COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

STROUHAL NUMBER DETERMINATION FOR SEVERAL REGULAR POLYGON CYLINDERS FOR REYNOLDS NUMBER UP TO 600

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Abstract. *Experimental flow visualization is a powerful tool to understanding the complex phenomena associated with the fluid dynamics. This work links that important experimental technique with the image processing, objecting an investigation of the vortex shedding from several prismatic bluff body cylinders with cross section formed by regular polygons – triangular, pentagonal, hexagonal and octagonal. Experiments were performed in a pilot vertical low turbulence hydrodynamic tunnel, with 146×146×500 mm of test section. The emission of liquid dye directly in non-perturbed flow by means of a long hypodermic needle has been utilized to create the flow image. A 3 CCD high-resolution video camera has been used to image capture and 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: Vortex meter, Strouhal number, Flow visualization, Vortex shedding.

1. INTRODUCTION

The flow past rigid bodies for geometries called non-aerodynamics or bluff-bodies, in the majority of times, due to boundary layer separation, generates vortex shedding. In adequate conditions, vortices are shedding from both, upper and lower body sides, alternately, making the vortices wake named *Von Kármán vortex street*. The vortex shedding frequency (f) is directly related to the free stream velocity (V) and to the characteristic dimension of the solid body (D) through a dimensionless parameter named Strouhal number, defined as

$$Sr = \frac{f\,D}{V} \tag{1}$$

The periodic vortex shedding from bluff bodies has been intensively studied since the STROUHAL's work of 1878. Nowadays, several experimental and numerical studies have been realized showing close relation for Strouhal number with the geometric form of the bluff body and the flow regime, for example: Okajima (1982) for rectangular cylinders with several aspect ratios using aerodynamics and hydrodynamic tunnels for a large Reynolds range, Kawakita & Silvares (1993) with ten different rigid body formats and a high blockage ratio (about 30%), Vieira *et al*. (1997) for elliptical cylinder with aspect ratio equal to 0.6, and Mansur *et al*. (1996) and Lindquist *et al*. (1997) for square cylinders in water medium.

The idea of building a flow meter based on the assumption of Strouhal number variation as a function of Reynolds number (R) was first proposed by ANATOL ROSHKO in 1953. He studied vortex shedding from a circular cylinder and established the functional relationship between (Sr) and (R) within certain ranges of Reynolds number with sufficient accuracy to enable it to be used as a mean of measuring air speed - Ower & Pankhurrst (1977). Roshko found that the results of a large number of observations (valid only to circular cylinders and with a high length to diameter ratio) that could be well represented by the equation

$$Sr = 0.212\left(1 - \frac{C}{R}\right) \tag{2}$$

where (C) has the values 21.2 and 12.7 for the Reynolds number ranges 50 – 150 and 300 – 2000 respectively.

Equation (2) can be reduced to a form which express the direct relationship between the free flow velocity (V) and frequency of vortex shedding (f)

$$V = 4.72\ f\ D\ +\ \frac{C\mu}{D\rho} \tag{3}$$

In according to Roshko, these results may be used to measure flow speed as follows: a suitable cylinder of diameter (D) is inserted into the stream and the vortex-shedding frequency (f) is determined by means of several experimental means, discussed below. A first approximation to the value of (V) can be obtained from Eq. (3) neglecting the second term ($C\mu/D\rho$). The ratio of the second term to the first ($4.72\,f\,D$) is equal to $C/(R-C)$, having the maximum value, about 0.7, for the minimum Reynolds number (50) for which Roshko's results can be utilized. In high Reynolds numbers the ratio of the two terms of Eq. (3) is sensitively less; and it will generally be found that neglecting the second term of Eq. (3) when calculating (V) will give a sufficiently close approximation to the Reynolds Number (Re) showing which of the two (C) values should be inserted into Eq. (3) to recalculate (V) using the complete equation. It is important that the Reynolds number should be within one of the ranges specified by Roshko, i.e. 50–150 or 300–2000.

