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EXPERIMENTAL STUDY OF THE BISTABLE FLOW IN TUBE ARRAYS

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Abstract. *Flow on circular cylindrical arrays are commonly found in several engineering application as offshore structures, heat exchangers, transmission lines and chimmeys, therefore the understanding about the several phenomena that occur due this interaction is very important. This work analyzes experimentally the presence of phenomena able to cause alternations on the flow modes in cylinder arrays using a wind channel and hot wire anemometry. The cylinders placed side-by-side, where the phenomenon is easily detected, and in lime tube bank, were the phenomenon have been also found, are studied. Additionally to the classical statistic and spectral tools, wavelet transforms are used. The bistable flow can be an important dynamic instabilities generator, since they alternate the lift and drag coefficients, alternating the structure dynamic response.*

Keywords*. biased flow, tube bank, turbulent flow, hot wires*

1. Introduction

Several engineering applications, e.g. offshore structures, heat exchangers, transmission lines and chimneys, use circular cylinders placed as close arrays. Studies about the flow dynamic through circular cylinders placed side by side have been shown a flopping and random phenomenon that change the flow mode. Similar phenomenon has also been found in some tube banks. Thereby, new studies should be made to improve the understanding about flow induced vibration and structure-fluid interaction for the configurations where this phenomenon is present.

According Zdravkovich e Stonebanks (1988) the leading feature of flow-induced vibration in tube banks is the randomness of dynamic responses of tubes. In spite of the tubes are all of equal size, have the same dynamic characteristics, are arranged in regular equidistant rows and are subjected to an uniform and steady flow, the dynamic response of tubes is non-uniform and random to such an extent that the vibration of tubes resembles the Brownian motion of molecules.

Behind a tube row several wake sizes can be present and, consequently, several Strouhal numbers are expected. Therefore, the designers should be aware that a range of Strouhal numbers is relevant for any tube and not only two or a set of value as commonly used. Attention should be given also for the fact that a change between two different modes of flow can be an additional excitation mechanism on the tubes.

2. Historical review

According to Sumner et al. (1999), the cross steady flow through same diameter (D) circular cylinders placed side-by-side presents a wake with different modes depending on distance between the centers of the cylinders (T). For cylinders in contact (T/D=1) a bluff body behavior is found and the shedding frequency is lower than a single cylinder, because of the increase of the distance between the free shear layers from both sides of the cylinders.

At small pitch ratios (1,0 < T/D < 1.2) the bluff body behavior occurs yet, but the higher-momentum fluid, which enters through the gap, increases the base pressure and reduces the drag of both cylinders. The vortex-shedding frequency, however, tends to remain close to that observed for T/D = 1. Furthermore, a single vortex street is still observed in the combined wake of the two cylinders, and shedding occurs only from the outside shear layers. Three types of behavior were observed in the experiments: the first with a symmetrical near-wake, formation of a single vortex street, and a gap-flow oriented parallel to the flow axis. The second flow pattern, with an asymmetrical near-wake region with a deflected or biased gap-flow, although a single vortex street still seems to form further downstream (this pattern was that most commonly observed). And the third flow pattern showed no significant gap flow.

At large pitch ratios (T/D > 2.2) the biased flow disappears, and the side-by-side circular cylinders behave more independent, as isolated bluff bodies. However, some interaction or synchronization occurs between the two cylinders, predominantly as anti-phase vortex formation.

At intermediate pitch ratios (1.2 < T/D <2.0) the flow is characterized as a narrow near-wake behind a cylinder and a wide near-wake behind the other, which generate two dominants vortex-shedding frequencies - the higher associated with the narrow wake and the lower with the wide wake. The gap flow, biased towards the cylinder, has a narrow wake. In some cases, the biased gap flow is bistable and switches from one side to the other at irregular intervals of time. According previous studies, this pattern is independent from Reynolds number, and is not caused by cylinder misalignment or another external influences, but is a flow intrinsically feature. Peschard & Le Gal (1996) suggested the bistable behavior could be caused by turbulent perturbations from flow entrance.

According Kim and Durbim (1988) the transition between two asymmetric states is completely random and it is not associated with a natural frequency. The mean time between the transitions is on the order 10^3 times longer than vortex shedding period. Studying the dimensionless mean time intervals between the switches, they observed that the time decrease with the Reynolds number increasing. This is in according with Williamson (1985), who found a steady mean flow to Re = 200. As the Strouhal numbers are relatively independent from the Reynolds number, they concluded that is no correlation between the vortex shedding and the bistable feature.

