FLOW AROUND A SQUARE RIB NEAR A PLANE WALL

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Abstract. *In this work, vortex shedding phenomenon produced by a square cylindrical protuberance placed near a smooth flat wall with a small gap is experimentally studied by means of flow visualization and hot-film anemometry. Qualitative and quantitative information have been obtained for Reynolds numbers up to 1000. Qualitative results obtained by means of flow analysis show a complexe topological vortex structure and quantitative results depict the behaviour of the vortex shedding frequency in function of the Reynolds number.*

Keywords*: Vortex shedding, Flow visualization, Hydrodynamic vertical tunnel*

1. INTRODUCTION

The flow around a cylindrical obstacle has been intensively studied in the last century. On the other hand, the problem of the flow over a single rib transversally mounted near a wall has been less well investigated, despite of its recognized practical importance in terms of engineering. In this case, the flow field on the plate is strongly affected by the presence of a protuberance. The turbulence level increases, modifying heat transfer and drag coefficients. So, detailed knowledge of the flow field is necessary to improve design of different types of equipment, like discussed by Lohász *et al*. 2006.

Several different experimental tools have been employed to study this kind of problem. Flow visualization has allowed putting in evidence the complex topology of vortical structures generated in the protuberance vicinity Bassan *et al*. (2011). Measurements using hot-film or hot-wire anemometer have permitted to obtain quantitative information about velocity gradients and turbulent properties of the flow field. Combination of these two techniques is a very good way to investigate complex flows, as demonstrated by Freymuth *et al.* (1983).

In the present work, combination of flow visualization tools and hot film anemometry is done in order to investigate the isothermal incompressible flow past a squared cylinder positioned transversally in relation to the non perturbed flow and near a smooth flat plate, as showed in Fig. 1. By means of flow visualization, recirculation, boundary layer detachment, vortex shedding, and other complex mechanisms inherent to such a flow are visually identified. Measurements data obtained with a hot-film anemometer permit to obtain the flow velocity signal and, consequently, the vortex shedding frequency behind protuberance.

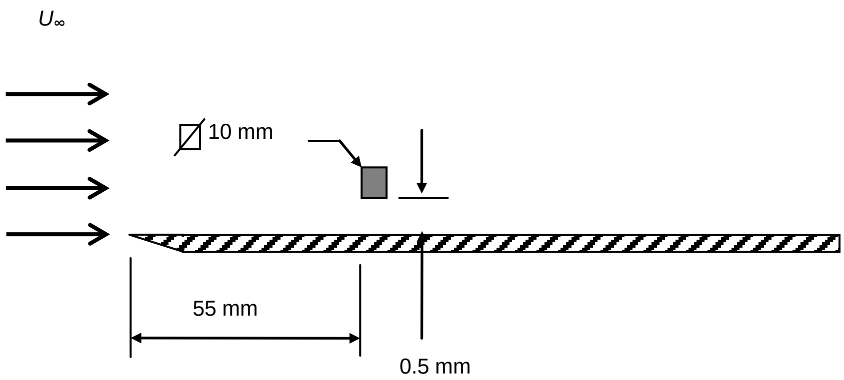


Figure 1. Square cylindrical rib close to a smooth flat plate with a small gap of 0.5 mm.

2. EXPERIMENTAL APPARATUS

All experiments have been performed for Reynolds numbers up to 1000 in a low turbulence hydrodynamic tunnel with a test section of $146 \times 146 \times 500$ mm. As described by Bassan *et al.* (2011), flow visualization images have been captured operating the hydrodynamic tunnel in blow-down mode producing a very low turbulence level (less than 0.2%). The Fig. 2 shows schematically the hydrodynamic vertical tunnel.

