EXPERIMENTAL STUDY OF THE PHENOMENON OF THE BISTABILITY IN BANKS OF CYLINDERS OF TRIANGULAR ARRANGEMENT

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Abstract. *By means of hot wire anemometry technique the presence of the phenomenon of the bistability in banks of tubes of triangular arrangement is investigated in an aerodynamic channel. There are many applications in engineering where cylindrical structures submitted to a transversely flowing fluid are present, as in heat exchangers, pipelines and transmission lines. Bistability occurs in flows over sets of bluff bodies forming a flip-flopping wake characterized by a biased flow switching at irregular intervals. Thus, the study concerning the phenomenon of the bistability in tube arrangements is important, since bistability can represent an additional source of dynamic instabilities. The aspect ratio p/d chosen was of 1.6, where "p" is the pitch or the distance between the centers of adjacent cylinders and "d" the diameter. The experimental data are analyzed by means of statistical, spectral and wavelet tools. 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. Results of flow around three cylinders in triangular arrangement are presented in two disposals: two cylinders upstream and one downstream, and vice versa. The results show tat bistable flow is easy detected from the disposal with one cylinder upstream and two downstream, but no bistable effect was detected from the other disposal.*

Keywords*: turbulent flow, hot wires, tube banks, wavelets.*

1. INTRODUCTION

Circular cylinders nearly disposed are a very common configuration in engineering applications, like heat exchangers, pipelines and transmission lines. Tube banks are the most used configuration for the analysis of the phenomena that occur in various arrangement types.

The flow impinging on circular cylinders placed side-by-size presents a floppy and random phenomenon that change the flow mode. This behavior is called in literature as bistable flow.

As flow induced vibration and structure-fluid interaction are very dependent of the arrangement or configuration of the cylinders (side-by-side or tandem), new studies are necessary to improve its understanding.

According to Zdravkovich and Stonebanks (1988) the leading feature of flow-induced vibration in tube banks is the randomness of dynamic responses of tubes, and even if the tubes are all of equal size, have the same dynamic characteristics, are arranged in regular equidistant rows and are subjected to an uniform steady flow the dynamic response of tubes is non-uniform and random.

As bistability has been found at two side-by-size cylinders classical geometry, and more recently at aligning tubes geometry, the triangular geometry was chosen, because of its large utilization in many engineering applications, and a need of new informations about this phenomenon, that can be an addition excitation mechanism on the tubes.

2. HISTORICAL REVIEW

The cross steady flow trough same diameter circular cylinder (d) placed side-by-side can present a wake with different modes, according Sumner *et al.* (1999), depending on distances between its centers, called pitch (p). Different flow behaviors can be found for different pitch-to-diameter ratios p/d.

When cylinders are in contact (p/d=1), they behave as a bluff body, and due the increasing of the distance between the free shear layer from both sides, the vortex shedding is lower than of a single cylinder.

At small pitch ratios (1.0<p/d<1.2) two cylinders placed side-by-side still behave as a bluff body, but the high-momentum fluid that enters trough the gap between tubes increases the base pressure and reduces the drag forces of both cylinders, with a vortex-shedding frequency close to that observed for p/d=1. In addition, a single vortex street is observed in the combined wake of the two cylinders, and vortex shedding occurs only from the outer shear layer. Three types of behavior were observed. The most commonly observed has an asymmetrical near-wake region with a defected or biased gap-flow, with a possible single vortex street forming downstream. Another, with a symmetrical near-wake formation of a single vortex street, and a gap-flow oriented parallel to the flow axis. And a third flow pattern showing no significant gap flow.

At large pitch ratios (p/d>2.2) the biased flow disappear, and side-by-side circular cylinders behave more independent, as isolated bluff bodies. Nevertheless, there is still some interaction or synchronization occurring between them, predominantly as anti-phase vortex formation.

At intermediate pitch ratios (1.2<p/d<2.0) the flow is characterized by a wide near-wake behind a cylinder and a narrow near-wake behind the other, as shown in Fig. 1a and Fig. 1b. This phenomenon generates two dominants vortex-shedding frequencies, each one associated with a wake: the narrow wake is associated with a higher frequency and the wide wake with a lower one.

Trough the gap, flow is biased towards the cylinder, and has a narrow wake. Bistable flow is characterized by switch of this gap flow, from one side to other at irregular time intervals. Thereby, if the flow velocity is measured downstream the cylinders, by example along the tangent to their external generatrixes, a switch mode can occur as shows the scheme in Fig. 1b. According to previous studies, this pattern is independent of Reynolds number, and it is not associated to cylinders misalignment or external influences, what suggest an intrinsically flow feature.

According to Kim and Durbim (1988) the transition between the asymmetric states is completely random and it is not associated with a natural frequency. They concluded that the mean time between the transitions is on order 10^3 times longer than vortex shedding period, and the mean time intervals between the switches decreases with the increasing of Reynolds number, trough a dimensionless study. This is in according with Williamson (1985), who found for Re=300 a steady mean flow. As Strouhal numbers are relatively independent from the Reynolds numbers (Žukauskas, 1972), they conclude that there is no correlation between the bistable feature and the vortex shedding.

