CHARACTERISTICS OF THE FLOW AROUND AN ELLIPTIC CYLINDER NEAR A SMOOTH FLAT PLATE

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Abstract. *The external flow around elliptic cross section tubes is very important since they are extensively deployed in several kinds of modern compact heat exchangers. An experimental study on incompressible water flow around a 0.33 aspect-ratio elliptical cross-section cylinder positioned parallel to a smooth flat plate leaving a selectable gap (0.2 and 1.0 elliptic minor axis units) was carried out. All tests were performed in a low-turbulence vertical hydrodynamic tunnel for minor axis based Reynolds numbers up to 2,200. Employing flow visualization by direct injection of liquid colored dyes, flow images of boundary layer detachments, recirculations, vortex shedding and other flow structures were obtained. Hot-film anemometry measurements in the cylinder wake were carried out in order to determine the vortex shedding frequencies as a function of Reynolds numbers and wall cylinder gaps. The results revealed a strong influence of the wall gap on the vortex geometry. For 0.2 gap or closer, a dominant vortex frequency ceased to be detected by measuring the flow velocity in the vortex wake. This vortex suppression is well known from the literature.*

Keywords: *Elliptic cylinder, Vortex shedding, Cross-flow, flow visualization ,Hydrodynamic tunnel*

1. INTRODUCTION

Experimental and numerical studies of the external flow around circular cylinders have been widely explored by researchers in various fields of engineering, so this is a branch of science reasonably understood. Such cylinders are defined as blunt bodies and provide a greater drag when compared with elliptical cylinders. Zdravkovich. MM, (1985), Bearman and Zdravkovich (1978), Wang and Tan (2007), among others, have investigated experimentally the behavior of the flow around a circular cylinder near the wall. In the other hand Choi and Lee JH, SL, (2000), investigated the flow around an elliptic cylinder positioned close to a flat plate for Reynolds numbers in the range of 14,000 selecting a number of gaps. However, when compared to existing studies on circular cylinders, there is a relative scarcity of works with elliptical cylinders and restricting further to those positioned close to a smooth flat plate with Reynolds numbers starting from 2 to 2200, the amount of papers decreases even further. Thus that shortage as well as a better understanding of the flow characteristics have served as driving motivation for the present study.

This study had the aim to investigate the flow behavior around elliptical cylinder positioned close to a smooth flat plate (wall) through imaging capture and vortex emission frequency determination, using the vertical hydrodynamic tunnel described in Section 2. An ellipse with an aspect ratio AR = 2b/2a = 0.33 was positioned parallel and distant GR = h/2b = 0.2 and 1.0 gap ratio of one of the flat walls, with the major axis 2a parallel to the wall as illustrated in Figure 1. The characteristic dimension in the Reynolds number was the minor axis length of the ellipse (2b). The analysis was conducted in almost-steady flow (both in continuous and blowdown modes), yielding a Reynolds number maximum range of 2 to 2200. By varying the Reynolds number, the experiments were repeated 10 times for each gap value. It could be observed that for all repetitions the flow exhibited very similar behavior. Therefore, the captured images shown in Figs. 3, 4 and 6 have been selected from a large number of tests. In the case of vortex suppression, a phenomenon that will be discussed later, the photographs depicted in Figure 7 belong to a time sequence of an experiment with the Reynolds number fixed in 520, although such sequences have been obtained for several other Reynolds number values.

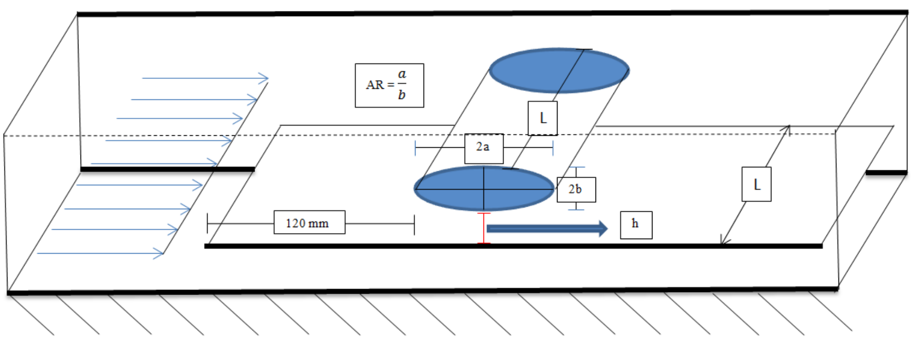


Figure 1. Elliptical cylinders tested: flow direction and geometric features

2. EXPERIMENTAL APPARATUS.

All experiments have been carried out in a vertical open circuit hydrodynamic tunnel with 146×146×500 mm test section with operational envelope up to 2 m/s. All tests have been performed over the Reynolds number range (Re) based on approach flow velocity (V) and ellipse minor axis (2b) up to 2,200.

