BIASED FLOW AFTER TWO SQUARE CYLINDERS SIDE-BY-SIDE

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Abstract. *This work presents a study of a turbulent biased flow on two square cylinders side-by-side. The flow in this regime forms one narrow and one wide street, with two distinct frequencies and a gap that may switch randomly from one side to the other. Velocity time series are obtained with the constant temperature hot wire anemometry technique in an aerodynamic channel. The aspect ratios T/L chosen were 1.25, 1.50, 1.75 and 2.0, where "T" is the distance between the centers of the adjacent square cylinders and "L" is the cylinder height. The experimental data are analyzed by means of statistical and wavelet tools. The probability distribution function (PDF) of the axial velocity is also shown. The use of wavelet transform seems to be of great importance, since it makes possible a joint analysis in time and frequency domains allowing the detection of non-permanent flow structures. The results show that the gap switches occur in very small time intervals, thus presenting an unstable feature which cannot be detected in the frequency spectrum. A comparison is performed between the results obtained for the square cylinders and those of circular cylinders by means of emphasize the differences between them.*

Keywords: *biased flow, wavelets, square cylinders, probability distribution function.*

1. INTRODUCTION

Slender engineering structures are used in many applications, like tall buildings, chimney groups, tube bundles in heat exchangers, chemical-reaction towers and offshore platforms. Two cylindrical structures in staggered arrangements, side by side or tandem are the simplest configuration of multiple structures.

The square cylinder is a representative model for bluff bodies with sharp corners, characterized by a fixed flow separation point, which are distinct from those of continuous curvature with oscillating separation points, usually represented by the circular cylinder. One example of interaction of the flow on square cylinders side-by-side is in construction engineering where tall buildings are erected in groups.

Sakamoto & Haniu (1988) investigated aerodynamic forces, Strouhal number, and cross-correlation between fluctuating pressures on two side-by-side square prisms, with an aspect ratio of 3, immersed in a thick turbulent boundary layer. No end plates were mounted; T/d examined was between 1.2 and 7.0, and Re based on the characteristic width of the prism was 1.52×10^5.

Kolàr et al. (1997) measured the wake of two side-by-side square cylinders using a two-component laser Doppler velocimetry, with $Re = 2.3\times10^4$. They examined the flow only at $T/d = 3$, where two coupled vortex streets occurred, providing no information on the flow in other possible regimes.

Agrawal et al. (2006) investigated numerically the laminar wake at $Re = 73$ of two side-by-side square cylinders at $T/d = 1.7$ and 3, using a lattice Boltzmann method. They observed both in and anti-phased vortex shedding from the two cylinders at $T/d = 3$ and a biased gap flow at $T/d = 1.7$, which could switch randomly from one side to the other, forming a narrow and a wide street behind the cylinders.

Rao et al. (2008) also used a lattice Boltzmann method to examine the flow structure, Cd and St at *T/d* = 2.0 – 3.7 and *Re* = 73 – 200. The gap flow between the cylinders was biased at *T/d* < 2.5, forming a narrow and a wide street. At *T/d* > 2.5 two coupled streets, either in-phased or anti-phased, were observed.

Alam et al. (2011) measured flow structure on two side-by-side square cylinders in four flow regimes using a particle imaging velocimetry (PIV) and laser-induced fluorescence (LIF). Biased flow was observed in *T/d* = 1.3 – 2.2 and *Re* = 1.7×10^4. They found a transition regime at *T/d* = 2.2 – 3.0, where the two distinct frequencies, characterized by the biased regime, collapse into one, from time to time and the narrow and wide streets change accordingly to two anti-phased or symmetric streets of the same frequency. They also separated the flow in regimes accordingly to its dependence on the aspect ratio *T/d*, Fig. 2, shows it schematically.

In this paper it is presented the study of biased flow behavior through square cylinder in four aspect ratios (*T/L*), 1.25, 1.50, 1.75 and 2.0 using wavelet transform and PDF distribution as analysis tools. Discrete and continuous wavelet transforms are used in this paper, basically to filter the temporal series and to determine the frequency bandwidths and analyze the energy content of the signal respectively. The results were compared with the ones for circular cylinders described in De Paula, 2013. The schematic arrangement for the square cylinders and the hot-wire probe, is shown in Fig. (1).