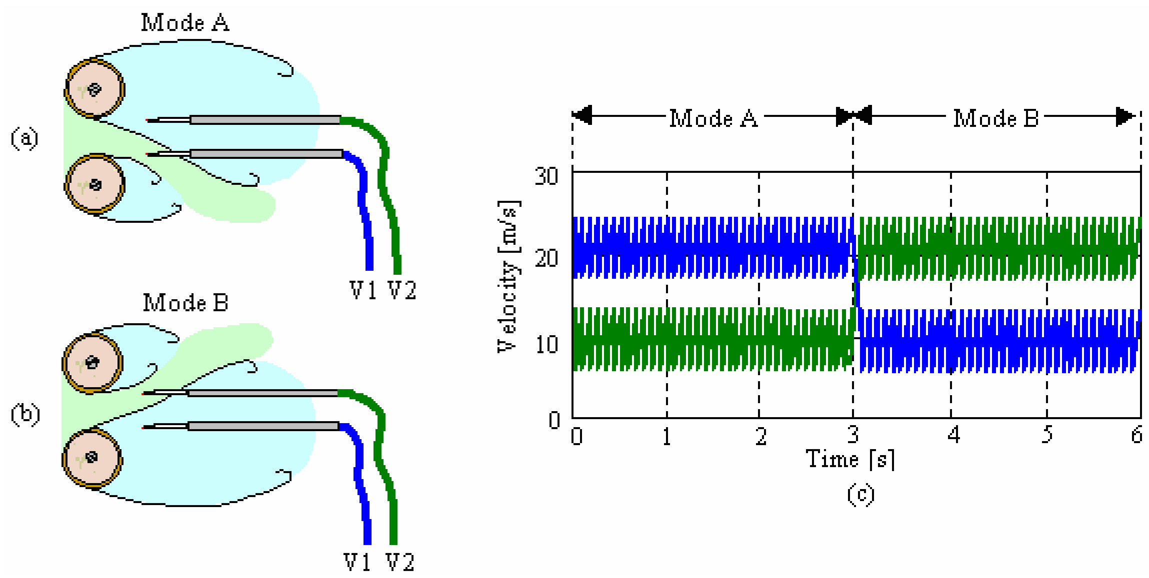


Figure 1. Bistability scheme for (a) mode A and (b) mode B, and the respective characteristical signals (c).

Olinto (2005) determined experimentally the presence of biased and bistable flow mode two cylinders placed in a side-by-size arrangement.

3. OBJECTIVES

The purpose of the present paper is to describe the biased and bistable flow mode for three tubes placed in a triangular arrangement, in two disposals: two cylinders upstream and one downstream, and vice versa (what corresponds to rotate in 60º the previous disposal), submitted to a perpendicular air flow provided by an aerodynamic channel.

4. THE EXPERIMENTAL TECHNIQUE

All the measurements were performed in an acrylic aerodynamic channel with a rectangular test section of 146 mm height and width of 193 mm, as shown in Fig. 2a. The air is impelled by a centrifugal blower of 0.64 kW, and passes through two honeycombs and two screens in a settling chamber, which reduce the turbulence intensity to about 1% in the test section.

The reference velocity is measured by a Pitot tube, placed on one side wall of the aerodynamic channel, before the test section. For the experiments, the calculated Reynolds number is Re = 3.2 x 10^4, relative at the tube diameter (32.1 mm) and the reference velocity of the air (at the entrance), 15.2 m/s.

Two hot wire probes (type DANTEC 55P11), with single wires perpendicular to the main flow, were used to measured velocity and velocity fluctuations by means of the DANTEC *StreamLine* constant hot-wire anemometry system. The wires of the both probes were maintained in horizontal position. Figure 3 shows a schematic view of the probes positions for the two tubes disposals, as well as the reference distance (x), measured from the downstream cylinder.

A 16 bits data acquisition board (NATIONAL 9215-A) with USB interface was used to convert the analogical signal to digital series.

The three tubes were rigidly attached to the top wall of test section. The probe supports were also made of acrylic material, and fixed in both left and right walls, as shown in Fig. 2b.

The mean error of the flow velocity determination with a hot wire was about 3%.