Guillaume and LaRue (1999) classified the bistable regime according to its behavior:

- Quasi-stable behavior, the switches in the flow mode not vary over time. A large amplitude perturbation can cause the changing on average values, but the values remain at the new values until another large perturbation is applied.
- Spontaneous flopping, the average values are always observed to alternate over time between relatively high and low values, even when no large perturbation is applied to the flow field.
- Forced flopping, after the initial large perturbation is applied and flopping occurs, there is no observable difference between forced and spontaneous flopping.

The authors found also that the wake fluctuation pattern depends on the tubes supports, tunnel geometry and downstream interferences (probe supports).

Zdravkovich (1977) studied the two side-by-side tubes geometry and found that, associated to the wakes, there are two different drag coefficients and the base pressure switches between two extreme values. According to his observations, there also exist a resultant force acting perpendicular to the free stream direction, which he called as a lift force. The drag force acting on the cylinders is also different for each one, because of the different base pressures. It was verified that de sum of high and low drag forces in bistable regime is always less than twice the drag of a single cylinder.

In addition, Williamson (1985) concluded that, when the wake inclines towards to higher frequency side, the cylinder of this side experiments a larger drag force. He also included that the near-wake structure is confuse for this flow asymmetric regime. His visualizations show that the inner vortices shedding from the gap are squeezed, distorted and amalgamated with the dominant outer vortices. Thus, at a certain distance from the cylinders, only the vortices generated at the outer surfaces of the pairs of cylinders are visualized.

Zdravkovich e Stonebanks (1988) studied the wake behind a tube row subjected to a perpendicular flow and concluded that it is formed by coalesced jet cells that sudden change their pattern. This state, which he defined as metastable, can be due to the rearrangement of the cell pattern behind the row and it is strongly dependent upon the number of tubes in the row.

At two rows, the authors concluded that the biased gap flow disappear in the first row and is reestablished after the second row. They argued that it should be a typical feature behind any last row.

Lê Gal et al. (1996) also studied the flow through a tube row. When the distance between the cylinder axes is more than two cylinder diameters, they found a identical and anti-phase vortex shedding. Conversely, when this distance is less than two cylinder diameters, the jets between the tubes are deviated and the wake merges to form clusters. The cell sizes depend on the initial conditions. If the flow velocity is varied quickly from rest, several different patterns can be formed. Regions with wake oscillations can also appear.

Sumner, et al. (1999) studied the flow fields for two and three cylinders placed side-by-side for path ratios between 1 and 6 and for Reynolds number varying between 500 and 3000. They did not found the bistable phenomenon presence and the flow remained deflected consistently towards the same cylinder. The flow organization pattern was synchronized in anti-phase vortex formation. Inside the biased flow range two frequency peaks were detected, as expected. They attributed this behavior without bistable phenomenon to the experimental apparatus characteristics.

According to Guillaume et al. (1999), who studied the flow through four and three tubes row, in the intermediate wake three mean vortex-shedding frequencies may occur, the lowest associated to wide wake, a second one with higher value, corresponding to narrow wake and the highest, due the interaction of both the lower and the second frequency. They also found that the wake fluctuation pattern depends on the tube supports, tunnel geometry and the downstream interference. Their velocity spectra show two peaks. Near the tubes (x/D = 2, where x is the distance between the tube center line and the probe position) the peaks are at St = 0.354 e 0.344, (where the Strouhal number St=f.D/V) for velocities of 5.2 e 10 m/s, respectively. These peaks are related to the narrow wake. For larger distances, the peaks are St = 0.1099 and 0.1143 and are related to the wide wake.

Zhou et al. (2002) studied the turbulent wake of two tubes placed side by side for velocity field and temperature. They experimented arrays with T/D = 1.5 and 3.0 and compared with single tube wake. They calculated the vortex convection velocity through the maximum phase-average vorticity. In the spectral analysis they found a single frequency peak, at T/D = 1.5, St= 0.11 and T/D = 3.0 and ∞, St = 0.21. It was not found two frequencies as found by previous authors. According to their results, the vortex generation inside the gap is essential to form two vortex streets.

A narrow gap can inhibit the internal vortex generation and thus two cylinders behave as a single structure generating just one vortex street.

