# EXPERIMENTAL INVESTIGATION OF THE FLOW PAST A ROTATING CIRCULAR CYLINDER

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***Abstract.*** *This work presents an experimental investigation of the flow past a rotating circular cylinder placed perpendicularly to a liquid flow. The experimental tests have been carried out in a vertical hydrodynamic tunnel with a test section of 146x146x500 mm operated by gravity action and conceived for measurement and flow visualization. The influence of the specific rotation of the body and of the Reynolds number on the flow patterns has been studied. The results show that the periodic vortex shedding is strongly affected by the rotating motion of the cylinder.*

***Keywords:*** *rotating circular cylinder, flow visualization, vortex shedding, flow patterns.*

## 1. Introduction

Due to its several engineering applications, flow past a circular cylinder has been exhaustively investigated for many decades and it became a classical problem of fluid mechanics. The geometry of this solid body is simple but the flow motion involves a set of very complex phenomena produced by the simultaneous interactions among different shear layers, namely, the boundary layer, the separation zone, and the vortex shedding in the wake. The intense research activity on this subject has substantially contributed to understanding many physical mechanisms related to this kind of flow but many of its aspects remain still obscures. The most works in the literature are concerned with still cylinders placed crosswise to the fluid flow. The volume of available information about the flow around rotating cylinders is sharply smaller, in spit of its great technological interest in boundary layer control on airfoils, as discussed by Modi *et al*.(1990), and lift enhancement. In fact, rotating cylinder is able to generate high values of lift force by means of Magnus effect, but it possesses the same inherent inconvenience of all bluff bodies of presenting elevated drag coefficient.

The Magnus effect was quite studied and used in some practical applications, like in the well-known embarkation Backau, a ship built in the thirties, which employed two rotating cylinders as a wind propulsion device. Almost twenty years later, this concept was again employed by the famous French explorer Jacques Yves Cousteau, who has transformed a British ship into the oceanographic ship Calipso. An attempt of replacement of wings by rotating cylinders in aircraft was also been accomplished in the decade of thirty. Several other applications were tested, as use of rotating cylinders in hydraulic pumps and Aeolian turbines, studied by Vieira (1961), or in dirigibles, as proposed by the Canadian Aeronautical Institute, in 1888.

The flow over a rotating cylinder immersed in a free stream is characterized by the Reynolds number ($Re$) and the specific rotation ($a$), defined as:

$$Re = \frac{U\,d}{n} \qquad (1)$$

$$a = \frac{f\;d}{2\;U} \qquad (2)$$

where $U$ is the free stream velocity, $d$ is the diameter of the cylinder, $n$ is the kinematics viscosity of the fluid, and $w$ is the angular speed of the cylinder.

In the periodic regime of vortex shedding, the fundamental shedding frequency ($f$) is directly related to the free stream velocity ($U$) and to the cylinder's diameter ($d$) through the Strouhal number ($St$), as follows:

$$St = \frac{f\,d}{U} \qquad (3)$$

The first works involving cylinders in rotation were developed for small specific speeds ($a$) and low Reynolds number ($Re$) – Matsui (1967), Steele & Harding (1970). Starting from the eighty years, several experimental studies have been achieved for elevate values of $a$ and $Re$ – Coutanceau & Menard (1985), Badr & Dennis (1985) and Badr *et al*. (1990). More recently, the problem was also numerically studied by Chang & Chern (1991), Chen *et al*. (1993) and Ou (1995).

According to Goldstein (1938), the inhibition of the vortex generation at high rotation rates can be easily identified in rehearsals of flow visualization. It is very well-known that an increase in the circulation around a fixed cylinder can eventually conduct to a standard flow, with closed streamlines surrounding the cylinder. Similar results were found in the pioneer experimental studies of the development with time of the flow past a rotating cylinder by Prandtl (1927).