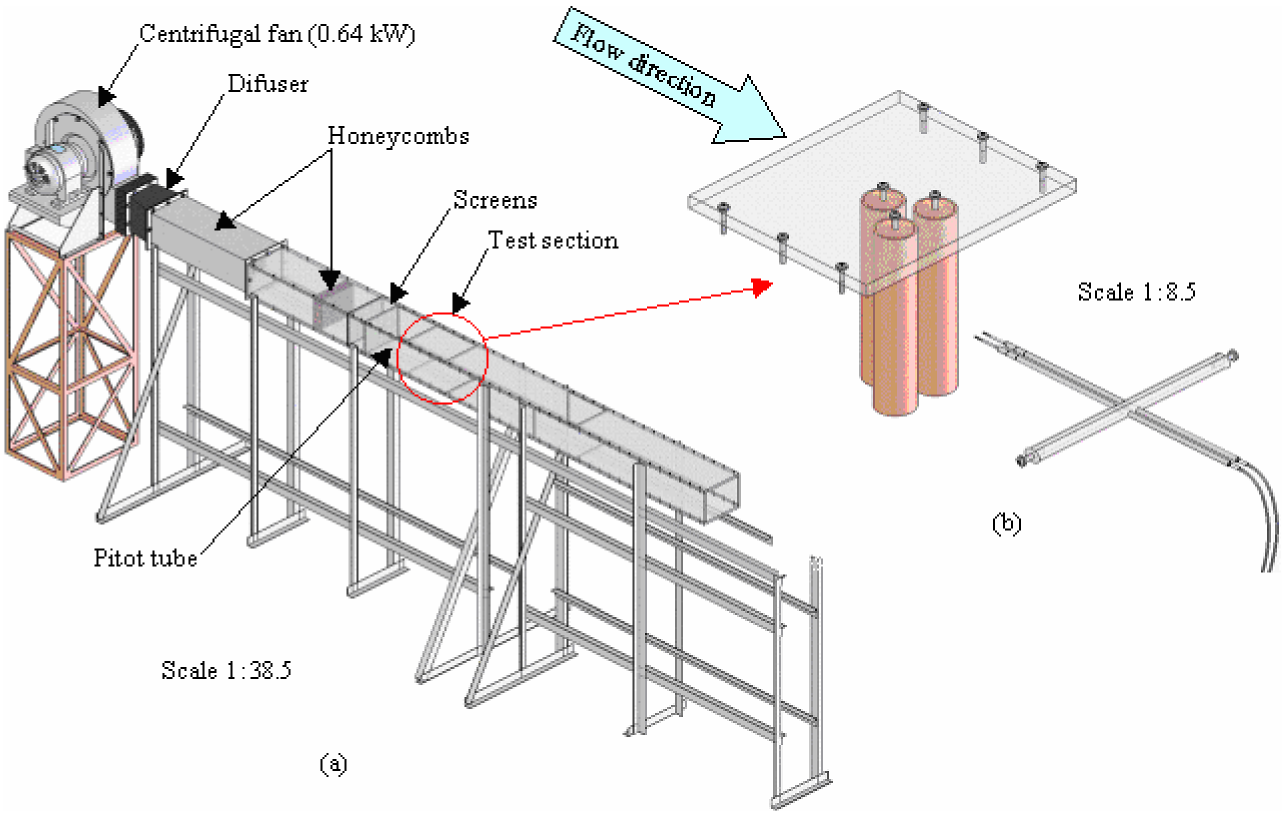


Figure 2. Schematic view of (a) the aerodynamic channel and (b) test section.

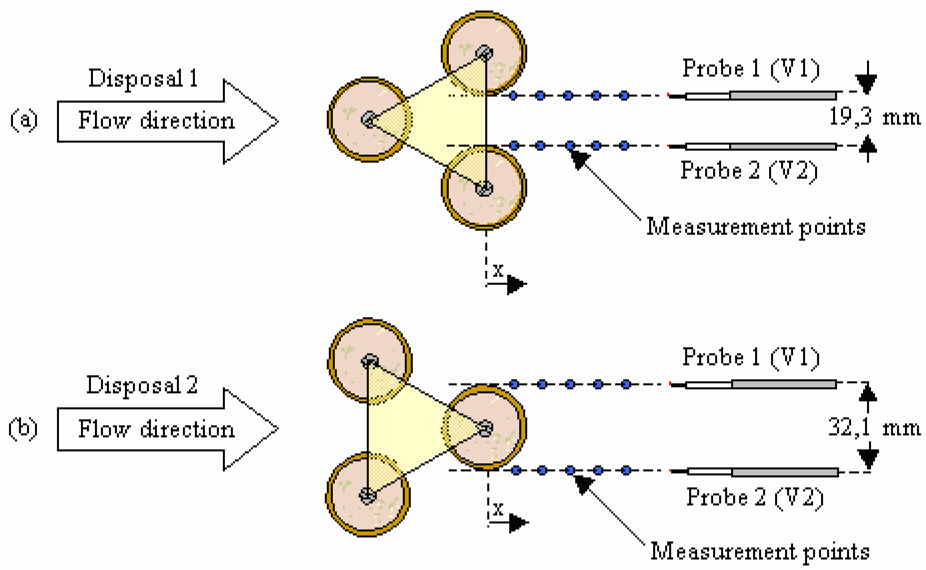


Figure 3. Schematic view of the probes positions for the tubes arrangements: (a) Disposal 1 and (b) disposal 2.

5. MATHEMATICAL TOOLS

In order to characterize the studied flows and arrangements, a time series can be analyzed by three ways: time domain, frequency domain and ensemble time-frequency domain.

The time domain analysis performed consists in calculate the four moments of the probability density function. By order: mean, standard deviation, skewness and kurtosis.

A frequency domain analysis (or spectral analysis) was made by means of the power spectral density function (PSD), which gives the energy distribution of the signal in time frequency domain (Bendat and Piersol, 1971). In essence, it consists in a Fourier transform of the autocorrelation function. Nevertheless, the stationary hypothesis of a time signal must be accomplished.

The ensemble time-frequency domain analysis was made trough wavelet transform, in two ways: discrete and continuous wavelet transform. A wavelet analysis is applied to analyze transient signals, where the stationary hypothesis cannot be maintained. The first one is used to make a multilevel decomposition of a time signal, and after reconstruct it in several bandwidth values, accordingly with the selected decomposition level. This technique is useful to filter and/or to decompose a desired signal. The last one is used to analyze the energy contained from a signal, which is also called spectrogram. This graphics are presented in 3D representation, where the base axis represent the time and the frequency, and the elevation is the energy contained from the signal. The Daubechies “db20” functions were used to the bases of the both discrete and continuous wavelet transforms.

Indrusiak (2004) presents a more complete review of discrete and continuous wavelet transforms, applied to transient turbulent flows.

All mathematical analysis was made with MATLAB 5.3 software and its specific toolboxes for statistical, spectral and wavelet analysis.

6. RESULTS

In order to identify the occurrence of the bistable phenomenon presence, due to the switch of biased flow direction, time series measurements were performed in the aerodynamic channel, as characterized in Tab. 1.

Table 1 – Time series characteristics for the two disposals.

	x [mm]	*x/D*	f_s [Hz]	f_c [Hz]	*t* [s]
Disposals A and B	10, 20, 30, 40 and 50	0.31, 0.62, 0.93, 1.25 and 1.56	1000	300	131
Disposal A	10	0.31	3000	1000	43.7
Disposal A	7	0.22	25000	10000	5.24

6.1. Disposal 1

The first signal obtained from a a 1000 Hz acquisition frequency at 10 mm distance from the two downstream cylinders shows the bistable phenomenon presence (Fig. 4a). The mode switches can be clearly viewed trough the wavelet decomposition shown in Fig. 4b, where the signal is reconstructed for a band of frequencies from 0-3.9063 Hz.

For a 131 s time interval, about 55 mode switches occurred.

The signal obtained now from a 10 mm distance, but at higher acquisition frequency (25 kHz) is shown in Fig. 5a. From this signal is possible to view only one mode switch, due to the reduced observation time. Figure 5b shows a reconstruction of these signals for a band of frequencies from 0-6.1035 Hz and from 0-3.0517 Hz. From this figure, velocity signals present a change of biased flow direction at about 2.25 s.