Today, vortex shedding flow meter or only vortex meter, has been used in steady flow in several industrial applications for over two decades and have proven themselves to be accurate and reliable. Vortex meter is a flow meter with a simple configuration, high accuracy, linearity, wide dynamic range, poor dependency of fluid viscosity and no containing moving parts submitted to deterioration, it is in fact high reliability – Wolochuk *et al*. (1996); Yokoi & Kamemoto (1994) and Unal & Rockwell (1988).

Because these merits, an accumulation of knowledge about the influence of various different non-aerodynamics body shapes on the vortex shedding frequency has been desired.

Vortex meter is an excellent device for flow measurement, but the main drawback of such vortex flow meter is the very complicated design. It is related to numerous and miscellaneous factors influencing the vortex shedding. First of all, the phenomenon is influenced by the bluff body geometry, where the regularity and power of the generated vortices are strongly sensitive on the shape and dimensions, Pankanin & Krystkowicz (1995). Prismatic bluff bodies of several shape cross sections positioned in cross flow have been tested as a shedder by many manufacturers in a constant search to a stable vortex shedding curve, Doebelin, (1994). In this work four different prismatic bluff bodies in relative low Reynolds number (up to 600) and low blockage ratio (no more than 5 %) have been experimentally tested, using hydrodynamic flow visualization as a work tool, for obtaining the Strouhal – Reynolds behavior.

2. OBTAINING VORTEX SHEDDING FREQUENCY

Since the famous Strouhal´s experiment of the eolic harp in the past century, several accurate methods for determining the vortex shedding frequency have been proposed in technical literature. The determination of the frequency (f), is possible using a simple method of flow observation, e.g. by means of smoke trails in conjunction with a stroboscope light. Direct injection of smoke tracers, generally produced by a large variety of smokelike materials such as vapors, fumes and mists, usually upstream of the fluid dynamic model, are intensively used for qualitative flow visualization in wind tunnels, see Mueller (1983). According to Ower & Pankhurst (1977) there are no published records of the direct use of such a quantitative method, but it is not true, because Brown (1952), successfully, utilized a smoke tracer produced by burning wheat straw under a slight pressure and insufficient oxygen and a mechanical stroboscope light driven by a synchronous motor to measure the frequency (f) shedding from a circular cylinder in a low turbulence subsonic wind tunnel.

More recently, Chrysler and Mitsubishi automobile companies have been testing the use of vortex meter to measure the airflow entering in the internal combustion engines. Fuel injection control circuits contain a multitude of sensors and actuators that operate to maintain optimum engine operating conditions. Vortex meter permits to determinate volumetric airflow using a bluff body positioned in the manifold of the mainstream flow. The vortex shedding frequency is detected by an ultrasonic transmitter and receiver arrangement. As the vortex passes between the transmitter and receiver the electrical signal on the receiver is interrupted and the frequency of interruptions indicates the vortex shedding frequency, Sasaki *et al*. (1982). The use of ultrasonic sensors in industrial applications is done because they are immune to noise and vibrations in the pipes and they are reliable, Basile (1995).