Theoretical studies based on boundary layer equations were accomplished by Moore (1957) and Glauert (1957), and indicated that for high values of $\alpha$ it is possible to obtain permanent regime without detachment of vortex, for a wide range of the Reynolds number.

Aldoss & Abou-Arab (1990) obtained experimental results of the flow around a circular cylinders positioned obliquely to airflow. The velocity profiles upstream and downstream the cylinder, the friction coefficient, and the separation and stagnation points were obtained for different specific rotation ($a$), from 0 to 1.25. The authors have been compared results from static cylinders and rotating ones and they observed that the position of the stagnation point is strongly affected by the parameter $a$, but this is not true for the separation points. The wake of a rotating cylinder is sharply asymmetric, because it suffers a deviation in the direction of the rotation, decreasing its length and width, while the upstream flow is not very influenced by the movement of rotation of the solid body.

Modi *et al*. (1990) investigated the concept of moving surface boundary layer control through a planned experimental program completed by a flow visualization study. The moving surface was provided by rotating cylinders located at the leading and trailing edges of the airfoil. The authors conclude that the rotating cylinders provide an increase of the maximum lift of the aerofólio, and that, in general, the performance is improved when the speed of the cylinder's surface approaches to the free stream velocity.

Barnes (2000) carried out measurements to a cylinder with rotation movement and Reynolds number up to 65. In this study, it was observed that the Strouhal number for the vortex shedding of a rotating cylinder is not very dependent of the $a$ value. In addition, measures were made to determine for which values of ($a$) vortices detachment are suppressed, for Reynolds numbers between 50 and 65. Due to the low values employed for the Reynolds number, the flow was considered two-dimensional, since there is an enormous disagreement in relation to the detachment of vortices in the few works that treat the flow as being three-dimensional. The experiments were accomplished in a tank with glass walls, having 2.5 m of length, 315 mm of width and 300 mm of depth. An apparatus was built, constituted of engagements and an electric motor that provided rotation and translation movement to the test body inside the tank. The process that turned possible the control of the rotation of the cylinder was not mentioned, in spite of that, he mentioned himself the existence of a small idiosyncrasy in the rotation of the test body, equal for 0,07mm. A series of additional measures was accomplished to determine the stability of the flow, that is, for which values of $Re$ the vortex shedding is suppressed. For fixed values of $Re$ and small magnitude of $a$, the stability of the flow agrees with the results presented in the literature, but this agreement gradually degenerate as $a$ rises.

Kimura *et al*. (1992) carried out an experimental and numerical study of the flow about a circular cylinder in rotation and translation movements for Reynolds numbers between $10^2$ and $10^5$, and $a$ varying from 0 to 2.1. This work had as main objective to investigate the effect produced by the rotation of the cylinder in the vortex wake. High Reynolds numbers were used so that the diffusion of the vorticity was neglected. In the experimental study, flow visualization by hydrogen bubbles generation was used in a water tank, and a hot wire anemometer was employed to the velocity profile measurements in the Reynolds number range of $3.10^4$ to $7.10^4$. Two cylinders were used with diameters of 1 and 3 cm, and length of 10 and 12 cm, respectively. In the numerical part of the work, the method of the discreet vortices was used for the flow simulation, in order to determine the critical specific rotation for which the detachment of vortexes possesses the smallest width or null width.

Badr *et al* (1990) carried out a theoretical and experimental study of the flow around a circular cylinder that simultaneously begins a rotation and translation movement starting from the rest, in order to examine the effect of rotation increasing on the flow structure. The range of the Reynolds number used was $10^3$ to $10^4$, and $\alpha$ varied from 0.5 to 3. The theoretical study was based on the two-dimensional unsteady numerical solution of the Navier-Stokes equations, while the experimental investigation was concerned with flow visualizations using solid suspended particles. An excellent agreement was observed between numerical and experimental results over all the velocity range considered, except for the highest rotation rates. In this case, three-dimensional effects become more pronounced in the experiments and the laminar flow breaks down, while the calculated flow starts to approach a steady state.