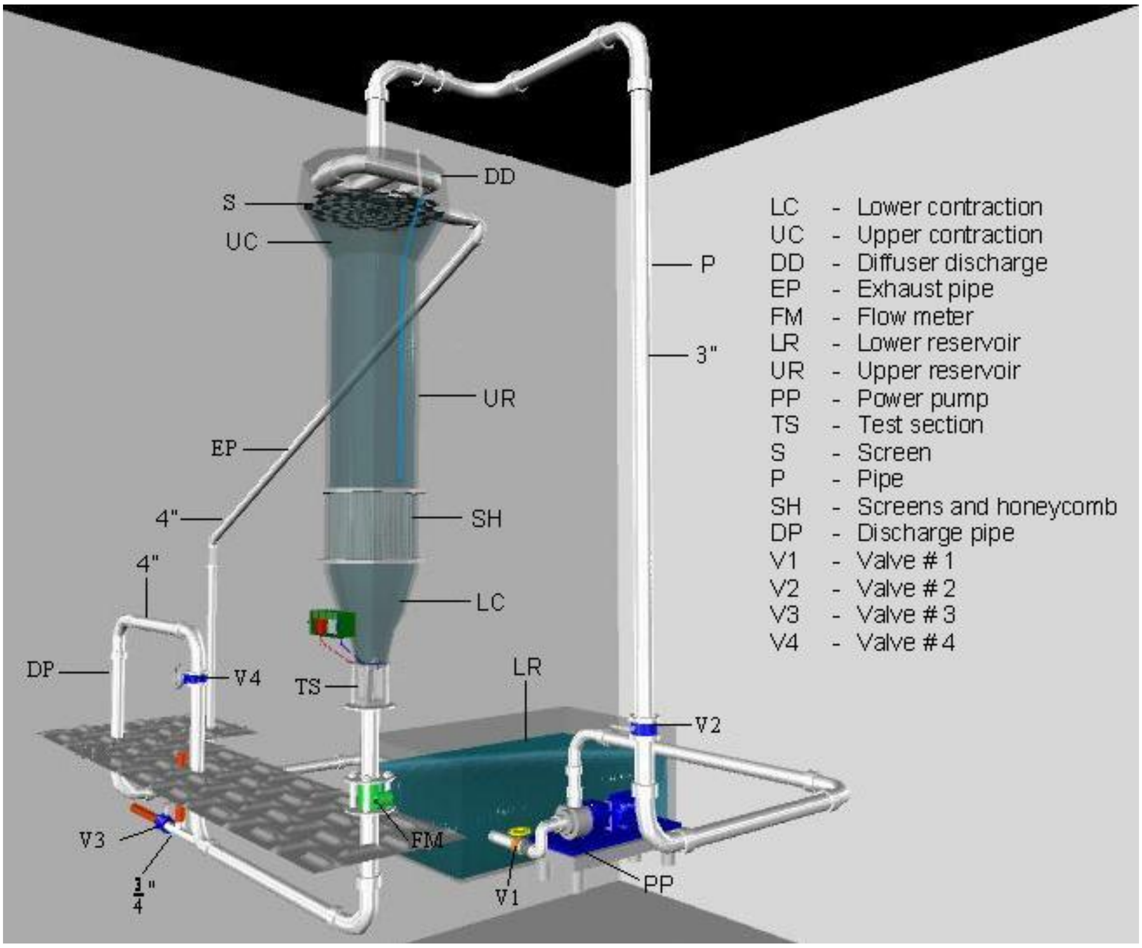
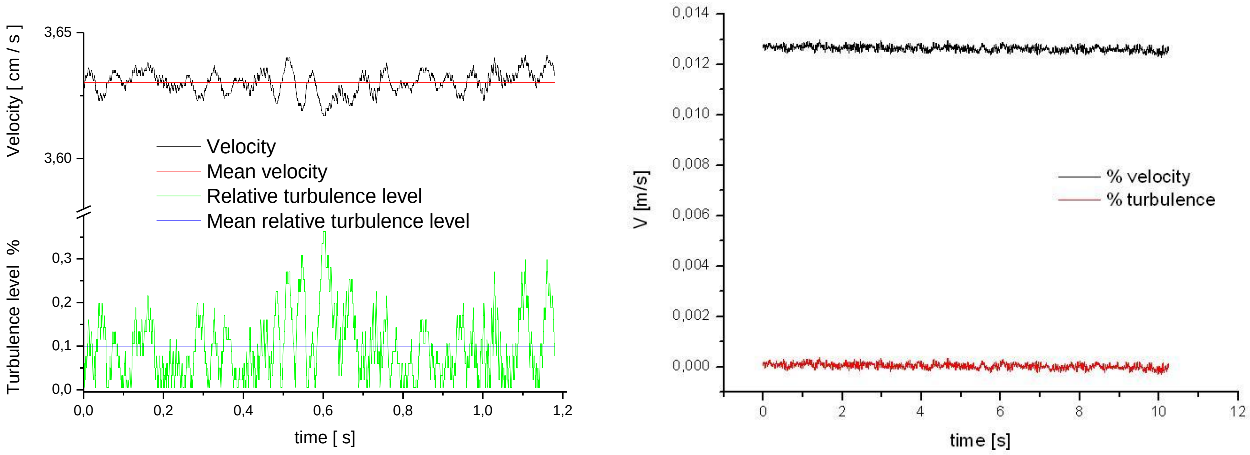