To analyze the energy contained from velocity signals, continuous wavelet transforms (spectrograms) of the velocity signals were made, as shown in Fig. 6. The spectrogram in the Fig. 6a (relative to the signal V1) presents a lower energy contained in the firsts 2.25 s, distributed in the range of 20 o 150 Hz, exactly the opposed of signal V2 spectrogram (Fig. 6b), that shows higher energy values. The higher energy contained of V2 in this time interval is relative to the high velocity measured from the biased flow, and the lower energy contained of V1 is relative to the low velocity measured from the wide wake. After 2.25 s, this characteristic changes, and the signal V1 spectrogram presents a higher energy contained, opposed to V2 spectrogram, also distributed in the range of 20 o 150 Hz.

Nevertheless, at about 2.25 s both signals present an increase in the energy values, indicating that the switching between two modes does not occur instantaneously, but it starts with an increasing in the velocity fluctuations, for several frequencies, as observed by Alam *et al.* (2003), that concluded that between two flow modes there is an intermediary mode, with a different characteristic frequency from those in the narrow and wide wake.

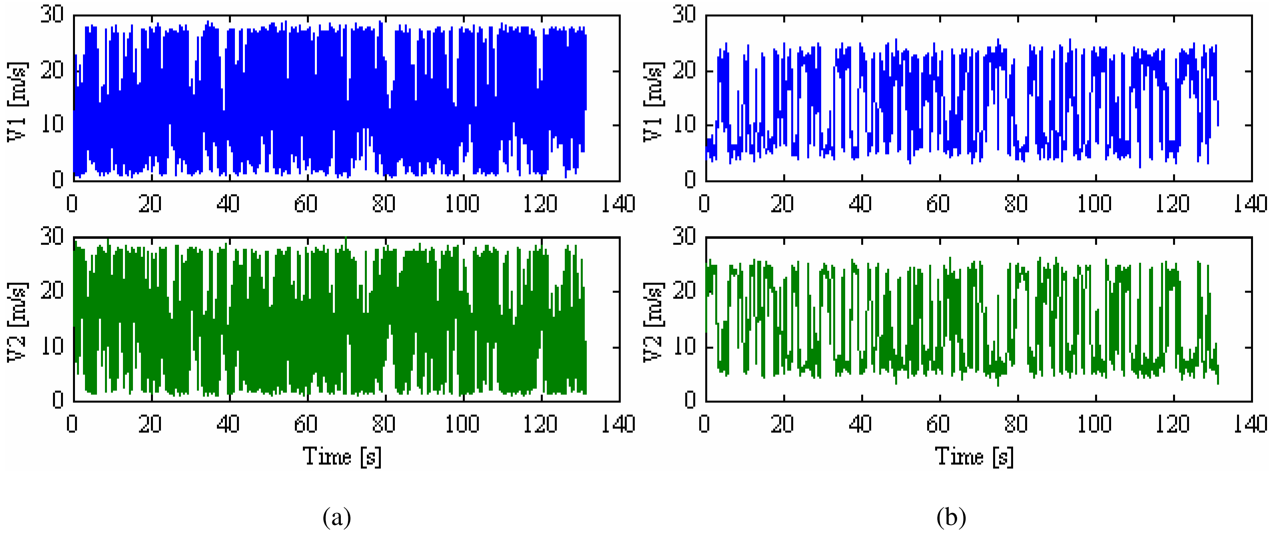


Figure 4. (a) Velocity signals for disposal 1 at x = 10 mm and frequency acquisition of 1000 Hz and (b) they're respective wavelet reconstruction for a band of frequencies from 0-3.9063 Hz.

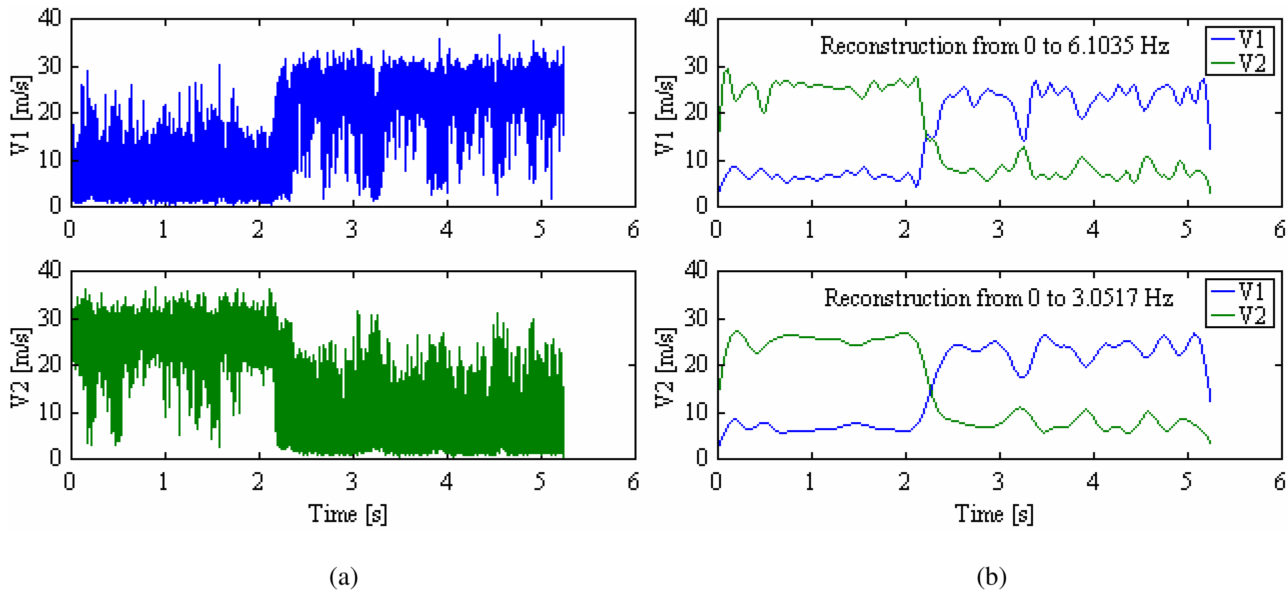


Figure 5. (a) Velocity signals for arrangement 1 at x = 7 mm and frequency acquisition of 25000 Hz, and (b) reconstructed signals from 0 to 6.1035 Hz and from 0 to 3.0517 Hz by means of discrete wavelet transform.