This present work proposes an experimental investigation of the flow past a rotating circular cylinder, positioned perpendicularly to the main stream, to observe the configuration of the wake, in function of the variation of the parameters that govern this flow type, namely, $a$ and $Re$.

## 2. Experimental facility

The flow generation system is an open circuit vertical hydrodynamic tunnel, continuously operated by gravitational action – Fig.1. The test section, made of high resistance optical Plexiglas, has been especially conceived to permit the flow visualization around models and solid obstacles. Measurements carried out with a hot-film anemometer have confirmed the quality of the flow inside the test section, combining good velocity profile uniformity and low turbulent intensity – always lower than 1%.

Dye liquid injection upstream the cylinder has been employed, in order to make the flow visible. The injection device is made of a pressurized reservoir, connected to a long elbow shaped hypodermic needle having an external diameter of 0.7 mm. The speed and pressure of injected dye are controlled by a needle valve, in order to produce a sharp and steady filament, while introducing the least possible disturbance in the free stream.

A careful lighting constitutes, undoubtedly, the first step to obtain a good quality picture. In this work, the best results have been obtained with a back-light illumination setup, employing two reflectors with six 150 W Photo Flood incandescent bulbs each. A translucent screen has been placed between the light sources and the test section, in order to generate a diffuse lighting, to retain infrared radiation, and to provide an evenly lightened background.