The hydrodynamic tunnel is a prototype device used in the Laboratory of Flow Visualization – Fig. 2 (a, b). This experimental apparatus consists in a water reservoir with three distinct cross section regions, the upper and lower reservoirs, and the testing section. The larger cross section upper reservoir houses internally a compartment for screens and honeycombs in order to minimize turbulent flows. Right after the lower reservoir there is a contraction section with 16:1 in contraction ratio. The test section has 177.2 cm² of entry area and 192.5 cm ² of exit área. Boundary layer thickness effects on velocity profile are controlled by divergent cross section in the test section. The model body is positioned on the test section where the area is 184 cm², 120 mm away from the entry of the test section.

The hydrodynamic tunnel is operated by gravitational action, and can be used in continuous or blowdown mode. In this work, blowdown or intermittent mode has been used in order to obtain the flow visualized images and continuous mode in the measurement of the vortex shedding frequency. The free flow velocity has been determined utilizing a Yokogawa electromagnetic flowmeter ADMAG AXF100G. The uncertainty in the free flow velocity determination is estimated in less than ±3%, producing a maximum uncertain less than 5% in the Reynolds number. For further information on the water tunnel characteristics, reference may be made to Bassan et al. (2011a, b) and Fonseca*et al.* (2013).

For very low Reynolds numbers (up to 10) minute main flow disturbances induce large turbulent effects. In this situation, flow control is a very delicate operation and only fully possible in blow-down mode. In this, the tunnel is discharged through a butterfly valve with a reduction of 1:20 in the diameter ratio between the external actuator driver to the internal variation of the opening disk, permitting high precision control under small velocities. All the fluid that passes through this valve returns to the external reservoir and becomes available to be pumped back into the tunnel again. Liquid dyes were injected into the test section by means of0.5 mm circular cross section needles. Two dye colors, red and blue, stored in separate tanks, were used. As an important precaution, the liquid dye must not be injected in jet form, i.e. the input speed of the liquid dye should not be higher than the velocity of the fluid in the test section.

In continuous operation mode a RMS turbulence intensity less than 0.24% is measured, i.e., flow in the tunnel shows velocity fluctuations small enough to allow the study of turbulent flows. For operation under blowdown mode, even lower main flow turbulence intensities are reached, due to the decrease in the disturbance levels, as seeing inBassan, R.A., 2011

3. RESULTS

In the present work the non-dimensional distance GR = h/2b between the elliptic cylinder to the flat plate and the Reynolds number (Re) are the two main parameters of influence of the problem. As it will be discussed, for GR = 0.2 the cylinder is close enough to the wall such that wall effects are noticeable. For GR = 1.0, wall effects can still be observed, but are moderate. Only for distances several times higher the effects of the wall would be negligible. Therefore, only the moderate and severe effects of the presence of the wall are analised.