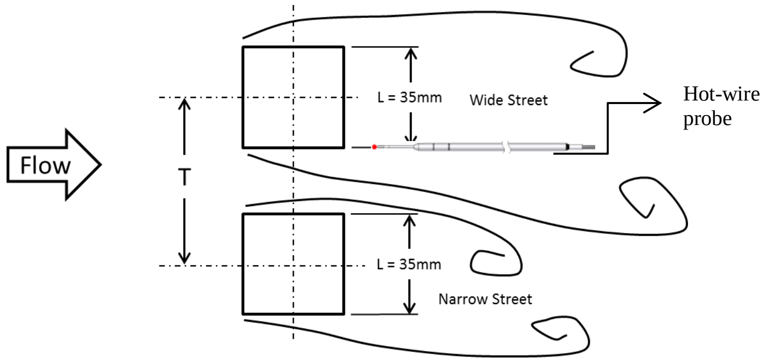

Figure 1. Schematic of square cylinders and hot-wire arrangement.

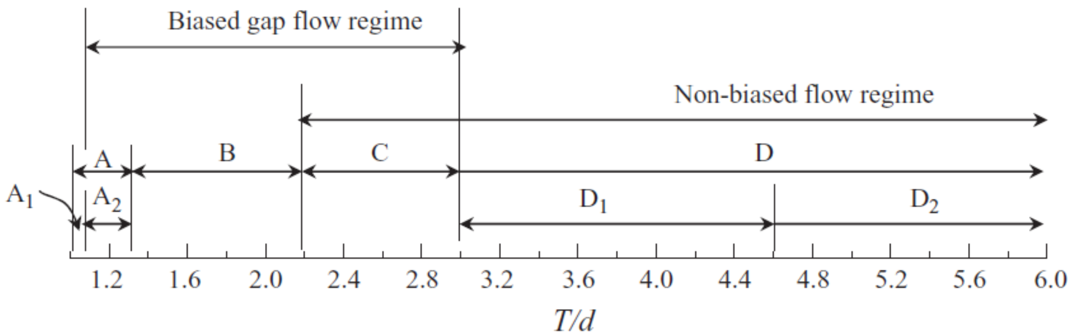

Figure 2. Dependence of flow regimes on *T/d*: A, single-body regime (A1, perfectly single-body wake; A2, single-body-like wake); B, two-frequency regime; C, transition regime; D, coupled vortex street (CVS) regime (D1, anti-phase-dominated vortex shedding; D2, anti-phase–in-phase mixed vortex shedding) Alam et al. (2011).

2. BACKGROUND : WAVELET TRANSFORMS AND PDF

According to Tennekes & Lumley (1972) the time domain, or statistical analysis consists on determining the first four moments of the probability density function: mean (average), standard deviation, skewness and kurtosis. The frequency domain, or spectral analysis can be done through the power spectral density function (PSD). The joint time-frequency domain analysis was made through wavelet transform. The wavelet analysis can be applied to time varying signals, where the stationary hypothesis cannot be maintained, to allow the detection of non-permanent flow structures.

The continuous wavelet transform of a function g(t) is given by:

$$\tilde{X}_g(a,b) = \int_{-\infty}^{\infty} g(t)\psi_{a,b}(t)dt \tag{1}$$

where ψ is the wavelet function and the parameters a and $b$are, respectively, scale and position coefficients ($a, b \in \Re$) and $a > 0$. The respective wavelet spectrum is defined as:

$$P_{gg}(a,b) = \left|\tilde{X}_g(a,b)\right|^2 \tag{2}$$

While the auto spectral density function or Fourier spectrum gives the energy for each frequency over the entire time domain, in the wavelet spectrum, Eq. (2), the energy is related to each time and scale (or frequency). This characteristic of the wavelet transform allows the representation of the distribution of the energy of the transient signal over time–frequency domains, Indrusiak et al. (2006).

Bendat & Piersol (2010) says that the underlying concept in probability theory is that of a set, defined as a collection of objects (also called points or elements) about which it is possible to determine whether any particular object is a member of the set. In particular, the possible outcomes of an experiment (or a measurement) represent a set of points called the sample space. These points may be grouped together in various ways, called events, and under suitable conditions probability functions may be assigned to each. These probabilities always lie between zero and one, the probability of an impossible event being zero and the probability of the certain event being one. Sample spaces are either finite or infinite.