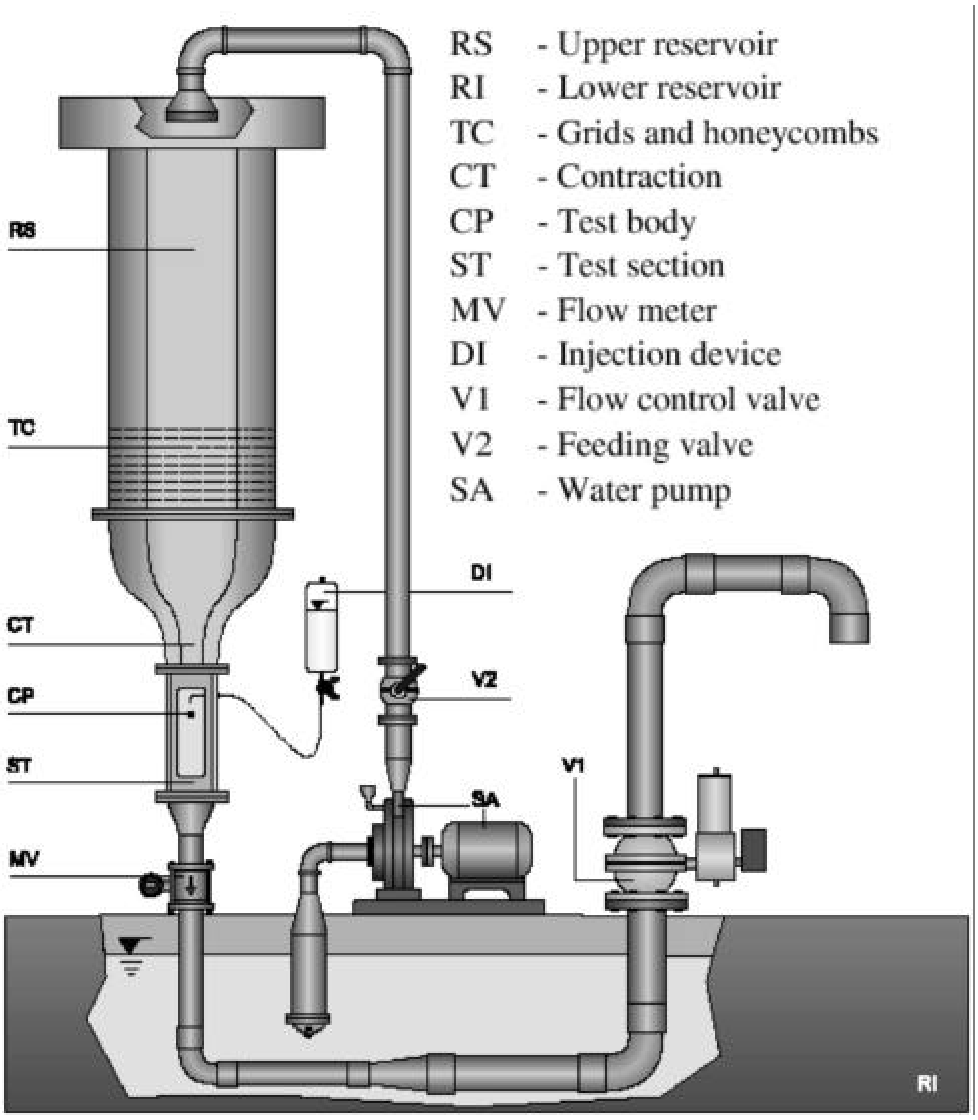
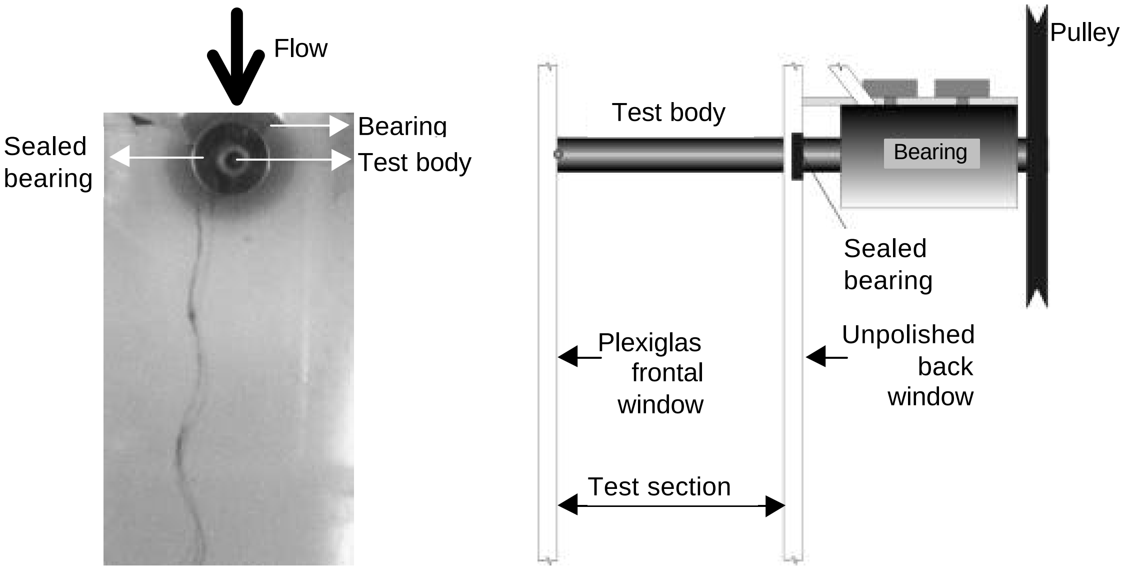



Figure 1. Vertical hydrodynamic tunnel for flow visualization.

**3 - Results and Discussion**

All flow visualization experiments have been carried out for a cylinder with 6 mm of diameter, for Reynolds numbers up to 600, and an absolute clockwise rotation varying between 50 and 300 rpm.