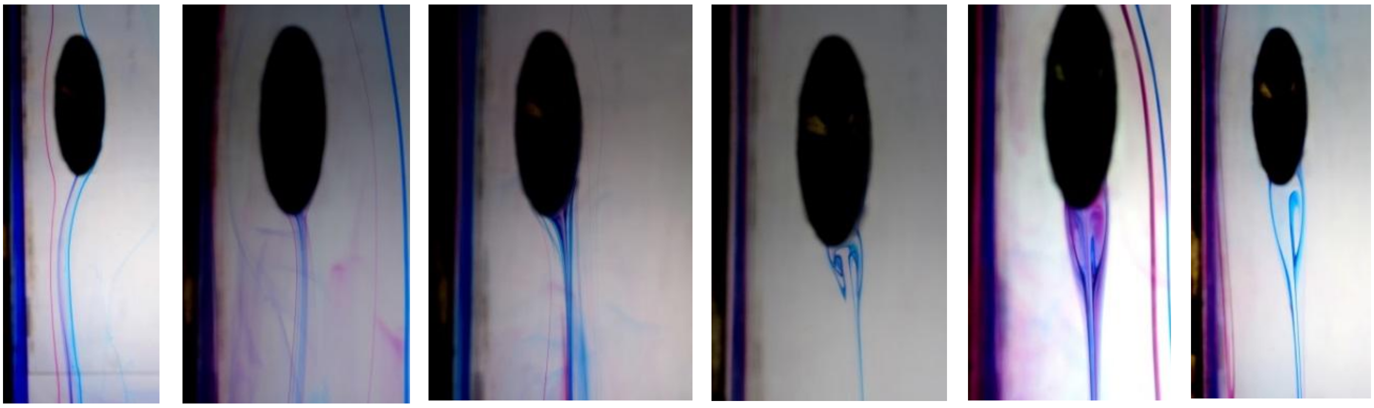
3.1. Moderate wall effects, GR=1.0

When the tests are carried out down to a very low Reynolds number (creeping flow) the flow presents a peculiarity: immediately downstream the elliptical cylinder, current flow lines tend to move *closer* to the wall. This effect was noticed right from Reynolds number of 2, the lowest number to which some measure could be accquired. However, going up in Reynolds number range, the lines *departure* from the wall, as seen in figure 2(b), although it was not possible to precisely identify to which Reynolds number the flow would change effects.

For creeping flow, Fig. 2(a), the inertia are less representative than viscous forces. In this situation the fluid that approximates the gap decelerates, decreasing the associated kinetic energy and increasing static pressure. After passing through the gap the fluid is re-accelerated causing a pressure drop, so that the downstream the elliptical cylinder, current lines tend to approach the wall.

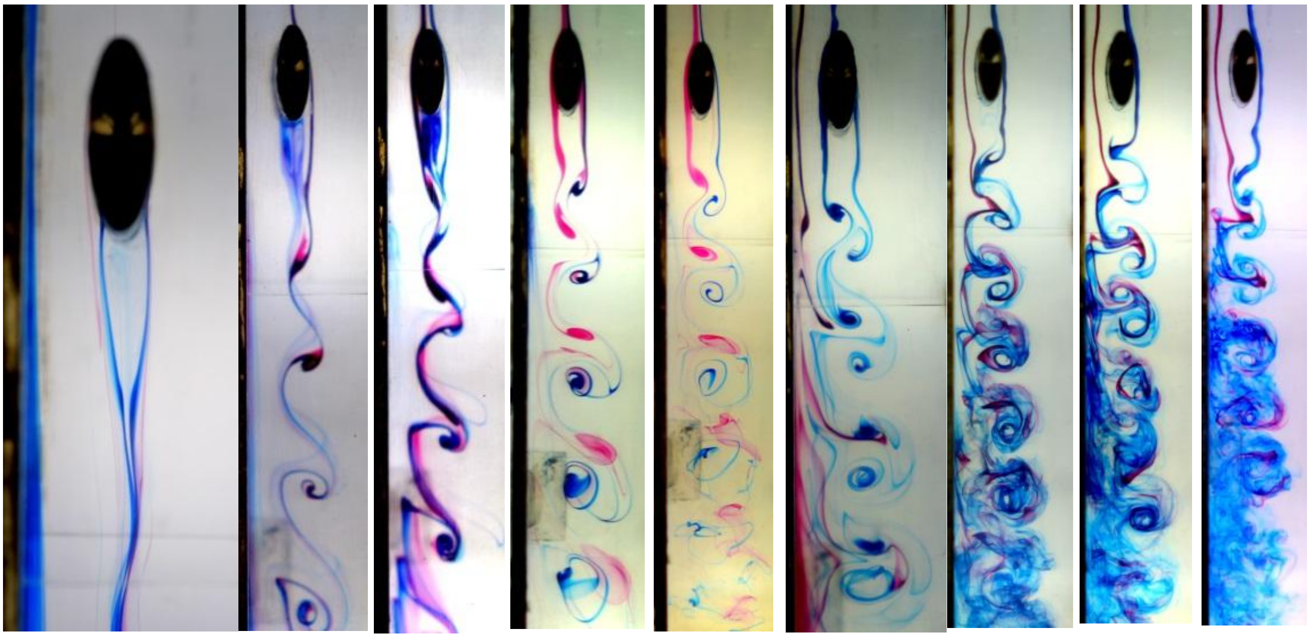
However, for Reynolds numbers a little higher, as shown in Fig. 2(b), increased main flow speeds turn inertia more significant than viscous forces. Fluid that approximates the gap is now accelerated. After passing through the gap, the fluid is slowed down, increasing downstream pressure, which pushes current lines away from the wall.