Figure 2. The vertical hydrodynamic tunnel

The water tunnel is operated by gravitational action and can be used in continuous or blow-down mode. Blow-down mode has been used in this work due to its lower turbulence level, although in this mode, the free stream mean velocity decreases with the water level inside the upper reservoir. To account for that, it has been estimated that, for a period up to 15 seconds, the effects of decreasing free stream mean velocity are overshadowed by turbulence fluctuations.

The water contained in the bottom reservoir (LR) positioned below the floor is sucked by a centrifugal pump (PP) and conducted to the upper part of the tunnel through the pipe (P), of 75 mm in nominal diameter. A flow control valve (V4) remains closed until the water level inside the tunnel reaches its maximum level. At this instant, the pump is turned off. After 2 or 3 hours, the water inside the tunnel remains in rest. The test starts with the opening of the flow control valve (V4). The test section velocity (TS) is obtained by means of an electromagnetic flow meter (FM). In order to visualize the flow, liquid dyes are injected upstream of the region of interest, through long needles with an O.D. of 0.7 mm.

The volumetric flow rate in the tunnel has been determined utilizing a Yokogawa electromagnetic flowmeter. The uncertain in the free stream velocity is less than 4%, in more adverse case, producing less than 5% of maximum uncertain in the Reynolds number (based in the protuberance height, i.e. 10 mm). Fig. 3 shows the non perturbed free stream velocity and the turbulence level produced in the test section. Fig. 4 depicts the non perturbed velocity profile in the test section for different mean velocities. The hydrodynamic tunnel conjugates low turbulence levels with flat velocity profiles.



(a) in blow down or non steady operation mode (b) in continuum or steady operation mode

Figure 3. Velocity and turbulence level measurements in the hydrodynamic tunnel test section.

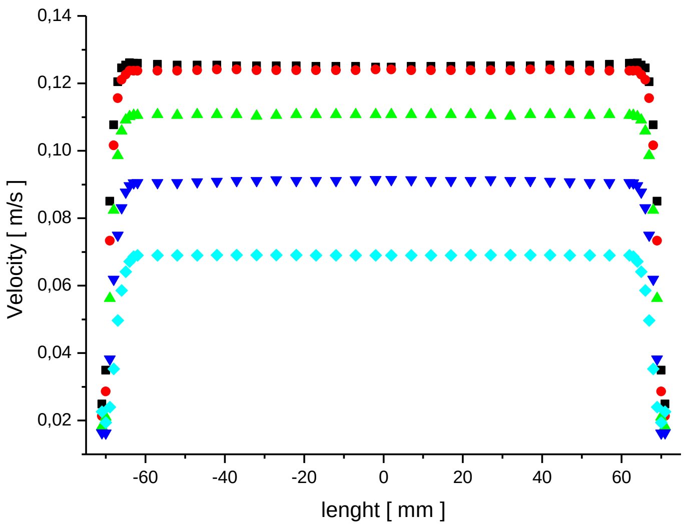


Figure 3. Non perturbed velocity profile in the hydrodynamic tunnel test section.