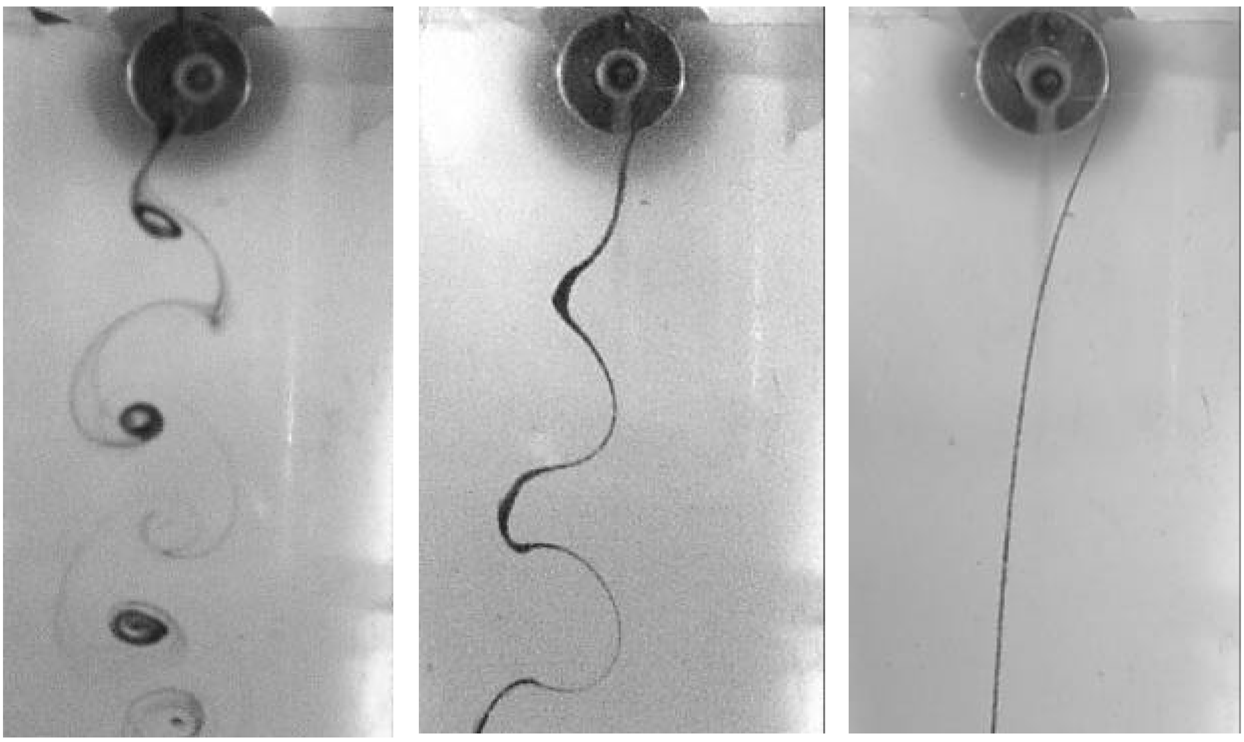
The Fig.2(a) shows a detail of the test model in the test section. The presence of two opaque black circles and a centralized gray shadow with a larger diameter can be noted. The central black circle in the frontal view is the test body. The larger black circle represents the sealed bearing utilized to avoid water leakage through the cylinder-to-window gap, as indicated on the Fig.2(b). The gray shadow, noticed behind the retainer, is the bearing case that provides sufficient support to the test model minimizing vibrations. It is important to emphasize that all the mentioned components are located outside of the test section, being just the circular cylinder immersed in the flow stream.




(a) Frontal view (b) Lateral view (no scale)