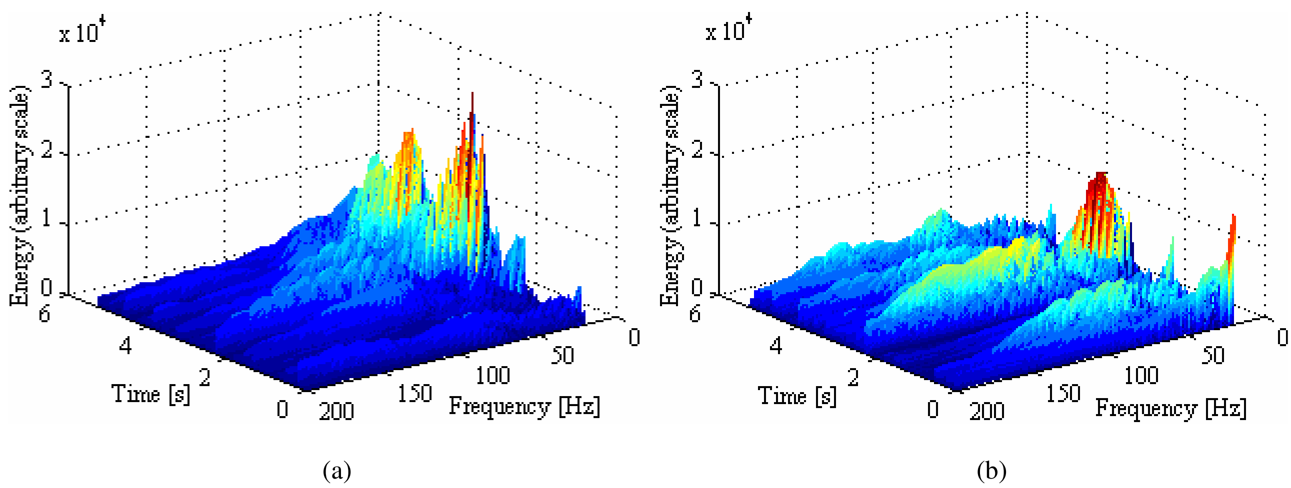


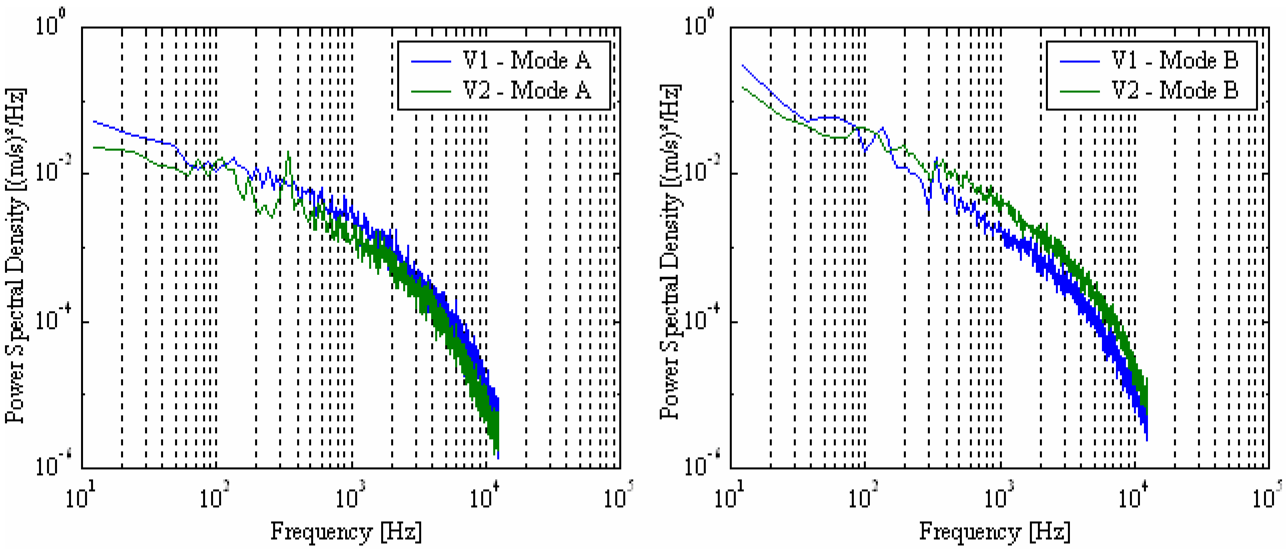
Figure 6. Continuous wavelet spectrum of the velocity signals of the figure 5: (a) V1 and (b) V2.

In order to study the flow modes, two segments of the velocities signals were separated to a statistical analysis, and called of mode A and B, for the time series V1 and V2, respectively. Table 2 shows the statistical characteristics from the velocity series V1 and V2. The first mode (A) is composed by the values measured from 0.6 to 1.91 s, corresponding to a cluster with 32768 elements. The second mode (B) has 65536 elements, and the observed time interval is from 2.4 to 5.02 s. The switches between the velocity signals carry the statistical characteristics from each mode, and are associated to the switch in the gap flow direction.

Table 2. Statistical characteristics from the velocity series V1 and V2 for the disposal 2.