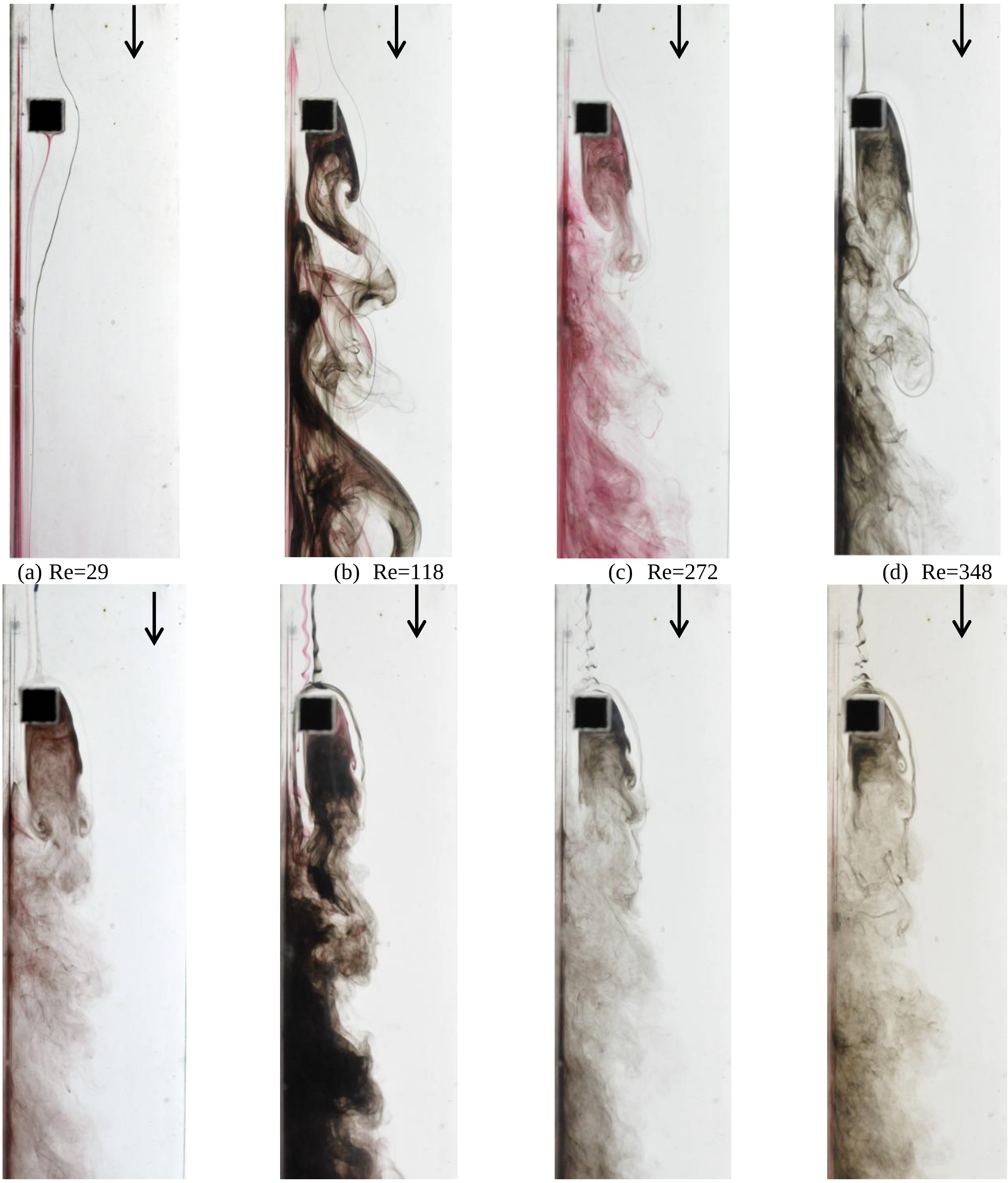
The flow visualization technique applied in the present work is the direct injection of opaque liquid dye in non-perturbed flow by means a rake of long hypodermic needles of 0.7 mm O.D. A solution of PVA pigments, tap water and ethyl alcohol have been used as dye. Strong amount of this colored dye has been injected directly in the non perturbed stream, sufficient to color the entire flow field. Subtly, the injection dye is stopped and the clean water flow wash the entire flow field, except in the cylinder wake, because in that region the flow speed is significantly small than in other ones. This procedure permits to see, for some few seconds, the re-circulating bubble and the wake downstream the protuberance. Details of the flow visualization liquid dye injection technique is available in the work of Bassan *et al.* (2012).