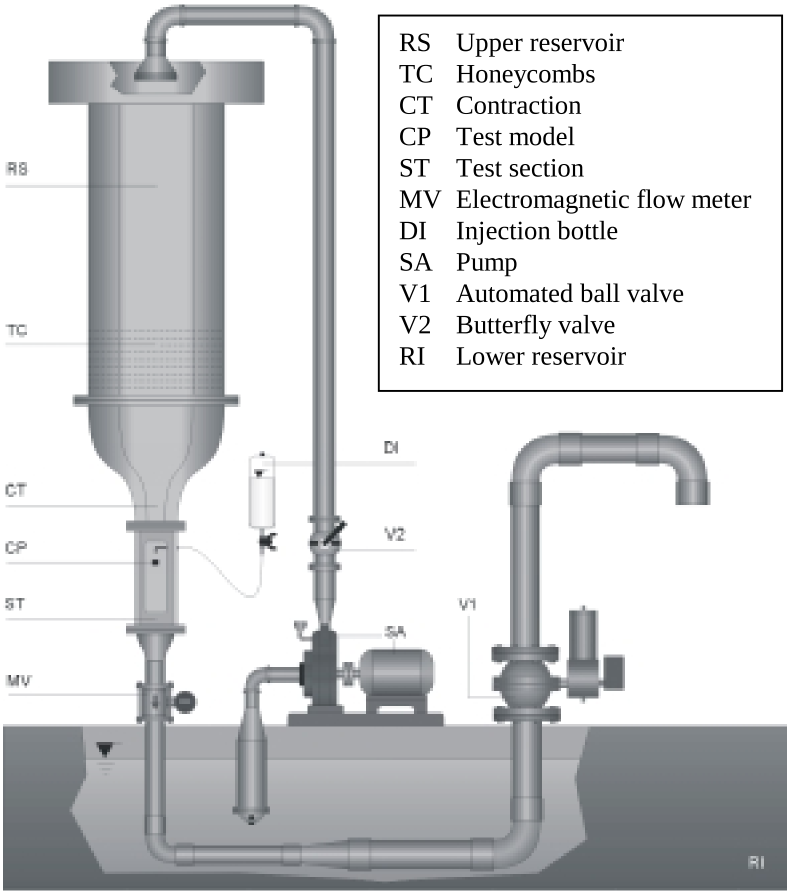
Generally, in the vortex shedding flow meters for industrial applications are made utilizing a magnetic sensor assembled at an end of the bluff-body. This magnetic sensor captures small bluff-body oscillations due to vortices shedding, Doebelin (1994).

The vortex shedding frequency, in industrial vortex meters, for maximum flow rate, are of the order of 200 to 500 Hz. In this work, the main aim is the use of vortex meter application for small velocity flow measurement with low blockage ratio, in other words for shedding frequency about 1 Hz.

In scientific laboratories, vortex-shedding frequency is measured by several means. Modi & Dikshit (1975) employed successfully a high sensible pressure transducer positioned at the centerline of the vortex wake and Sarpkaya & Kline (1982) measured the lift force actuating on the body using small pressure sensors. Many researchers prefer to determine a spectral analysis of the flow velocity in a fixed point on the wake. In that cases, the velocity signal are obtained by several ways, hot-wire anemometers – Van Atta (1968), Okajima (1982) and Kawakita & Silvares (1993) – laser Doppler Anemometers – Tokumaru & Dimotakis (1991) and Durão *et al* (1991), at last, using particle image velocimetry – Agüi & Jiménez (1997) and Lourenço *et al*. (1997).

3. EXPERIMENTAL APPARATUS DESCRIPTION

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 less than 1.1 % of turbulence level in the more adverse way of operation. The water tunnel is shown in Fig. 1. More details about that water tunnel facility and its operation are available in Vieira *et al*. (1997).



RS	Upper reservoir
TC	Honeycombs
CT	Contraction
CP	Test model
ST	Test section
MV	Electromagnetic flow meter
DI	Injection bottle
SA	Pump
V1	Automated ball valve
V2	Butterfly valve
RI	Lower reservoir

Figure 1- Hydrodynamic pilot tunnel.

The flow visualization technique applied in this work is the direct injection of opaque liquid dye in non-perturbed flow by means of a long hypodermic needle. The dye utilized is a solution of black PVA pigments, water and ethyl alcohol. The flow image has intensively been illuminated by two (1000 W) halogen lamps, air cooled by means of a little fan, shielded by white velvet-like translucent paper in order to provide an uniformly diffuse bright background against which the dye patterns were photographed.

The animated images, captured in this experimental work, uses broadcast quality SVHS – NTSC analogue video recorder that permits efficient and inexpensive storage of a large temporal sequence of images in a ratio of 30 fps (frames per second). A JVC KY-27C video camera with 3 CCD – charge coupled device – and high resolution (over 800 horizontal lines) and a BR-S822U JVC videocassette recording (VCR) equipped with a TC (time counter) board have been used to capture video images. Time counter board permits to record a precision temporal identification of each frame.

Observing, in a very controlled slow motion, the images recorded in video is possible to identify the precise moment of the beginning of the vortex shedding process. Identified a complete vortex shedding period, time counter board permits to determine the time associated with the process and consequently the vortex frequency. An estimate of errors associated to vortex shedding frequency shown is about ±5%. More details about the technique to determine the vortex shedding frequency using a VCR are search in the work of Mansur *et al*. (1996) and Vieira (1997).