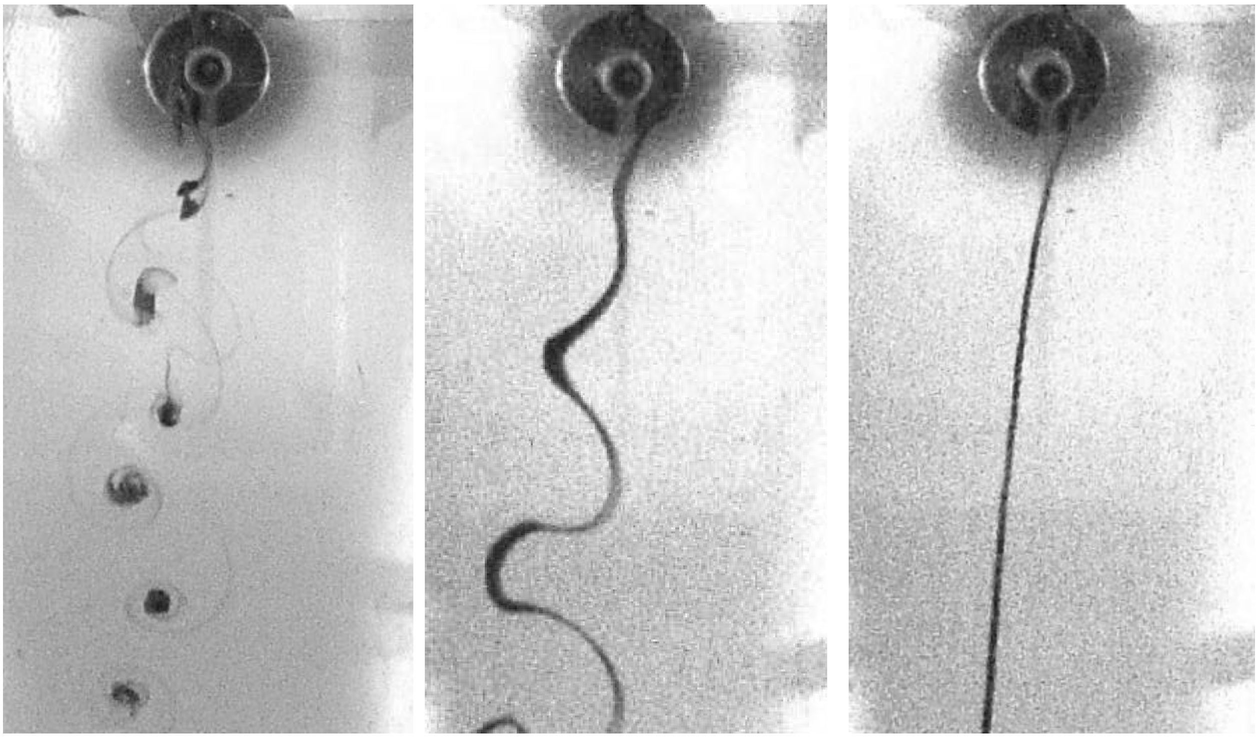
Figure 2 - Frontal view of the test section and schematic representation of the rotation system outside test section.

The Fig.3 depict still photographic images showing the flow around the solid body, for a constant Reynolds number about 115, and three different values of the ($\alpha$) parameter. The Fig.3(a) shows clearly the presence of alternated vortices in the wake. Those vortices are displaced from the vertical symmetry line due to the cylinder clockwise motion. With the increasing of the $a$ parameter, Fig.3(b), the vortex shedding phenomenon is partially inhibit, and an incipient regime of eddies generation is attaint, also characterized by an oscillating instability in wake with an accurate frequency. A subsequent increase of the $\alpha$ parameter, Fig.3(c), produces a total absence of vortices in the wake. The same tendency can be observed in the results of Fig.4, where the Reynolds number was fixed about 150, and for different values of specific velocities ($a$) have been investigated.



(a) $\alpha = 0.83$ (b) $\alpha = 1.88$ (c) $\alpha = 2.90$

Figure 3 - Flow visualization around a circular cylinder in clockwise rotation, with $d$ = 6mm, $Re \approx 115$, and $a$ variable.



(a) α = 1.56 (b) α = 2.02 (c) α = 2.27

Figure 4 - Flow visualization around a circular cylinder in clockwise rotation, with d = 6mm, Re ≈ 150, and α variable.