In terms of the underlying probability measure in the sample space, one may define a probability distribution function $P(x)$ as the probability that is assigned to the set of points k satisfying the desired inequality $x(k) < x$ as given in the Eq. (xx).

$$P(x) = Prob\left[x(k) \le x\right] \tag{3}$$

Mathematical tools were developed using Matlab® software and its specific toolboxes for statistical, spectral and wavelet analysis.

3. EXPERIMENTAL TECHNIQUE

The experimental study was performed by means of hot-wire anemometry measurements in an aerodynamic channel. The aspect ratios for the square cylinders were T/L = 1.25, 1.50, 1.75 and 2.0, where "T" is the distance between the centers of adjacent cylinders and "L" is the cylinder high. The Reynolds numbers (Re) for all the experiments were calculated with the mean velocity of the tube bank, the hydraulic diameter of the square cylinders and the kinetic viscosity of the fluid.

The aerodynamic channel used in the experiments is made of acrylic glass, with a rectangular test section of 0.146 m height, width of 0.193 m and 1.02 m of length. The air flow is driven by a centrifugal blower of 0.64 kW, and passes through two honeycombs and two screens, to reduce the turbulence intensity to about 1% in the test section. Upstream the test section, placed in one of the side walls, there is a Pitot tube, which measures the reference velocity of the non-perturbed flow, description of teste section available in De Paula and Möller, 2013.

The velocity of the flow and its fluctuations are measured by means of a DANTEC StreamLine constant hot-wire anemometry system, with a hot-wire probe (type DANTEC 55P11), with single wire perpendicular to the main flow. The wire of the probe was maintained in horizontal position, and the measurements were performed aligning the probe along the tangent to the external generatrices of two adjacent tubes. The data acquisition is performed by an A/D 16-bit board (NATIONAL INSTRUMENTS 9215-A). The tubes are rigidly attached to the top wall of the test section. The mean error of the flow velocity determination with a hot-wire was about 3%.

4. RESULTS

4.1 Velocity measures

The results for measures velocity obtained from the experiments performed with two square cylinders side-by-side are shown in Fig. 3, the signals where obtained with an acquisition frequency of 3 kHz at a distance of 4 mm downstream the cylinders with aspect ratios of T/L = 1.25; 1.50; 1.75 and 2.00. The Reynolds number is 1.73×10^4.

The results are in accordance to those shown in Alam et al. (2011). From Fig. 3(b), it is possible to observe that the velocity signals keep switching in two different levels. This feature is clearly observed from the discrete wavelet reconstructions of level 9 (which provide frequencies from 0 to 0.488 Hz) of the signals. This behavior happens in T/L = 1.75, Fig. 3(c) however the switching takes a longer time to occur, being possible to see only one switch of the wake in the whole acquired signal. In T/L = 2.00, Fig. 3(d), the wake behind the cylinders keep switching fast reminding the flap of a flag, which is called flip-flop behavior.

For the aspect ratio of T/L = 1.25 the switching phenomenon was not observed, due to the narrow gap between the cylinders. A very narrow gap can inhibit the formation of inner vortices, and the tubes start to behave as a single structure. Due to this and that the formation of vortices from the internal shear layers of the gap is important for the formation of two wakes, the two different frequencies were not detected in this case.