Still images are also captured using chemical pellicle roll film and a *Nikon* F4s (SLR) single lens reflex camera equipped with a special *Nikkor* medical macro lens of 120 mm and f/1:4. The pictures have been obtained in f/1:11 in 1/250 s. Negative B&W (black and white) roll film 135 type (24 x 36 mm in size) *Kodak T-Max* 400 (ISO 400), developed by *Kodak T-max RS* developer in non-pushed conditions (7 minutes in 20 ^{o}C), has been used. This negative B&W chemical film, indicated to scientific applications, permits to obtain small grain pictures with high contrast jumps and recording fine details of the image. Enlarged positive copies have been made in high-contrast *Ilford B&W* paper.

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

4. RESULTS

Figures 2a-d show a Strouhal number curve as a function of Reynolds number for several prismatic cylinders with cross section forming regular polygons. All tests are performed for zero degree attack angle, positioning one of the edges of the cylinder tested exactly on the stagnation point. The characteristic dimension (D), used for calculating Reynolds and Strouhal dimensionless parameters, has been taken as the diameter of the circumference that encircles the regular polygon. All bodies tested have length to characteristic dimension (D) ratio more than 24.

Figure 3 and 4 show the von Kármán wake images generated by the triangle and octagon cylinder respectively.

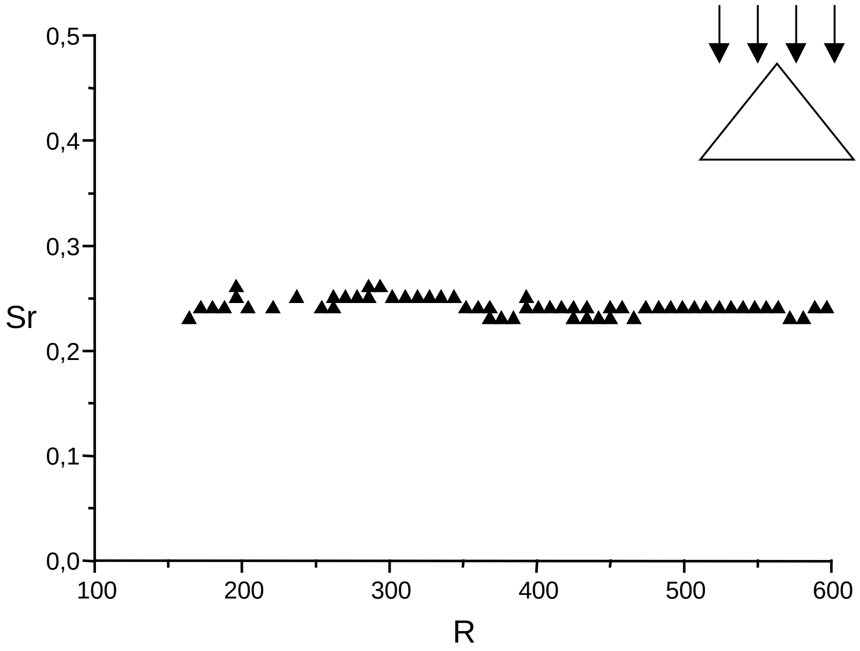


Figure 2(a)- Strouhal × Reynolds numbers curve for the regular triangular cylinder.