Flow asymmetry becomes more evident in Fig. 2 (c), by observing the detachment of the boundary layers along the cylinder surfaces. Notice that the flow traversing the elliptical cylinder lower surface features a detachment further downstream, while the fluid along the upper surface has a premature separation. Increasing the Reynolds numbers the asymmetry of the boundary layer detachments remains, recirculation bubbles, also asymmetrical, appearing now, as shown in Fig. 2(d).



(a) Re ≈ 2 (b) Re ≈ 6 (c) Re ≈ 29 (d) Re ≈ 59 (e) Re ≈ 78 (f) Re ≈ 107

Figure 2. Characteristics of flow, detachment of the boundary layer, bubbles recirculation and evident asymmetry. Elliptical cylinder with AR = 0.33 positioned at a distance GR = 1.0.



(a) Re≈184 (b) Re≈185 (c) Re≈212 (d) Re≈287 (e) Re≈ 382 (f) Re≈ 456 (g) Re≈677 (h) Re≈927 (i) Re≈1089

Figure 3. Flows in different Reynolds numbers, showing the characteristics of the flow around an elliptic cylinder with AR = 0.33 positioned at a distance GR = 1.0.

Gradually increasing Reynolds number the asymmetrical recirculation bubbles become more elongated in such a way that current lines reunite much further downstream. For Reynolds 185, Fig.3(b), clockwise rotating vortices are shed, generated from the upper surface of the elliptical cylinder. In Fig. 3(c), for Reynolds 212, there is an incipient vortex formation (shown by arrow) generated from the lower surface. However, without enough energy yet, they are not completely formed. This fact indicates a persistent predominance, in terms of energy, of upper-surface generated vortices over the lower surface ones, so that there is a range of Reynolds numbers within there is no emission of alternating vortices. Considering a line extending the major axis of the ellipse (axis of symmetry), which is parallel to the wall, it can be observed that the vortices dislocate from the axis of symmetry, away from the wall.

From Reynolds 287 on, Fig. 3(c) alternating vortices begin to shed. However, predominance of the vortex generated on the upper surface is still evident, as the vortex generated in lower surface suffer a stretch deviating from the wall and elongating around the predominant vortex generated in the upper surface, which is much closer to the wall. Near the wall in Fig.3(f), Reynolds 456, there is the beginning of formation of a vortex that is destroyed due to influences of the alternating vortices, which have opposite signs vorticity.

3.1.1. Vortex emission frequency, GR = 1.0

The emission frequencies of vortices for this setup wereeasily identified and measured, as can be observed in Fig.4 (a), (b),(c) for different Reynolds numbers and the relationship between frequencies and Reynolds numbers in Fig. 4(d), without the need to place the hot wire anemometer sensor in any special position. Even so, the images were useful to choose the best position of the sensor.