All still images have been captured using a D 90 Nikon DSLR camera equipped with a special Nikkor medical macro lens with 120 mm and f/1:4. The pictures have been obtained in f/1:11 resulting in a good depth of field. The very expensive Nikkor macro lens was originally designed for application in full frame (24 ×36 mm) chemical 35 mm roll film SLR cameras and after adapted for a half frame (23.6×15.8 mm) digital SLR camera, resulted in an excellent optical device for capture close up images. Cold illumination by means of fluorescent lamps with high color temperature, but minimal heat emission, has been adapted in the tunnel allowing sharp and well defined images. A Rosco color illuminating filter Cinegel#3308 converts daylight fluorescent lamps to 5,500 K, while a diffuser Cinegel#3007, a low density slight filter, provides a good illumination for still and video image capture.

Velocity measurements have been performed with 55R11 and 55R14 fiber-film probes made by Dantec Measurement Technology, with 70 μm diameter quartz fiber coated with 2 μm nickel film and with an overall length of 3 mm. They are a straight general-purpose type sensor which permits a wide measurement range in water medium. For very small velocities (up to 0.10 m/s) special care must be adopted in order to reduce the convection effect around the probe. Indeed, a hot-wire probe immersed in recirculation zones might produces a high level of thermal convection interfering in the measurements, like discussed by Rivir *et al.* (1996). A Dantec StreamLine 90C10 frame 90C10 permits simultaneously measurements in 3 channels. An A/D board NI-DAQmx 8.7.1 (16 bits), has been utilized in order to record the output voltage signal. Single element hot-film probe has been positioned downstream the protuberance to obtain temporal flow velocity fluctuations. Data acquired by the probes have been processed to obtain a frequency spectrum with a FFT - Fast Fourier Transform. Ftest statistical functions have been also utilized to examine the periodic nature of the vortex wake.

3. RESULTS

Results include several flow visualized images of vortex generation and shedding by a square rib positioned near a flat smooth wall. The pictures are obtained for Reynolds numbers from 29 up to 993.



(a) Re=29 (b) Re=118 (c) Re=272 (d) Re=348

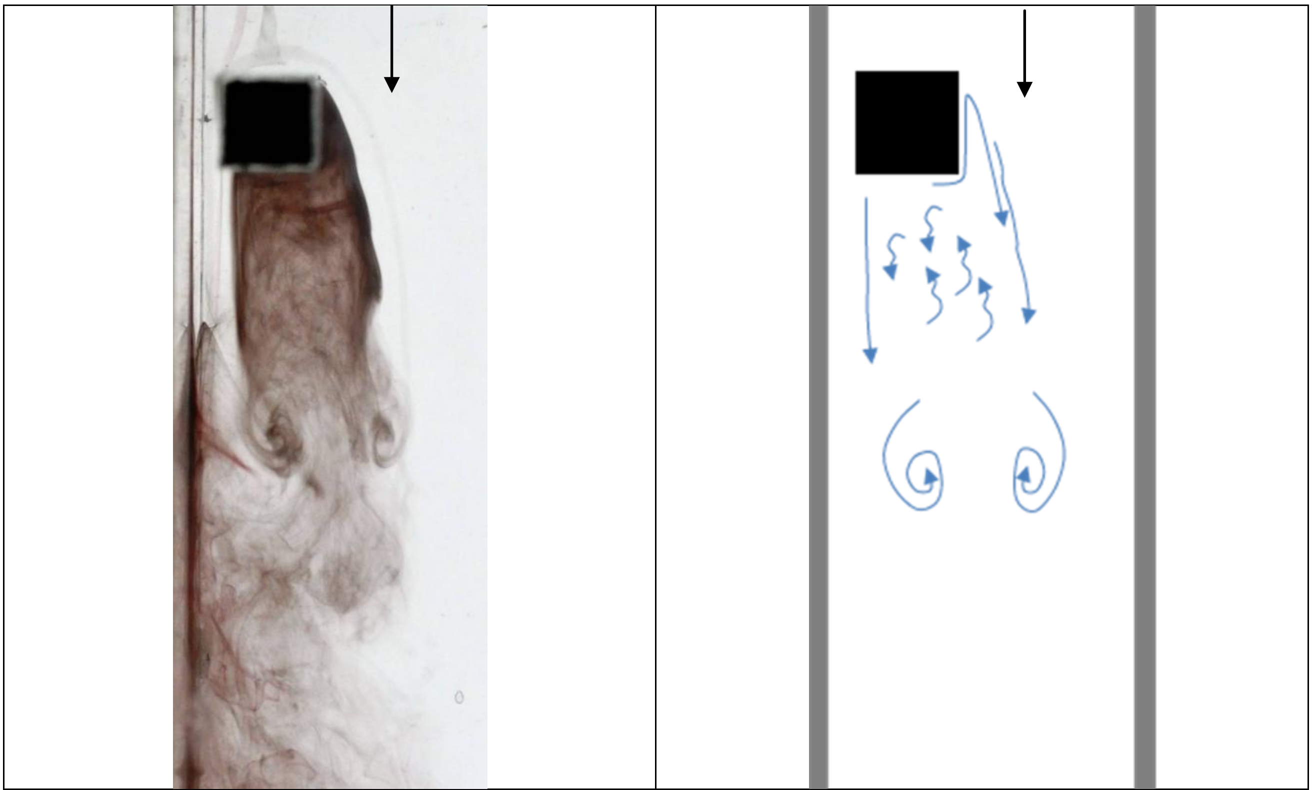
(e) Re=557 (f) Re=675 (g) Re=848 (h) Re=993