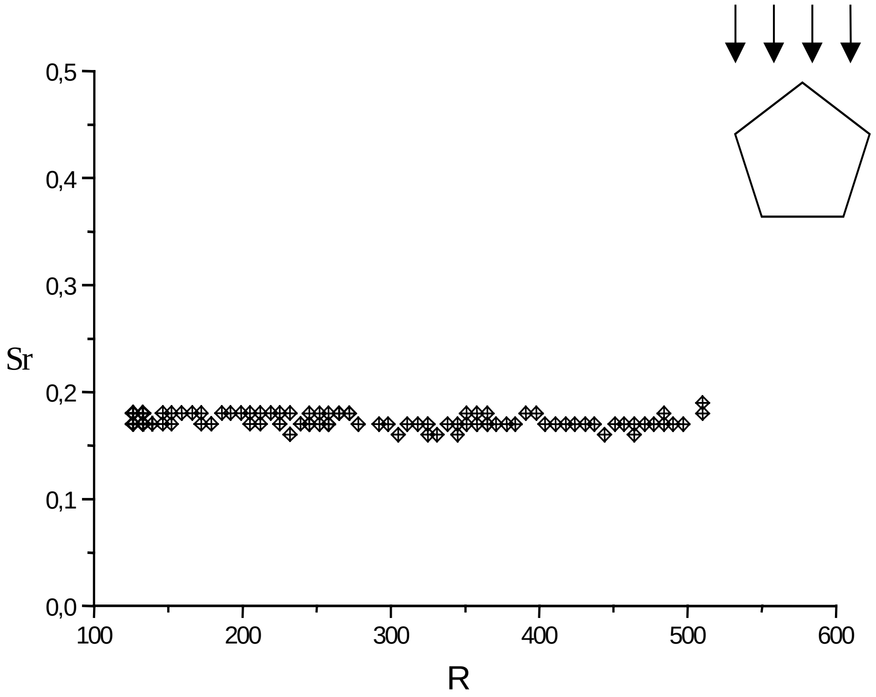


Figure 2(b) Strouhal × Reynolds numbers curve for a regular pentagonal cylinder.

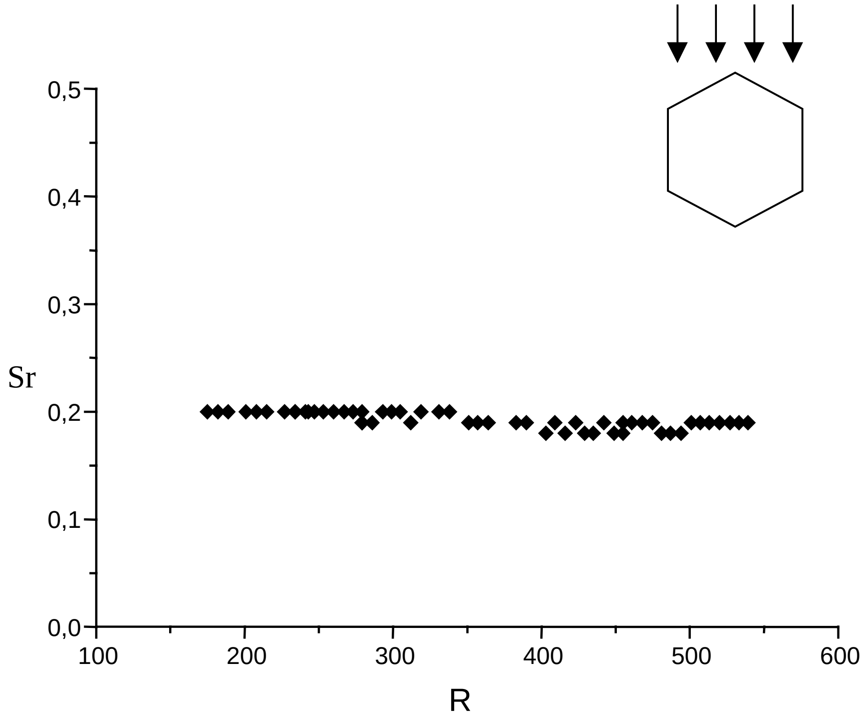


Figure 2(c) Strouhal × Reynolds numbers curve for a regular hexagon cylinder.