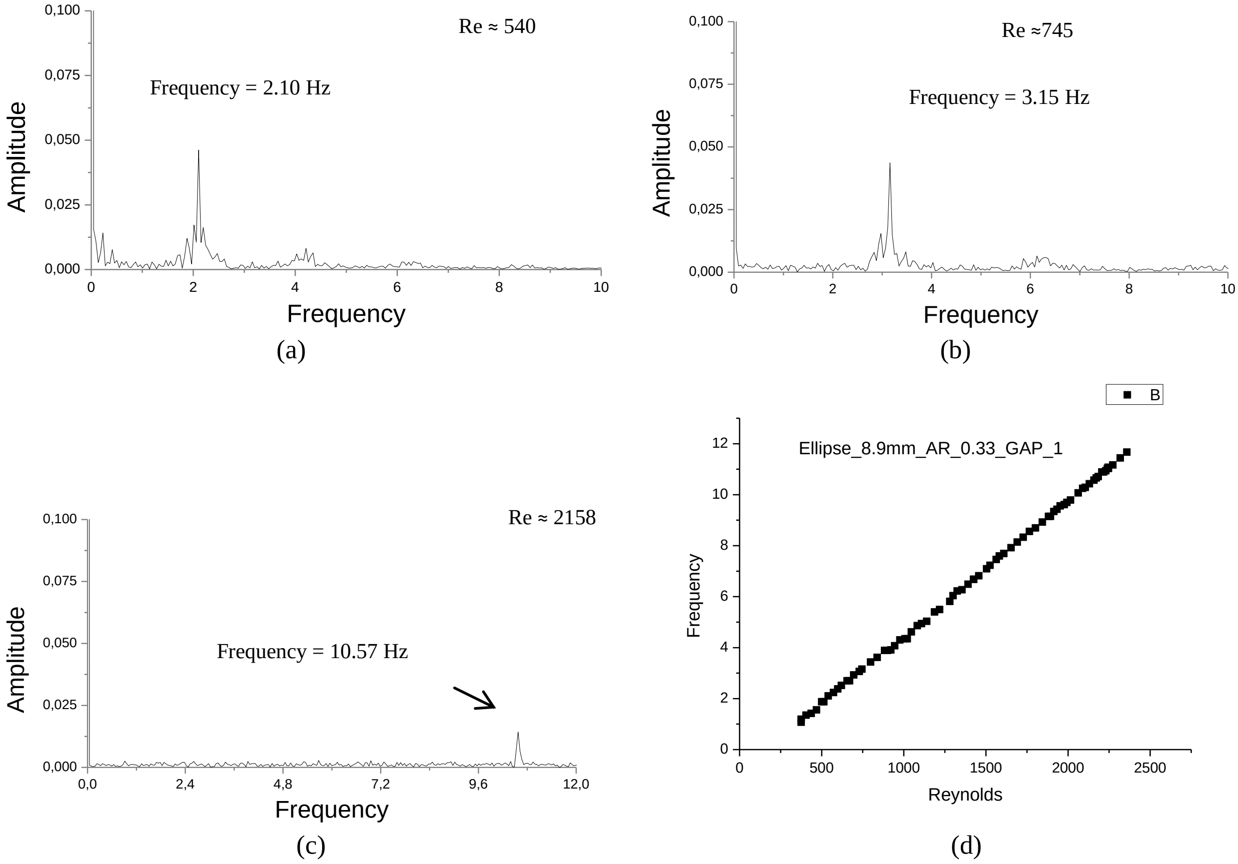
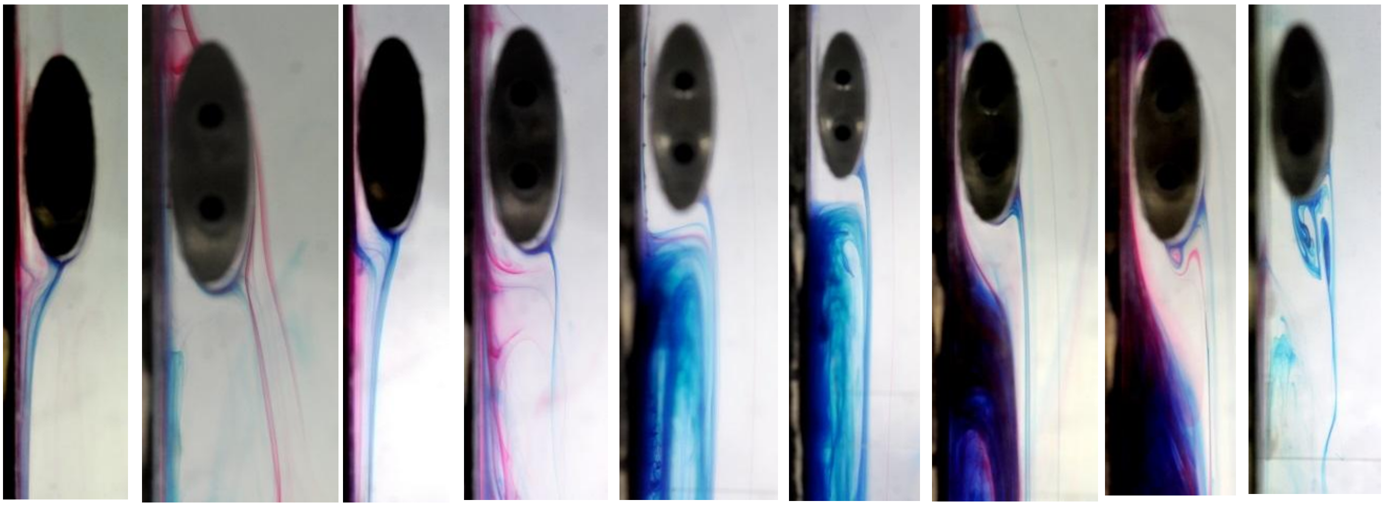