Figure 4. Vortex shedding visualization in several Reynolds numbers.

We can to observe the liquid dye injected into the test section near to the flat plate and upstream of the square cylinder. The flow is downward, as indicated by the arrows. For Re ≈ 29 - Fig. 4(a) - the ink streaklines contour almost perfectly the square cylinder without sensible detachment. A moderate detachment occurs only in the rear face of the cylinder. No appreciable detachment occurs in the boundary layer in the flat plate downstream the square cylinder. Increasing the Reynolds number Re ≈ 118 - Fig. 4(b) – a clear detachment occurs in the right leading edge of the cylinder generating large coherent structures in the turbulent wake. Because the adverse pressure gradient, generated by the cylinder wake, occurs a tangible detachment of the boundary layer in the flat plate.

Finally, to higher Reynolds number is observed the formation and shedding of the vortex, as shown in Fig.4(b-c). For Re ≈ 848, is observed on the right side of the body the formation of kelvin helmholtz instabilities.

An enlarged still photographic image for Re = 557 has been edited to show the coherent structures - Fig. 5 (a) – and a sketch showing the kelvin helmholtz instabilities is depicted in Fig. 5 (b).



(a) Flow visualized image captured - Re=557	(b) Draw Re=557,

Figure 5. Captured photographic image (a) and schematic sketch (b) of coherent structures.

Figure 6 shows the curve of the vortices shedding frequency as a function of Reynolds number.

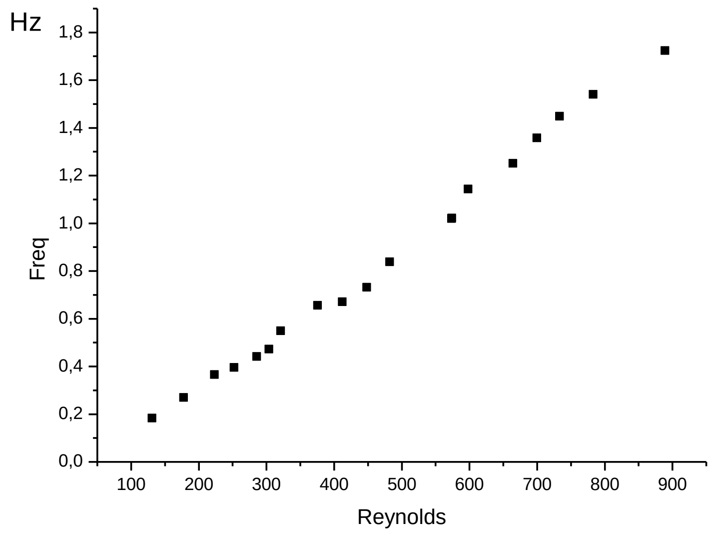
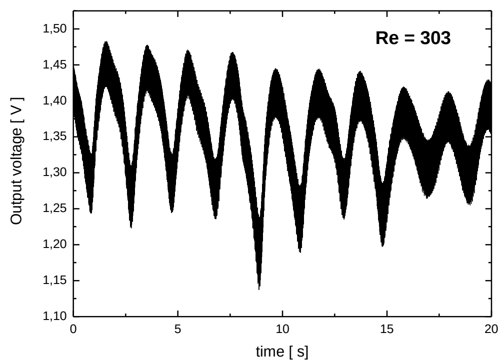
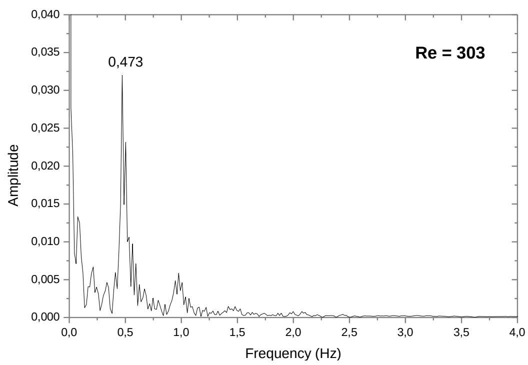


