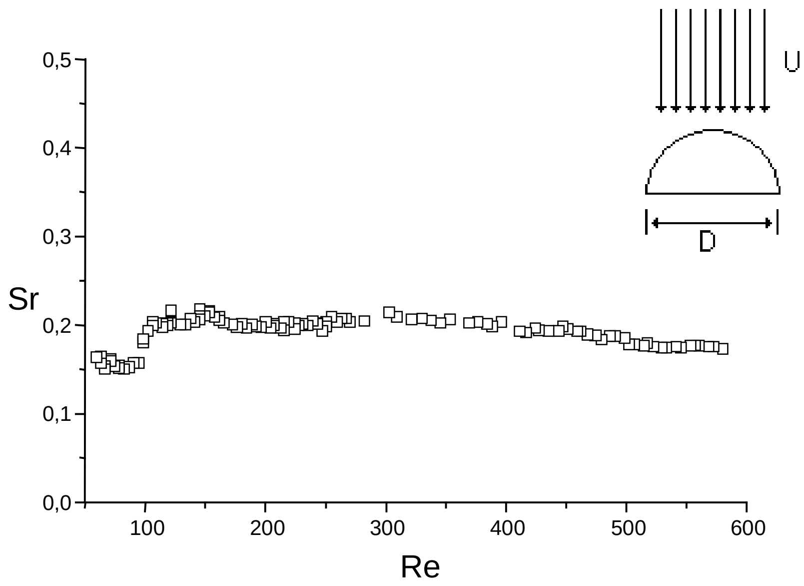

Figure 4. Strouhal behavior in function of Reynolds (flat face turned downstream)

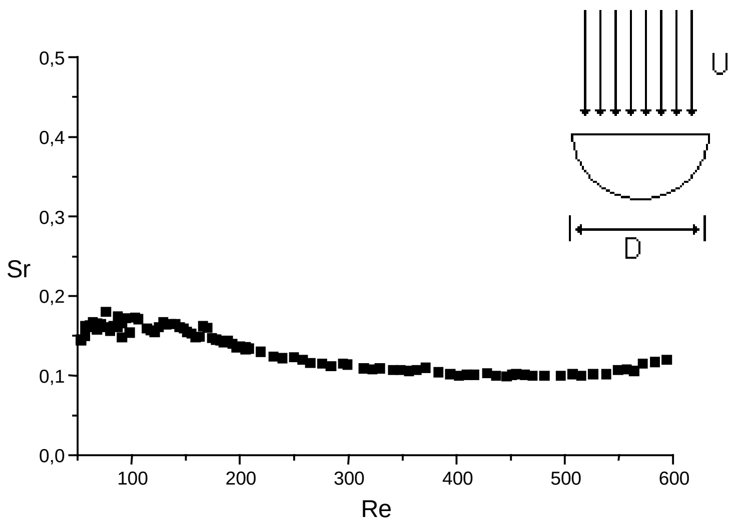

Figure 5. Strouhal behavior in function of Reynolds (flat face turned upstream)

4. CONCLUSIONS

In this work semi-circular section prismatic bluff bodies for relative low Reynolds number (up to 600) and low blockage ratio (5 %) has been experimentally tested, using hydrodynamic flow visualization as a working tool, for obtaining the Strouhal – Reynolds behavior.

In the Figures 3 and 4 a number of images of the wake for two opposite attack angles are depicted. For Reynolds less than approximately 200, the wake images are very sharp, and the vortex is clearly identifiable. In opposition, for Reynolds more than 200, the vortex wake is relatively more turbulent and the corresponding images is less clear, forcing the images to be captured using a higher dye tracer flow rate.

Flat face turned upstream wake images, Figure 3, show two particular images in relative low Reynolds. For Reynolds equals to 25, the flow contours the body, generating a stable small re-circulating bubble next to the curved face and the dye pattern wake is attached, generating small wave perturbation. For increased Reynolds, i.e. about 50, the re-circulating bubble is bigger and unstable and the dye pattern shows higher wave amplitude. For Reynolds number equals to 60, the flow exhibits an entire developed vortex shedding wake forming a full-configured von Kármán vortex street.

The Strouhal curves for the two opposite attack angles analyzed show appreciable difference. Figure 6 depicts a comparative analysis of the Strouhal number curves obtained in this work, for semi-circular section, and the traditional results obtained by Anatol Roshko, in 1953, for a circular cylinder.

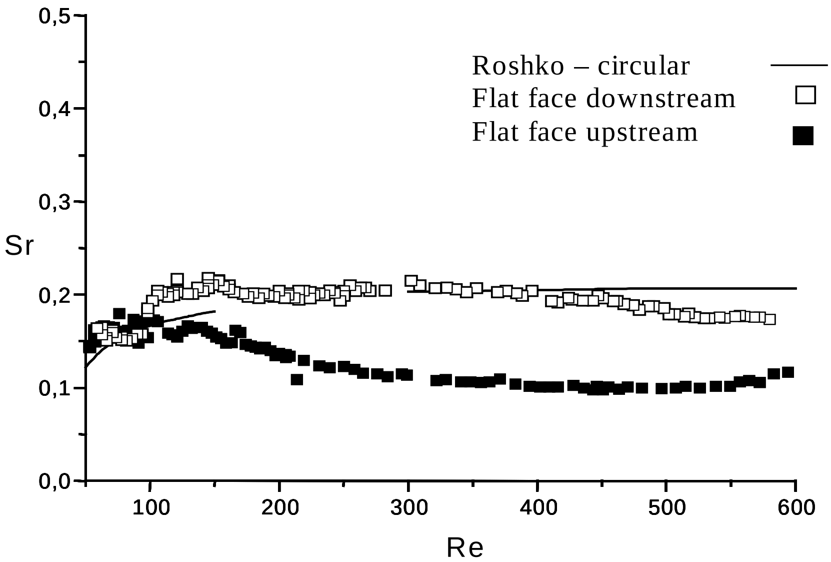

Figure 6. Comparative Strouhal-Reynolds curves

Strouhal behavior for the semi-circular section with the flat face turned downstream is very close – in the range of Reynolds range 300 - 400 – to full circular cylinder section results obtained by Roshko. Apparently, in this range, the influence of the after-shape of the circular section is negligibly small in the detachment process. Obviously, the Strouhal generated by a semi-circular section with a flat face turned upstream differs appreciably, because the detachment promoted by the sharp edges.

Unfortunately, the testes have been restricted to Reynolds numbers up to 600, because the limitations in flow visualization technique and image capture hardware. Video image has been captured at a rate of approximately 30 fps (frames per second) using NTSC system, which allows the precise determination of shedding frequency limited to approximately 10 Hz maximum. In order to extend the present work to higher Reynolds numbers using the same technique, either a high-speed video camera, able to capture thousands of frames per second, or bigger tunnel facilities, able to test larger models, will be necessary.

Finally, in this work, no tentative has been made to reach the optimum configuration for achieving parallel vortex shedding in the wake of the bluff bodies. In order to accomplish this, the implementation of endplate devices has already been scheduled for future works.

5. ACKNOWLEDGEMENTS

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