	Mode A		Mode B	
	V1	V2	V1	V2
Mean velocity [m/s]	6.47	25.58	23.28	7.66
Standard deviation [m/s]	3.45	2.87	4.59	4.6
Skewness	1.46	-1.63	-1.84	1.26
Kurtosis	7.22	10.11	6.79	4.71

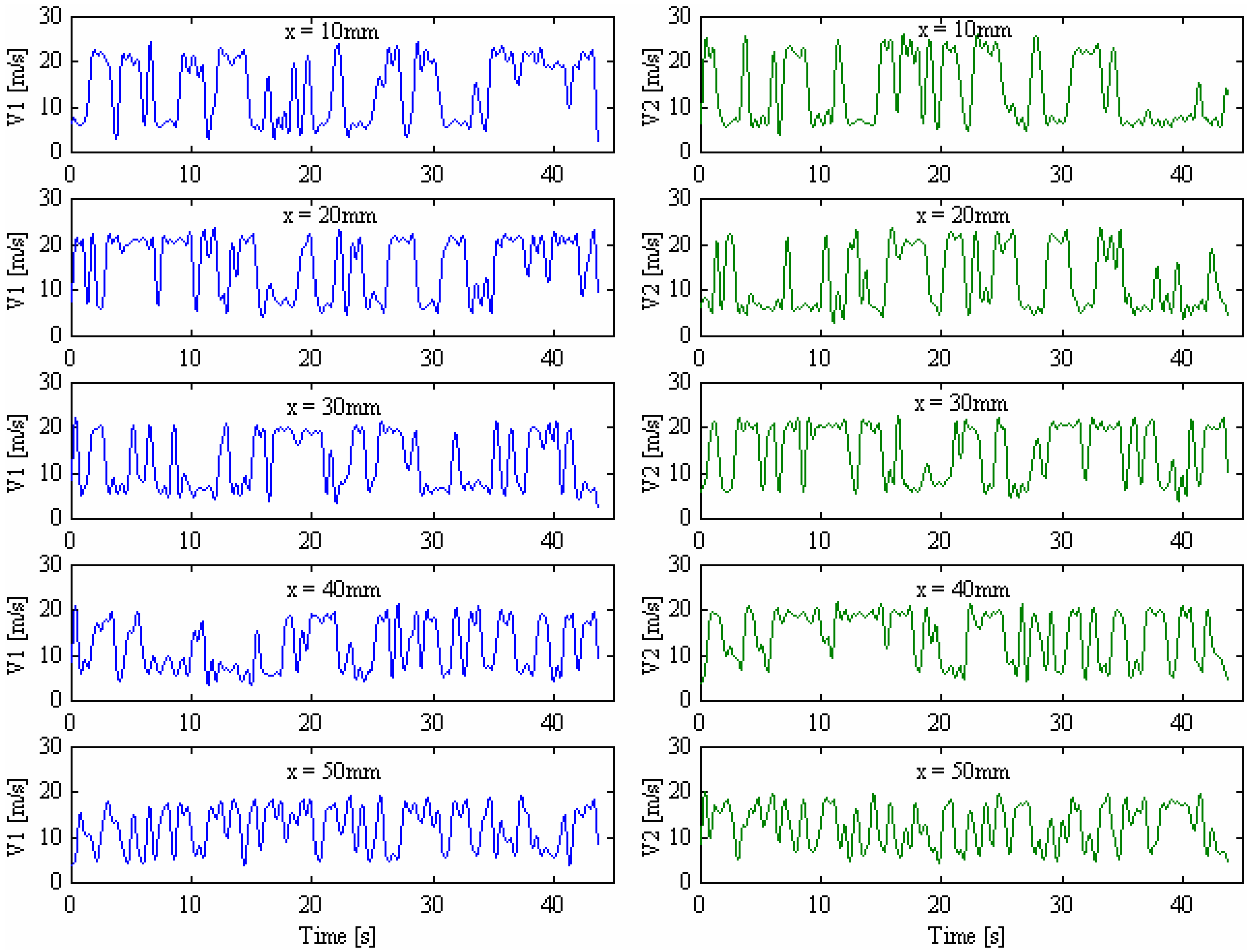
The power spectral density functions of the signals are presented in Fig. 7, and show a mean frequency at 135 Hz for velocity signal V1 in both modes, and about 100 Hz for V2 in both modes, corresponding to Strouhal numbers of 0.285 and 0.211, respectively, calculated with the reference velocity. The expected was that the mean frequencies had changed from the velocity signals, but it did not occur. There are also peaks at 340 Hz for mode B (Str=0.718) in both velocity signals. For mode A, a shedding frequency was not possible to find. All this problems can be caused by the high blockage ratio used in this experiment. Although, as the mean statistical error associated to the power spectral density function was considerably high, due to the high frequency acquisition (25 kHz).



(a) (b)

Figure 7. Power spectral density of the signal velocities: (a) mode A and (b) mode B.

To analyze if the bistable effect happened at a great distance, larger than x = 10 mm, Fig. 8 shows the recomposed signals obtained at a various reference distances “x” (from x = 10 mm at x = 50 mm), from 0 to 1.4648 Hz, and acquisition frequency of 3000 Hz. It can be observed that bistable effect persists even for x = 50 mm, but this characteristic fades, or appears not so clearly.



(a) (b)

Figure 8. Reconstructed signals from 0 to 1.4648 Hz by means of discrete wavelet transform: (a) V1 and (b) V2.

6.2. Disposal 2

As can be seen from the velocity signals obtained at x = 10 mm after the downstream cylinder at an acquisition frequency of 1000 Hz (Fig. 9a), no particular features can be observed.