Figure 6. Fequency of vortices as a function of Reynolds.

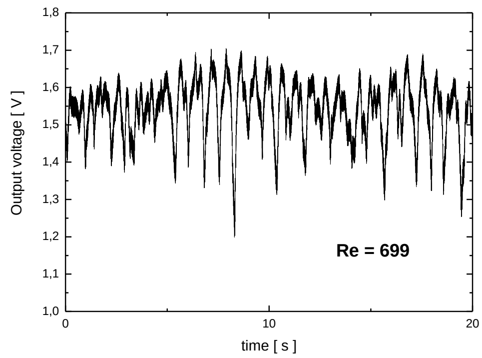
Figure 7(a) shows a temporal signal of velocity obtained at $Re \approx 303$ with the hot-film probe positioned downstream the protuberance. By using a FFT algorithm, this signal has been transposed to the frequency domain. The spectrum frequency, presented in Fig. 7(b), indicates that the shedding vortex frequency is about 0,473 Hz. For Reynolds equals to 699 Fig. 7(c) is showed the temporal non calibrated velocity and in Fig. 7(c) the spectrum frequency showing a shedding vortex frequency of 1,358 Hz



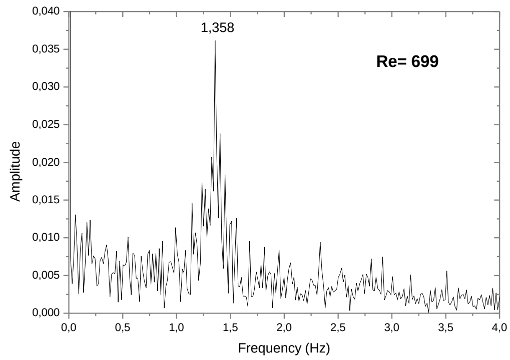
(a) Non calibrated velocity Re ≈ 303



(b) Amplitude spectrum frequency Re ≈ 303



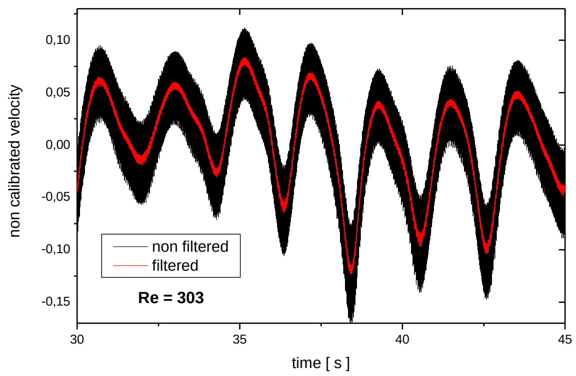
(c) Non calibrated velocity Re ≈ 699



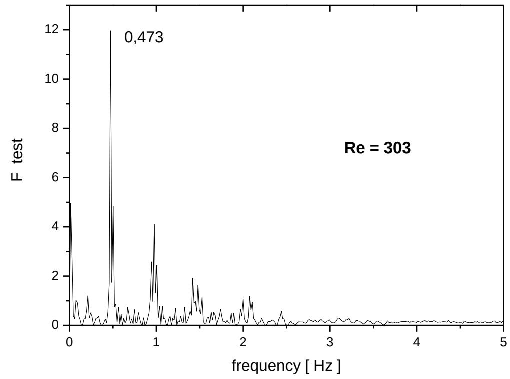
(d) Amplitude spectrum frequency Re ≈ 699

Figure 7. Vortex shedding frequency determination.