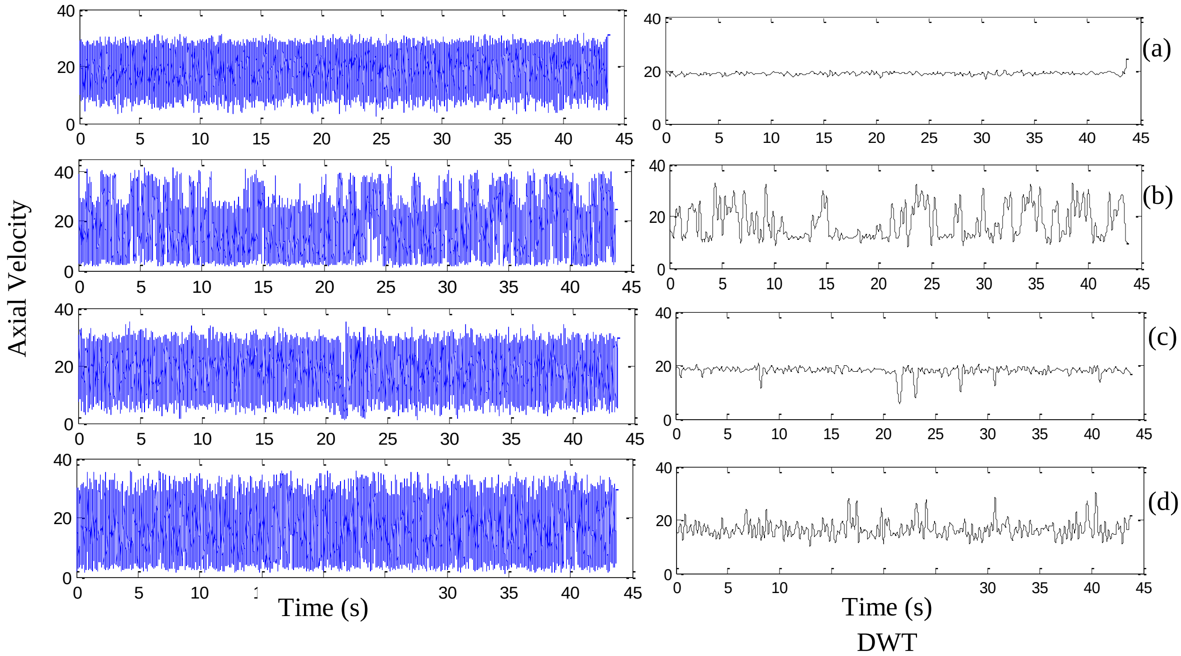

Figure 3. Measured velocity obtained for f_s = 3 kHz, $Re = 1.73 \times 10^4$ and discrete wavelet transform (DWT) for: (a) T/L = 1.25; (b) T/L = 1.50; (c) T/L = 1.75 and (d) T/L = 2.00.

When comparing with two circular cylinders, which results are shown in Fig. (4), one can see that the square cylinders switching mode cannot be defined as a bistable regime. Despite the characteristic of switching the narrow and wide wakes, the square cylinders present a flip-flop behavior. This difference is clearer when analyzing the DWT of the circular cylinder, Fig. 4(b). When a switch occur it forms a different level in the signal, which is for the circular cylinder somehow smoother when compared to that of square cylinders which is full of pikes and keep flapping from one side to the other.

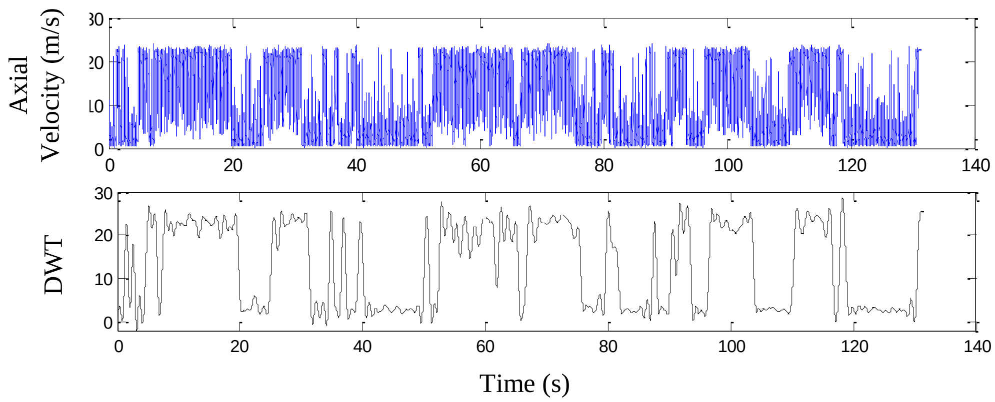

Figure 4. (a) Measured velocity and (b) discrete wavelet transform for two circular cylinders side-by-side with P/d = 1.26.