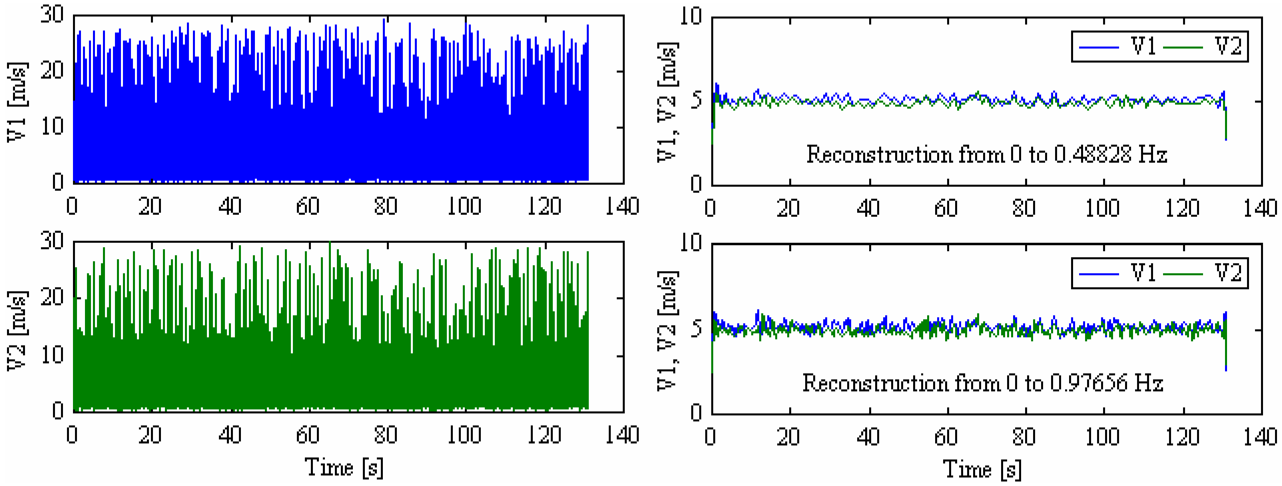
Recomposing them with a discrete wavelet transform, the filtered signals for a bandwidth from 0-0.48828 Hz and from 0-0.97656 Hz are show in Fig. 9b, and present no switches mode for all observed time, what means that bistable effect was not identified.

The crosscorrelation function of velocity signals V1 and V2 is presented in Fig. 10a where a 180º phase is visible.

The power spectral density functions of the signals are presented in Fig. 10b, and show a very pronounced peak at 60 Hz. It corresponds to a Strouhal number of 0.13, calculated with reference velocity. The other two peaks, at 120 Hz and 180 Hz correspond to first and second harmonics and are inherent to the vortex shedding from cylinders in cross flow, Ziada (2006).

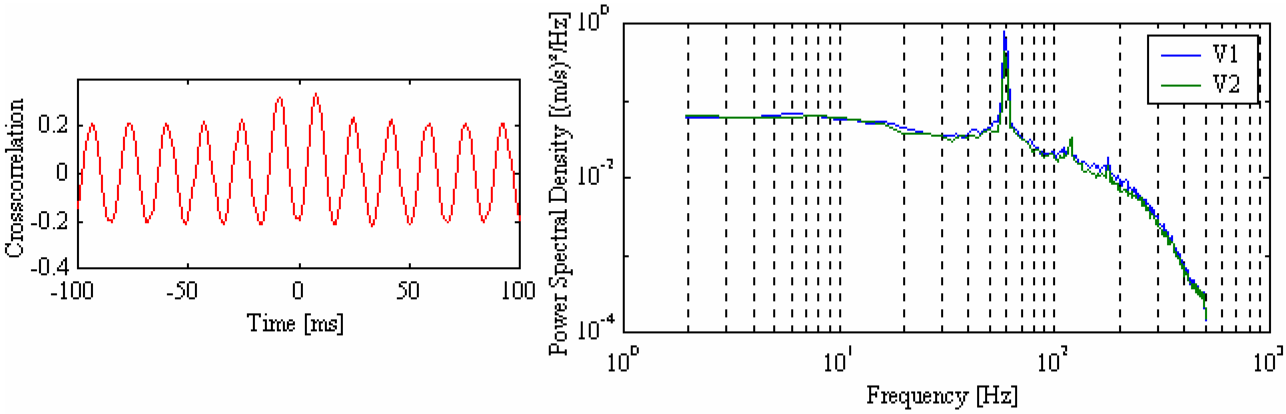
As the both velocity signals present an stationary characteristic, a statistical analysis can be made without to divide them in different modes. So, they're analyzed by all 131 s without cuts. Table 3 shows the statistical characteristics from the series. As can be seen, the values are very similar, what means that the probes are measuring the same wide wake, downstream the single cylinder.

Continuous wavelet transforms were also calculated for both signals (Fig. 11) and show a distributed energy region about 60 Hz through all the time series, what means that the changing characteristic behavior is not present for both signals.



(a) (b)

Figure 9. (a) Velocity signals and (b) recomposed signals (from 0 to 0.48828 Hz and from 0 to 0.97656 Hz) obtained at x = 10 mm and acquisition frequency of 1000 Hz.

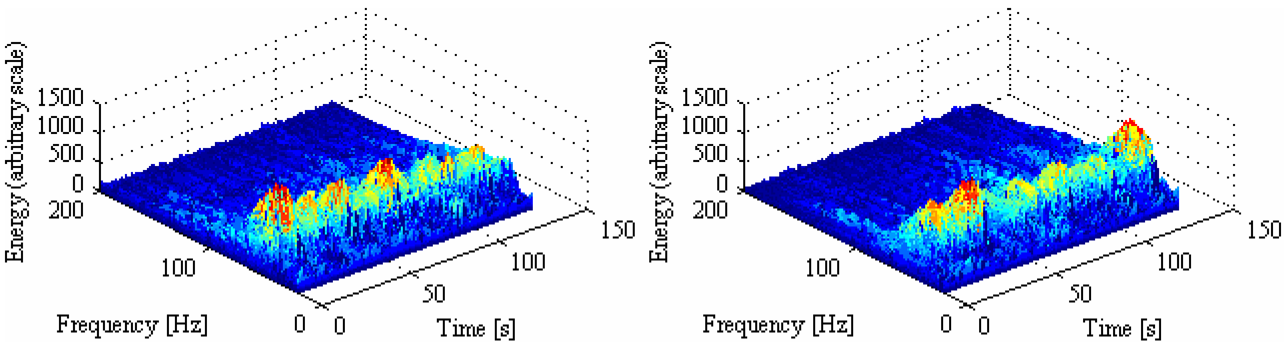


(a) (b)

Figure 10. (a) Crosscorrelation function and (b) power spectral density function of velocity signals V1 and V2.

Table 3. Statistical characteristics from the velocity series V1 and V2 for the disposal 2.