The images in the Fig. 5 show the flow around the same solid body, for the (α) parameter fixed about 2, and three different values of the number Reynolds. The Fig. 5 (a) shows the complete absence of alternated vortex in the wake of the cylinder, with a very small instability. With the increasing of the Reynolds number, Fig. 5 (b), is possible to observe the incipient vortex shedding regime, absolutely similar these showed in the Figs. 3 (b) and 4 (b). A subsequent increase of the Re, Fig. 5 (c), shows clearly the presence of vortices alternated in the wake of the flow

(a) Re=109 (b) Re=167 (c) Re=232

Figure 5 - Flow visualization around a circular cylinder in clockwise rotation, with d = 6mm, α ≈ 2.0, and different *Re*.

Figure 6 depicts the some experimental points obtained for the Reynolds number in function of the α parameter for several rotations, in the range of 50 to 300 rpm. The two flow regimes, namely, with vortices and without vortices, have been directly identified by flow visualized images. Previous hot-film anemometer measurements have been carried out and corroborates these visual results.

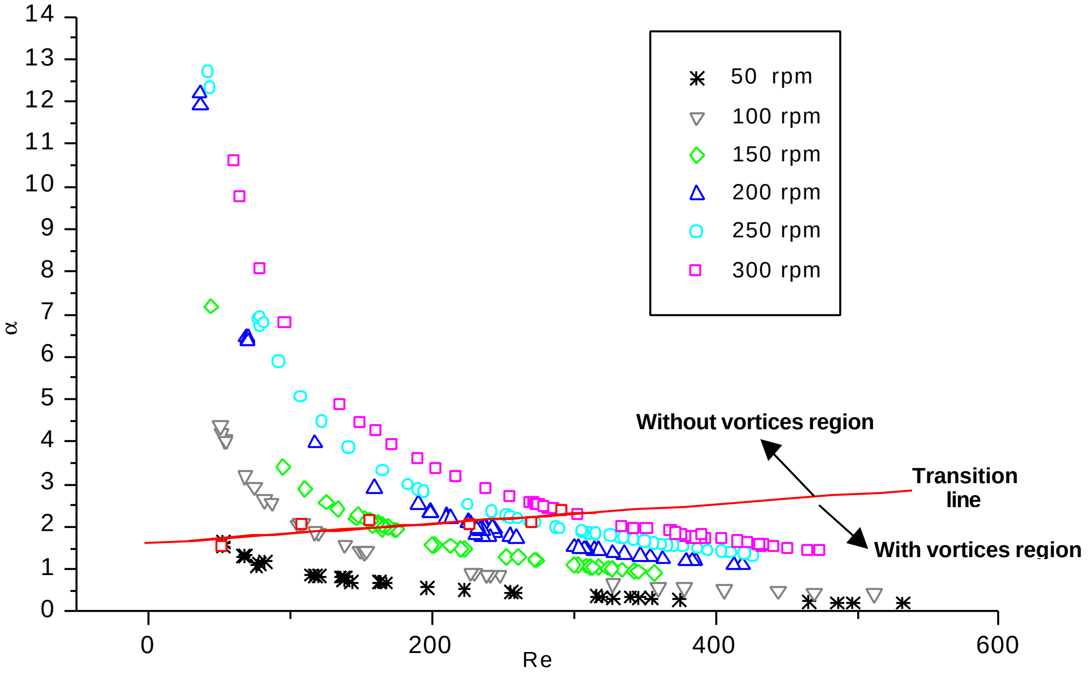



Figure 6 - Flow pattern map for a rotating circular cylinder

The continuos line in the Fig.6 represents the transition between the presence and absence of vortices in the flow. In the measurement range, this transition line shows a quasi linear behavior, which can be appropriately represented by:

$$a = 1.61168 + 0.0232 Re \quad (4)$$

For a fixed Reynolds number, the vortex shedding in the wake can be completely suppressed if the cylinder's rotation is sufficiently improved.