4.2 Probability Distribution Funcion

For the PDF distribution, the number of velocity intervals (bins) used in the simulations was of 100. From the simulations of the velocity signals we observed as was expected. For the cases T/L = 1.25 and T/L = 1.75 the distribution curves can be approximated by a Gaussian function Fig. 5(a) and (c), this is also verified by analyzing the central moments of those curves in Tab. (1). The values of the third and fourth moments are very close to zero and three which are the values defined for the normal distribution. For *T/L* = 1.50 two mean states of energy were observed, Fig. 5(b), which represent the switching between the two wake modes . This tendency can be seen also for *T/L* = 2.00, but not so evidently. For those cases to be possible to be described by a function it is necessary a high order analyses of the moments.

The frequency spectrum have been determined by plotting the power spectral density (PSD) of the fluctuation components of the axial velocity, for each different aspect ratio. We notice that in T/L = 1.50 there is a mean frequency at 100 Hz. For all the other aspect ratio there was no mean frequency detected.

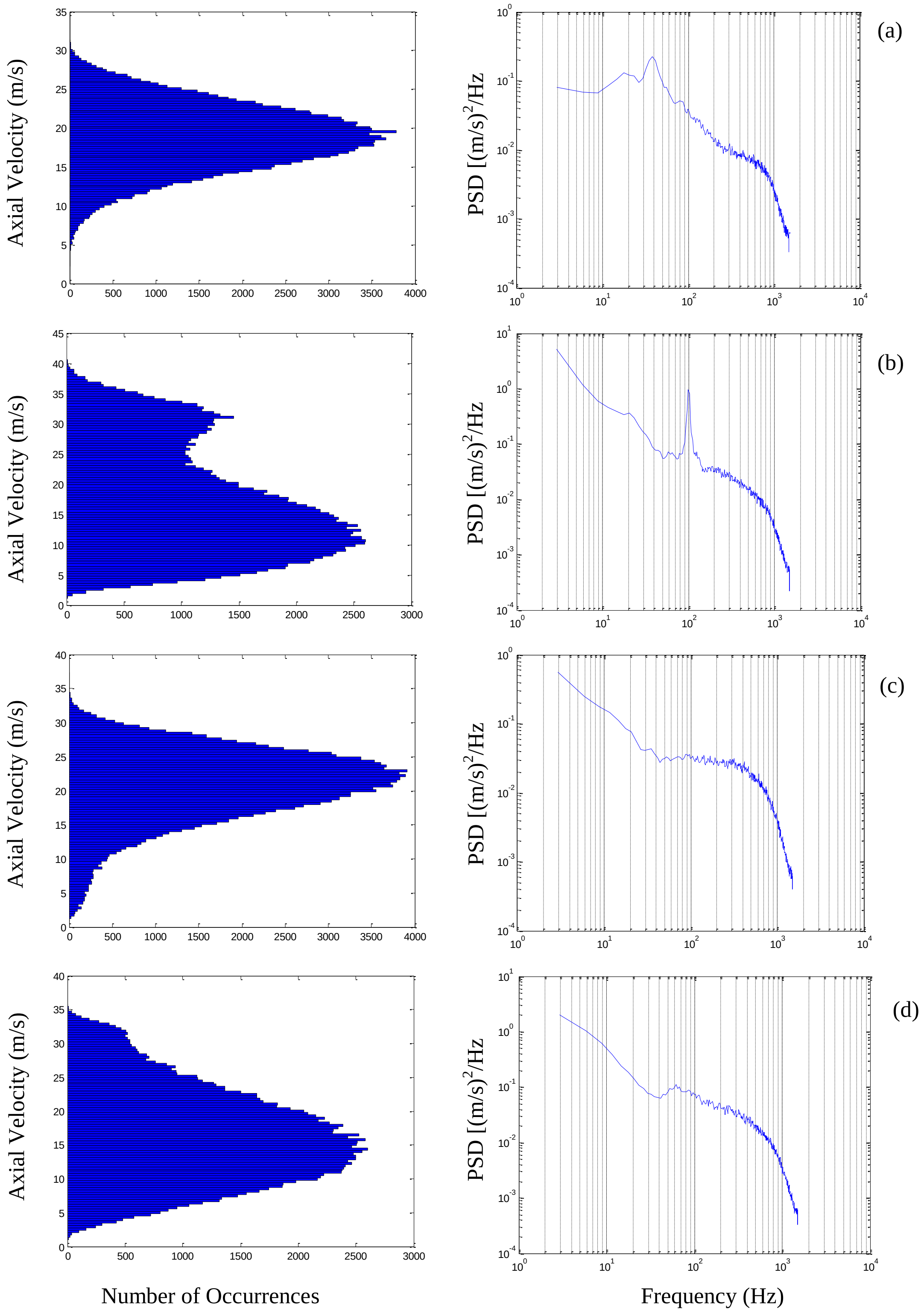

Figure 5. PDF and PSD of the axial velocity: (a) *T/L* = 1.25; (b) *T/L* = 1.50; (c) *T/L* = 1.75 and (d) *T/L* = 2.0.

Table 1. Statistical moments for *T/L* = 1.25 and 1.75.

	T/L	*T/L*
	1.25	1.75
Standart Deviation	4.16	4.98
Skewness	-0.15	-0.29
Kurtosis	2.84	2.94