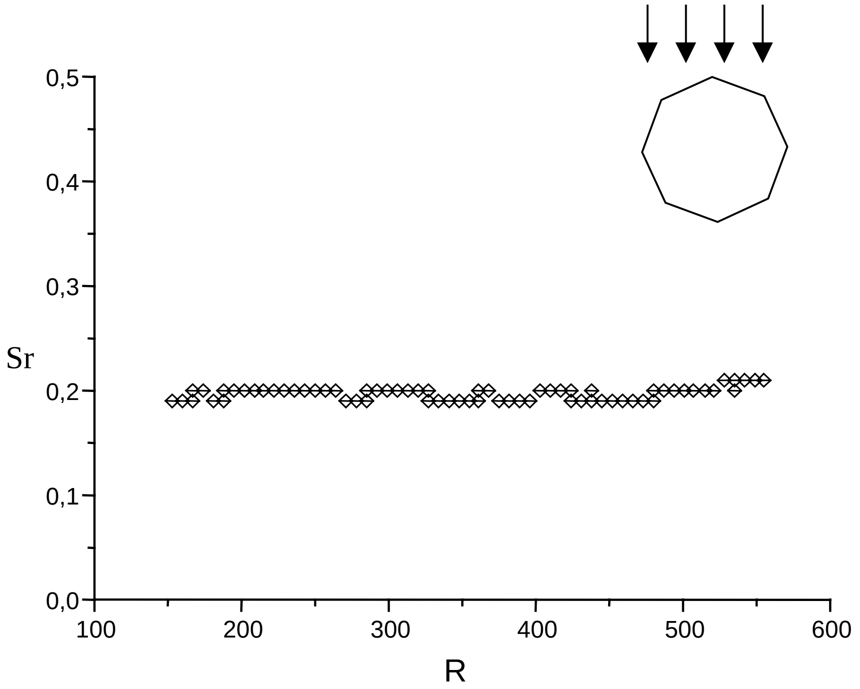


Figure 2(d) Strouhal × Reynolds numbers curve for a regular octagonal cylinder.

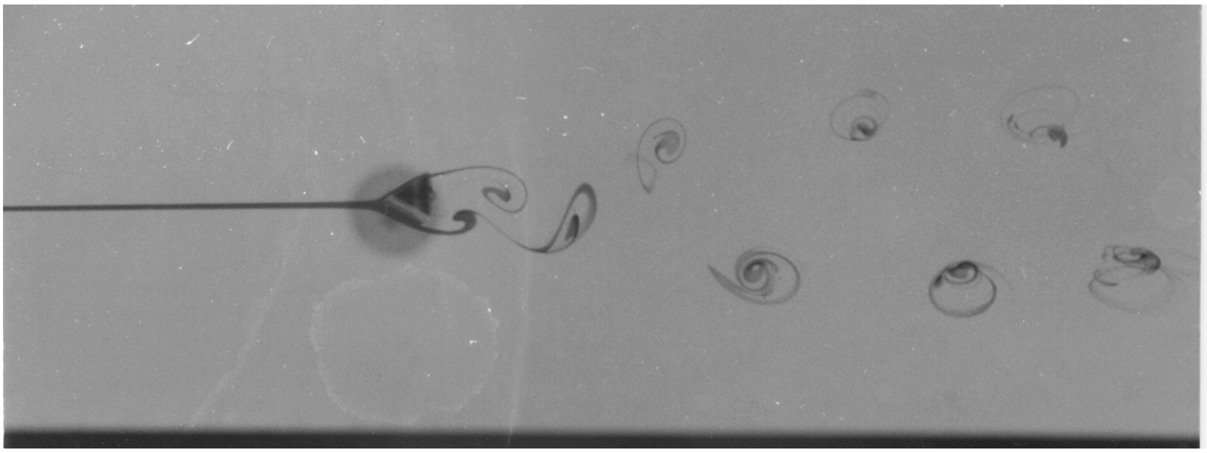


Figure 3 Wake generated by a triangular cylinder - Reynolds number about 200.