Figure 4 (a),(b),(c) FFT showing the frequency of vortex shedding for three different Reynolds numbers and (d)the relationship between vortex emission frequencies and Reynolds numbers, determined for 80 Reynolds number values.

3.2. Severe wall effects, GR = 0.2

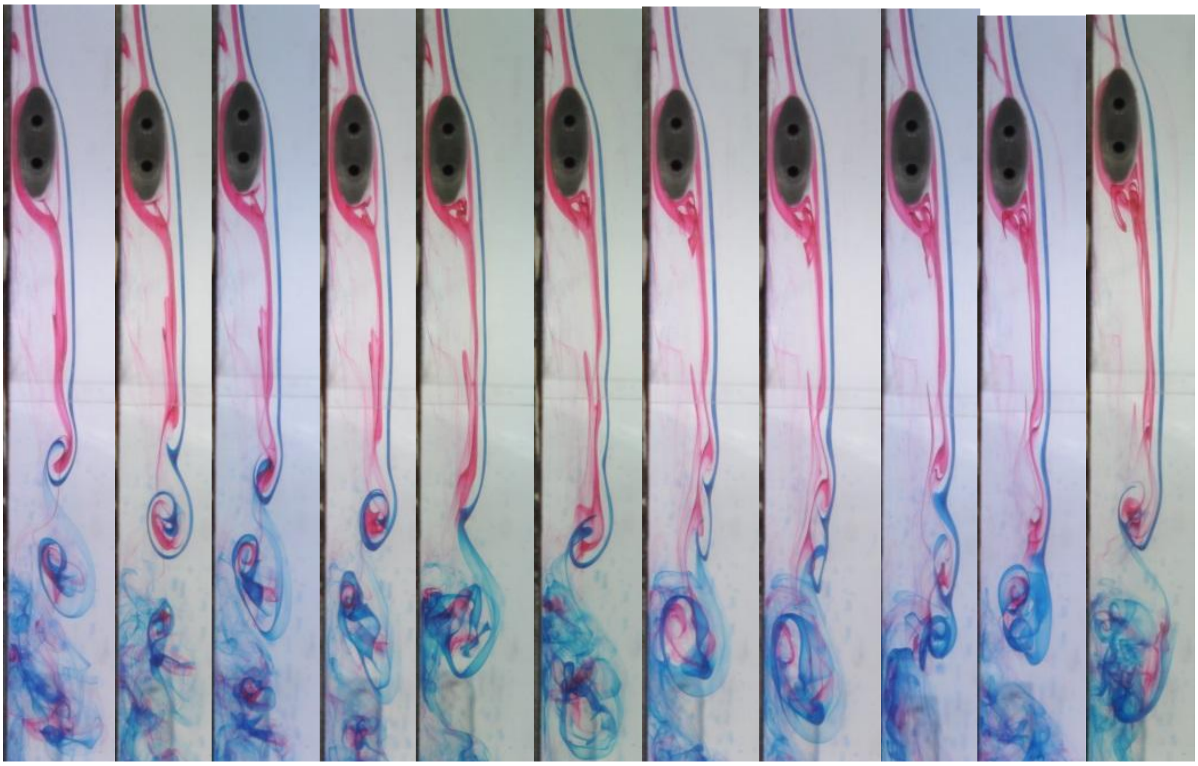
Compared to GR = 1.0, configuration with GR = 0.2 exhibits similar phenomena, though more intensified. The much smaller gap between the lower surface and the wall further restricts the flow, keeping the streamlines closer to thewall for Reynolds numbers much higher up to about 13 to 21. From then on, streamlines move away from the wall, Fig.5 (b, c) due to the phenomenon discussed above. Notice that the lower surface streamlines move back over the upper surface, suggesting an adverse pressure gradient and speed along the upper surface.