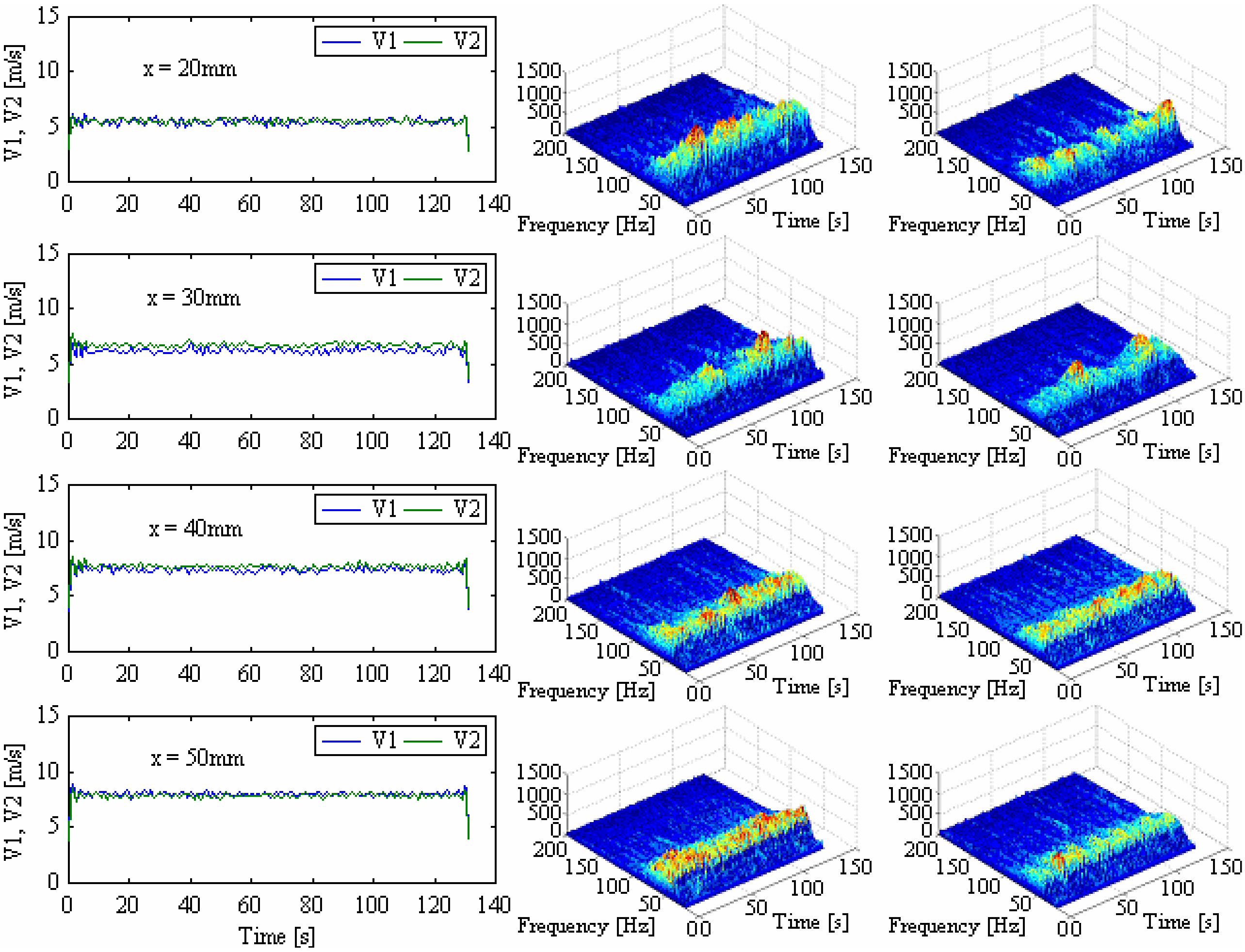
	V1	V2
Mean velocity [m/s]	5.15	4.94
Standard deviation [m/s]	2.98	2.59
Skewness	2.09	2.29
Kurtosis	12.01	14.84



(a) (b)

Figure 11. Continuous wavelet spectrum of the velocity signals of the figure 9a: (a) V1 and (b) V2.

In order to detect if the bistable effect happened at a large distance, greater than x = 10 mm, Fig. 12a shows the recomposed signals obtained at a various reference distances "x" (from x = 20 mm at x = 50 mm), from 0-0.48828 Hz and acquisition frequency of 1000 Hz. Figure 12b and 12c shows its respective continuous wavelet spectrum, for velocity signals V1 and V2, respectively. From these figures is possible to see that bistable flow does not occur in any of the analyzed positions.



(a) (b) (c)

Figure 12. (a) Reconstructed signals from 0-0.48828 Hz by means of discrete wavelet transform and continuous wavelet spectrum of the velocity signals (b) V1 and (c) V2, where the "z" axis represents energy (in arbitrary scale).

7. CONCLUSIONS

In this paper an experimental analysis of bistability phenomenon is presented for banks of tubes of triangular arrangement, by means of hot wire anemometry technique, using an aerodynamic channel. As bistability has been found at two side-by-size cylinders classical geometry, and more recently at aligning tubes geometry, the triangular geometry was chosen, because of its large utilization in many engineering applications, and a need of information about this phenomenon, that can be an addition excitation mechanism on the tubes.

Bistability effect was found in triangular arrangement, when one cylinder is upstream and two downstream (disposal A), but no bistable flow was detected from the disposal B (two cylinder upstream and one downstream). In fact, is only possible to analyze the measurement points, and a more accurate analysis is necessary to surely affirm that this phenomenon does not occur in disposal B, as these contemplating by measuring other points of interest.

Future works contemplating water channel visualizations are intended, together with a study of a range of p/d-ratios and different alignment angles, with a gradual increasing of cylinder numbers, until a tube bank is formed. This can better elucidate the bistable flow phenomenon in triangular cylinder arrangements.

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