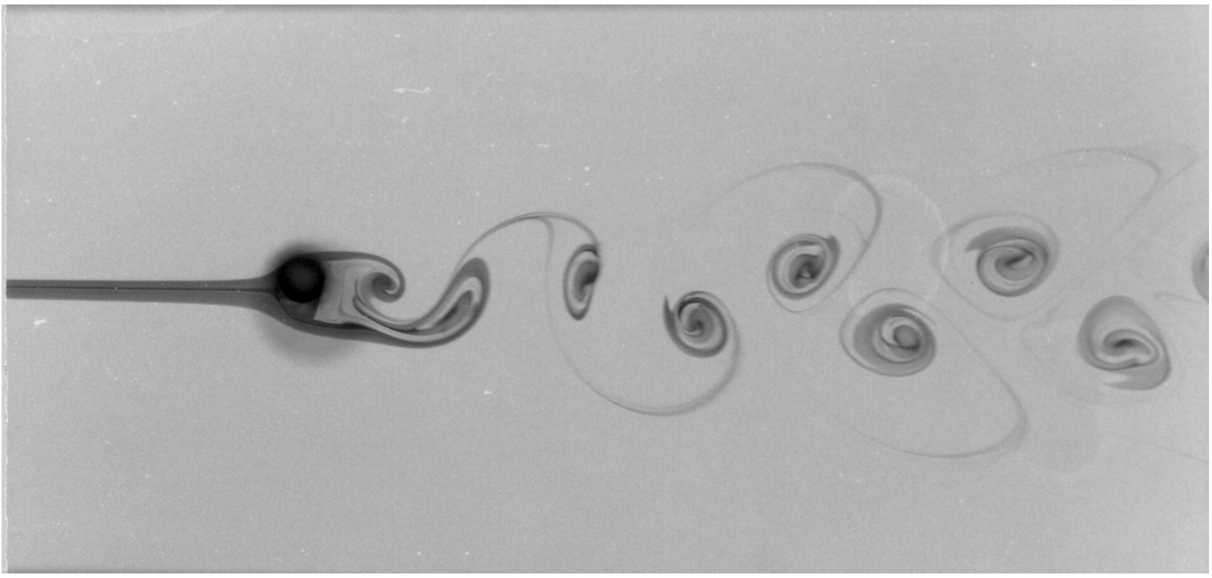


Figure 4 Wake generated by a octagonal cylinder - Reynolds number about 220.

5. CONCLUSIONS

Despite the fact that the flow around a circular cylinder and others bluff bodies has been studied for over 100 years, this problem type is still under intensive experimental and numerical investigation. In this work, a preliminary study of several bluff bodies have been realized willing to search the relation between the Strouhal and Reynolds numbers for different non-aerodynamic bodies submitted to low vortex shedding frequency.

The frame capture speed (30 fps) used in the broadcasting video camera offers a serious restraint to the maximum vortex shedding frequency possible to be visibly detected. In this work the maximum vortex frequency has been limited to the maximum of approximately 10 Hz. In this circumstance, to continue this work in a more high Reynolds numbers, it is necessary a high speed video camera possible to capture thousands of frames per second. Happily, today, high-speed video camera undergoes a sensible fall of prices due to the development of new electronic CCD sensors.

The vortex wakes generated by pentagon, hexagon and octagon cylinders show a similar structure, as the circular cylinder structure. But the wake generated by the triangular cylinder shown a different structure. The vortices are generated in the triangular cylinder very close to the upper side of the body and the vortex formation is hardly influenced by the edges, implying in high values of Strouhal when compared with the Strouhal curve produced by a circular cylinder. The Strouhal-Reynolds curve obtained by, Lindquist *et al*. (1997), for a square cylinder shown Strouhal values less than they obtained by the triangular cylinder. Finally, the generated frequency by the triangular cylinder presents a slightly bad behavior than that one generated by the other geometries.

Discontinuities in the Strouhal-Reynolds number curve, as observed in Roshko's curve in Eq. (1), have been attributed to the conditions of the approaching flow, cylinder vibrations or nonparallel vortex shedding, in according to Hammache & Gharib (1989). For experiments where the aspect ratios are not large enough, minimize the wall boundary layer effects is very difficult, if not impossible. A natural approach to suppress the three-dimensional effects and consequently to induce parallel vortex shedding, has been to employ endplates devices. In this work, none means has been used to reach the optimum configuration for achieving parallel vortex shedding in the wake of the bluff bodies. The use of endplates devices will be implemented in future works.

ACKNOWLEDGMENTS

The present work was, in part, supported by FAPESP. The experiments were conducted using the facilities of the Flow Visualization Laboratory of the Mechanical Engineering Department at UNESP – Ilha Solteira.

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