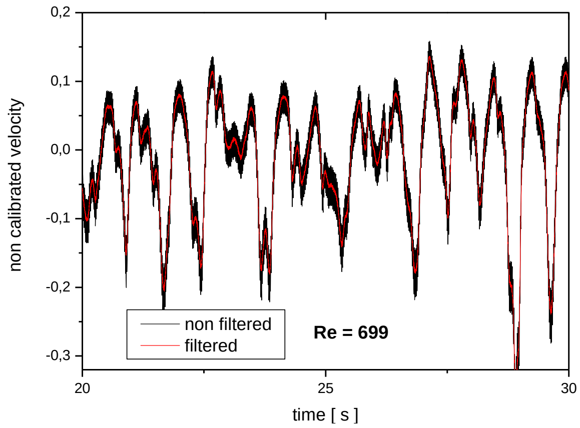
By means of a digital IIR (infinite impulse response) band stop filter a 60 Hz contamination has been filtered out, as can be seen in Fig8(a and c). Deploying a multitapered spectral estimation associated to a statistical F-test, the main oscillatory component has been singled out from the signal noise, for each case (Re ≈ 303 and 699) depicted in Fig. 8(b) and (d). Results obtained for fundamental vortex shedding frequency utilizing statistical F-test (Fig 8) are exactly the same obtained by FFT analysis (Fig.7).



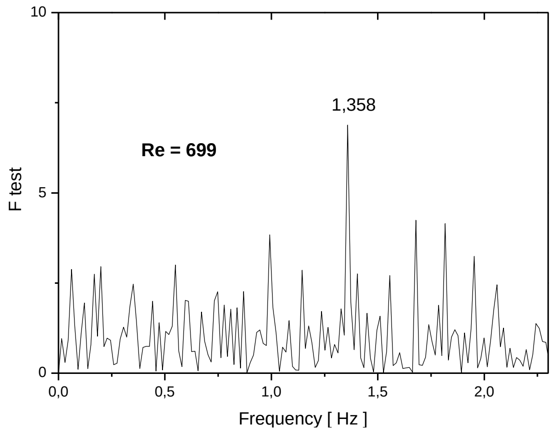
(a)Temporal non calibrated velocity Re≈303



(b) Statistical F-test Re≈303



(c)Temporal non calibrated velocity Re≈699



(c) Statistical F-test Re≈699

Figure 8. Vortex shedding frequency determination.

4. CONCLUSIONS

In this work, flow visualization by direct liquid injection and hot-film measurements have been performed to obtain qualitative and quantitative information about a flow around a square rib transversally positioned near a flat wall. Vortex shedding phenomenon has been qualitatively visualized by means of still images, while vortex shedding frequencies have been determined by hot-film measurements. Experimental flow visualization plays a key role in understanding of complex flow phenomena. That important experimental tool has been utilized in this work in order to obtain the first results of the study of flow around a square cylinder positioned near a flat smooth plate. The flow around a square cylinder placed in the vicinity of a solid plane wall can be shows a great complexity involving the development of various shear layers, including those separated from the upper and lower sides of the cylinder, as well as the boundary layer. The presence of a wall creates an asymmetric condition in the velocity and pressure fields around the cylinder. Also is possible to see a non uniform velocity profile over the wall in front of the cylinder. This non uniformity generates a shear layer with an asymmetric influence on the test body. Probably, this non symmetric influence results in a non zero lift force when the height gap is very small. The plane wall imposes a severe non rotational restriction to the cylinder wake resulting in a vortex shedding and wake development different from those of the alone square cylinder far the wall.

A lot of video tapes showing the vortex wake have been captured showing a defined vortex shedding frequency. But, a detailed video image exam reveals several visible instabilities in the vortex frequency. Auto correlation analysis shows weak stability of the vortex shedding frequency also named by weak periodicity.

For moderate and low Reynolds numbers, the correct probe positioning downstream protuberance is a very important factor to obtain a good noise to signal ratio. In this sense, flow visualization is an excellent tool, helping in the tedious work to position adequately the hot-film probes in the flow.

4. ACKNOWLEDGEMENTS

The authors are grateful to FAPESP and FUNDUNESP for the financial support granted to this work.

5. REFERENCES

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5. RESPONSIBILITY

The authors are the only responsible for the printed material included in this paper.