(a) Re≈6,5 (b) Re≈13 (c) Re≈21 (d) Re≈45 (e) Re≈ 96 (f) Re≈ 130 (g) Re≈219 (h) Re≈325 (i) Re≈402

Figure 5. Flow around the elliptical cylinder, AR = 0.33 positioned GR = 0.2, for various values of the Reynolds number.

For GR = 0.2,very asymmetric recirculation bubbles appear only for Reynolds numbers above 300, Fig.5 (g), (h), (i) and there is no occurrence of alternating vortex emission, even up to Reynolds number of 2200.



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k)

Figure 6. Time sequence of flow around an ellipse AR = 0.33 and GR = 0.2 for Reynolds number of 520. The period of time between two consecutive shots does not necessarily remain constant.

One of the particularities of the GR = 0.2 configuration is the destruction of the vortices shortly after its formation, staying briefly with well-defined characteristics. Fig. 6 shows a time sequence of images of the flow for Reynolds number 520.Notice that the vortices closer to the wall have lower speed compared to the ones farther from the wall, supper and lower vortices have a destructive interaction. For each of the images Fig (a), (b), (g) and (k) it is possible to observe the formation of vortices in a row with different distances between them. As this instead flow, an non periodic formation of vortices is suggested.

3.2.1. Vortex emission frequency, GR = 0.2

As presented and discussed previously the short interval of duration of vortices and non-periodicity in formation required that the experiment was repeated several times by putting the hot wire anemometer sensor probe in different positions along the x-axis, various positions in y for each x position, in a number of combinations. Data acquisition times with different time intervals were carried out for each of the combinations, as well as readings of the signals with ranges up to 210 s were collected, so that after terminating the measurements, windowing of the signals was performed, in an attempt to identify any dominant vortex frequency. However, for the entire range of Reynolds numbers researched (0 up to 2200), no dominant frequency could be identified.

Choi, J.H. and Lee, S.L. 2000 stated that when the GR = 0.2, there were no vortices shed from the cylinder. However from the present work, the formation of vortices for GR = 0.2 can be clearly observed from the images in Fig. 6 and 8, even that no dominant vortex frequency could be detected by using instrumentation, as depicted in Fig. 7 (a), (b), (c), (d).