From De Paula & Möller (2010) it's possible to see the PDF results for circular cylinders with an aspect ratio *P/d* = 1.26 as in Fig. (7). There are two states of energy which corresponds to the two modes, narrow-near wake and large wake. The energy distribution is well defined for each wake, and forms two distinct peaks in the PDF. In the square cylinders those peak are not so distinct, because the switching does not occur in a stable way. In the PSD there is a mean frequency at 80 Hz.

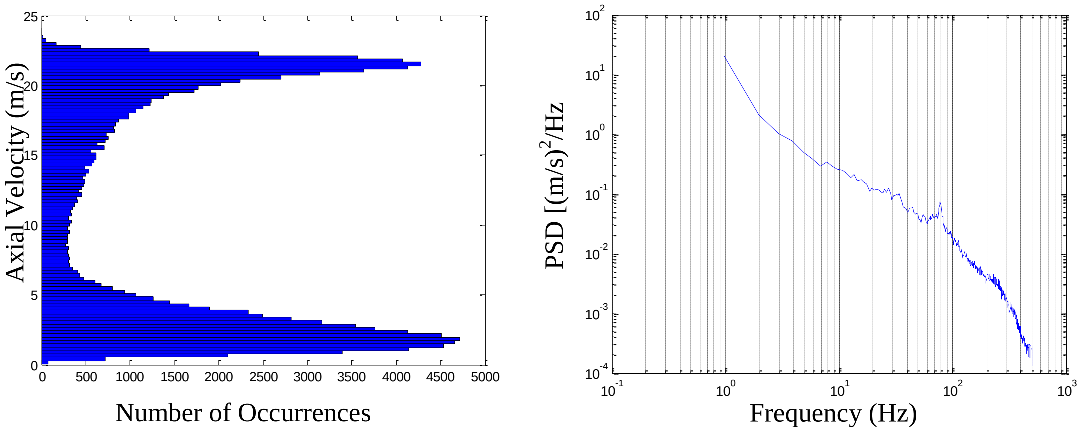

Figure 6. PDF and PSD for axial velocity for circular cylinder with *P/d* = 1.26.

5. CONCLUSIONS

In this paper an experimental analysis of the biased flow through square cylinders side-by-side is presented, by means of hot wire anemometry technique, using an aerodynamic channel for various aspect ratios *T/L*. The switching phenomenon has been found at T/L = 1.50; 1.75 and 2.0, but was not visible for the smallest aspect ratio T/L = 1.25.

The wake behind the cylinders at T/L = 1.50; 1.70 and 2.0 present distinct mean levels, that has a intermittent swapping of the gap flow, from one side to the other (flip-flop), Differently of the behavior found in circular cylinders, which is bistable. In fact, is only possible to analyze the measurement points, and a more accurate analysis is necessary to surely affirm that this phenomenon has an unstable characteristic in square cylinders.

The PDF analysis contributes to the idea that for certain aspect ratios (1.50 and 2.0) there is a more intense switching of the modes in the wake, but that this switch does not stabilize due to the intermittent characteristic. For the smallest aspect ratio (T/L = 1.25), the PDF distribution curve can be approximated by a Gaussian distribution, this can also be verified by the statistical moments analysis of the measured signal.

6. ACKNOWLEDGEMENTS

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