## 4 - Conclusion

An experimental study of the flow around a rotating circular cylinder has been achieved, using more than 400 visualized images, and the main conclusion can be expressed as follows. The flow patterns depend strongly on the Reynolds number and the α parameter;

(a) as the specific rotation (α) becomes large, the vortices shed disappears completely for a constant Reynolds number.
(b) with the increase of the number Reynolds, in according to Fig.6, can be observe a change in the flow regime dependently of the (α) values.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## 5 - References


Aldoss, T. K. and Abou-Arab, T. W., 1990, "Experimental Study of the Flow Around a Rotating Cylinder in Cross Flow", Experimental Thermal and Fluid Science, vol. 3, pp. 316-322.

Badr, H.M. and Dennis, S.C.R., 1985, "Time-Dependent Viscous Flow Past an Impulsively Started Rotating and Translating Circular Cylinder", Journal of Fluid Mechanics, vol.158, pp. 447-488.

Badr, H.M.; Coutanceau, M.; Dennis, S.C.R. and Mérnard C., 1990, "Unsteady Flow Past a Rotating Circular Cylinder at Reynolds Numbers $10^3$ and $10^4$", Journal of Fluid Mechanics, vol. 220, pp.459-484.

Barnes, F.H., 2000, "Vortex Shedding in the Wake of a Rotating Circular Cylinder at Low Reynolds Numbers", Journal of Physics, vol 33, pp.141-144.

Chang, C.C. and Chern, R.L., 1991, "Vortex Shedding From an Impulsively Started Rotating and Translating Circular Cylinder", Journal of Fluid Mechanics, vol. 233, pp.265-298.

Chen, Y.M.; Ou, Y.R. and Pearlastein, A.J., 1993, "Development to the Wake Behind a Circular Cylinder Impulsively Started Into Rotating and Rectilinear Motion", Journal of Fluid Mechanics, vol. 253, pp.449-484.

Coutanceau, M. and Menard, C., 1985, "Influence of Rotation on the Near-Wake Development Behind an Impulsively Started Circular Cylinder", Journal of Fluid Mechanics, vol.159, pp.399- 446.

Glauert, M. B., 1957, "The Flow Past a Rapidly Rotating Circular Cylinder", Proceeding of the Royal Society of London,. *A230*, pp.108-115.

Goldstein, S., 1938, "Modern Developments in Fluid Dynamics", Oxford University Press.

Kimura, T.; Tsutahara, M. and Wang, Z., 1992, "Wake of a Rotation Circular Cylinder", *AIAA Journal*, vol 30, nº2.

Matsui, T., 1967, "Flow Behind a Rotating Cylinder", The Physics of Fluids, vol. 10, nº9, Pt. II, p. S305.

Modi, V. J.; Mokhtarian, F. and Yokomizo, T.,1990, "Effect of Moving Surfaces on the Airfoil Boundary-layer Control", Journal of Aircraft, vol. 27, nº1, pp. 42-50.

Moore, D. W., 1957, "The Flow Past a Rapidly Rotating Cylinder in a Uniform Stream", Journal of Fluid Mechanics, vol 2, pp.541-550.

Ou, Y.R., 1995, "Mathematical Modeling and Numerical Simulation in External Flow Control", Flow Control, pp. 219-255.

Prandtl, L, 1957, “Applied Hydro and Aeromechanics”, Reprint of the Dover Publications, New York.

Steele, B.N. and Harding, M.H., 1970, "The Application of Rotating Cylinders to Ship Maneuvering", National Physical Laboratory Ship Reporter 148.

Vieira, R. C. C., 1961, "Contribuição ao Estudo das Aplicações dos Cilindros Rotativos", USP-São Carlos.

Vieira, E.D.R, 1997, “Estudo Qualitativo e Quantitativo de Escoamentos ao Redor de Corpos Não-Aerodinâmicos Utilizando-se de Técnicas de Visualização em Meio Hidrodinâmico”, Doctor of Sciences These, ITA - Instituto de Aeronáutica, São José dos Campos, 200 p.