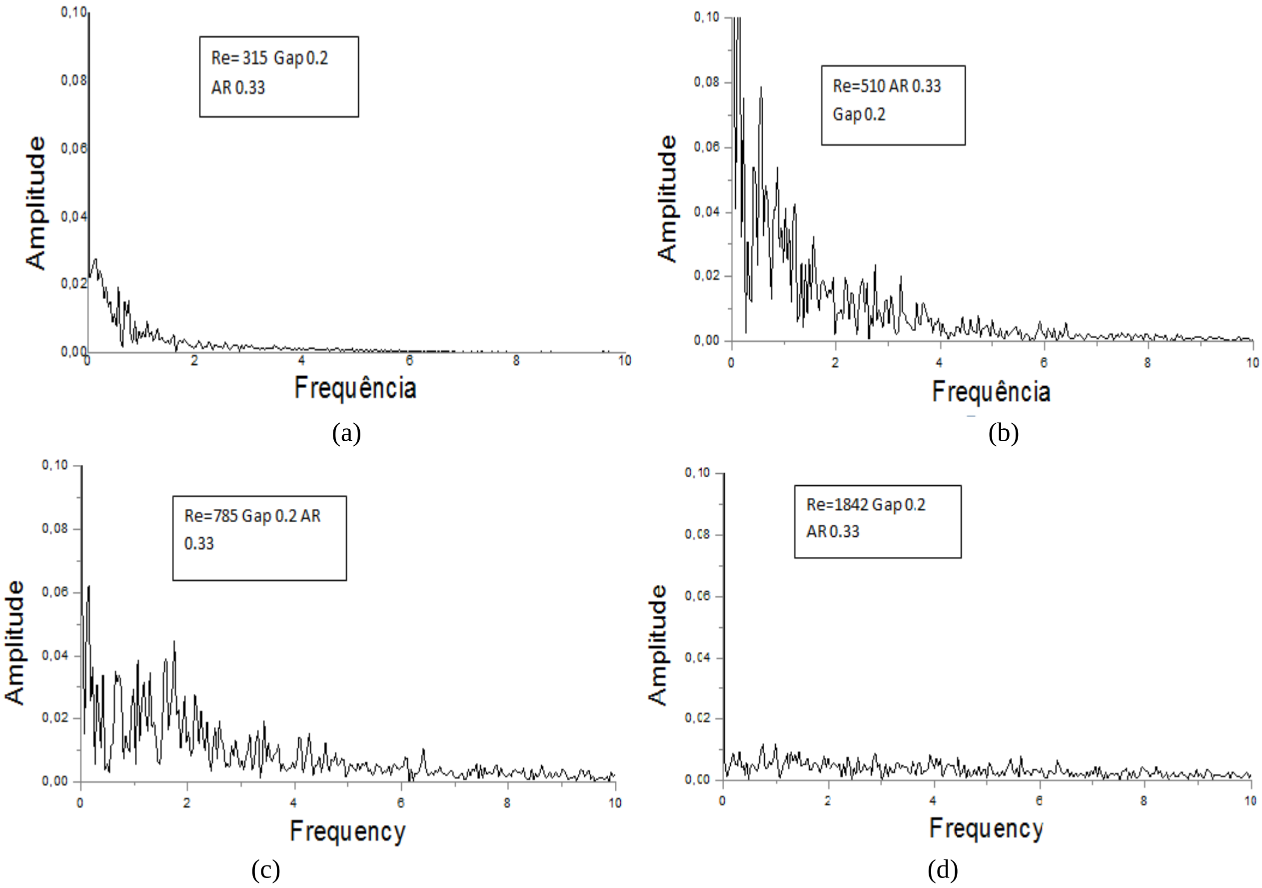


Figure 7 (a), (b), (c), (d). FFT of the emission frequency of vortices for four different Reynolds for GR = 0.2 and elliptical cylinder with AR = 0.33.

Figure 8.Flow around the cylinder elliptic GR = 0.2 with AR = 0.33, for Reynolds number of 812, showing vortex appearing and destruction

4. CONCLUSION

In this present effort or work a detailed study of the flow around an elliptical cylinder positioned near a flat smooth wall has been carried out. Flow images obtained by direct injection of liquid dyes allow to visualize the vortex shedding phenomena for a large range of Reynolds numbers (2 to 2200). Two gaps between the elliptical cylinder and the plane wall have been selected. For GR = 1.0 a moderate, but noticeable, influence of the wall is clearly observed. In this case, a hot film probe positioned in the wake allows to obtain the temporal velocity and, consequently, the vortex shedding frequency by using FFT. In the case of GR ≥1.0 a high value of signal to noise ratio (SNR) is easily obtained and the fundamental vortex frequency is rapidly observed. For GR = 0.2 the SNR is quite poor, independently of the probe position. For this case, many tests have been carried out in order to acquire the flow velocity data in the vortex wake using many different probe positions in the wake. In all cases, no matter the probe position in the vortex wake, the velocity signal FFT shows no dominant vortex shedding frequency. This situation has been named by different authors as "vortex suppression". The phenomenon of vortex suppression is due to the wall interference in the flow field. Vortex suppression is also observed in flow around rotating circular cylinders - Carvalho, 2003. In the case of the flow around rotating circular cylinders, a careful adjusting of the cylinder angular velocity causes a total vortex elimination, detected from the absence of a dominant frequency in the FFT and from the flow images captured. In the case of elliptical cylinder positioned with GR = 0.2, the FFT also does not show any dominant vortex frequency, but the flow images captured reveal the presence of large scale turbulence structures. Unfortunately, this large scale vortex structures are highly unstable and disappear rapidly. In this case, the vortex might be present for a while, but it is unstable, whereas in the case of rotating circular cylinders vortex suppression is clearly observed. For elliptical cylinders, only the stable vortex frequency is suppressed and several unstable vortex frequencies are observed in a very small space of time. It should be noticed that in several cases, vortices could be detected only by visualization, not from measurements alone. Further signal processing is on the way and detailed work should be done analyzing the influence of the gap, in a tentative of detecting all the transition Reynolds numbers just hinted in the present work.

5. ACKNOWLEDGEMENTS

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