Alam et al. (2003) investigated experimentally the flow through two cylinders placed side-by-side for Re = $5.5x10^4$, where the forces acting are insensible to the Reynolds number. They found for intermediate spacing (T/D=1.2 to 2.2) the biased bistable regime and studied the fluctuating and steady forces characteristics. Studding the drag coefficients, they found that for T/D varying in the range 1 to 2.5, two values for drag coefficients are found. They concluded that decreasing the wake width the drag coefficient increase, and this is associated with the increase of the gap velocity.

In the range T/D=1.1 to 2.5, they found two lift coefficients always generate forces which tend to separate the cylinders (repulsion). Thus, concluded the narrow wake cause greater drag force and lesser lift force, whilst the wide wake causes lesser drag force and increase lift. The lift force is in repulsion form for T/D>1,2. For T/D=1.1, the cylinder with narrow wake presents a attractive lift coefficient.

Alam et al. also demonstrate, using wavelet transform, the velocity energy spectra for two tubes with T/D=1.7, and concluded that, when a mode switch occur, an intermediate frequency may be present.

Indrusiak et al. (2003) studied transients flow through tube banks, using wavelet transforms, and found behind the third row a behavior with random change between the mean velocity values behind the tube lateral face. The intermittence found is similar to bistable mode found for tubes placed side-by-side and also was find for the steady flow part in the flowing studied.

3. Objectives

The purpose of this paper is to describe the biased and bistable flow mode for two tubes placed side-by-side perpendicularly to an impinging flow and relates with the intermittence found inside the tube bank.

4. Experimental Technique

The test section, shown schematically in Fig.1 is a rectangular channel, with 146 mm height and a width of 195 mm. Air was the working fluid, driven by a centrifugal blower, passed by a settling chamber and a set of honeycombs and screens, before reaching the tube row with about 1 % turbulence intensity.

Before the tube row a Pitot tube, at a fixed position, was applied to measure the reference velocity for the experiments. The Reynolds number, calculated with the tube diameter (32.1 mm) and the entrance (reference) velocity is Re = 3×10^4, for two tubes and Re = $1,5 \times 10^4$, for the tube bank.

Velocity and velocity fluctuations were measured by means of a DANTEC *StreamLine* constant temperature hot-wire anemometer. Pressure was measured by an ENDEVCO piezo-resistive pressure transducer, mounted inside one of the tubes of the row (Goulart, 2004). Figure 2a shows the probe position for two tubes experiments, whilst Fig. 2b shows the bank tubes instrumentation, where 1 is the transducer and 2 and 3 are the probes measuring respectively velocities V1 and V2.

Data acquisition of pressure and velocity fluctuations were performed simultaneously by a Keithley DAS-58 A/D-converter board controlled by a personal computer, which was also used for the evaluation of the results.

The tube bank was mounted with 25 tubes having a 32.1 mm diameter placed vertically and distributed at 5 row with 5 tubes each one. The pitch to diameter ratio it was T/D=1.26. The tube length was 146 mm and they were in close contact with both upper and lower horizontal walls.

5. Mathematical tools

To characterise the studied flows, from the obtained time series the probability density function and four moments are calculated, respectively: mean, standard deviation, skewness and kurtosis. Auto and cross correlation functions, together with spectral analysis were also applied. The wavelet transform is used for the study the transient flows, whereas it is not necessary the stationarity hypothesis. Wavelts can localise the bistable phenomenon in time and frequency domain. The continuous and discrete wavelet transforms are described in Indrusiak and Möller, 2004. The mathematical analysis was made with Matlab 5.3 software.

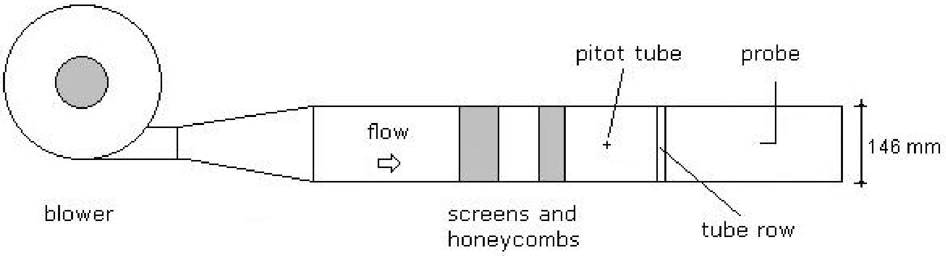


Figure 1 – Schematic view of the wind tunnel.

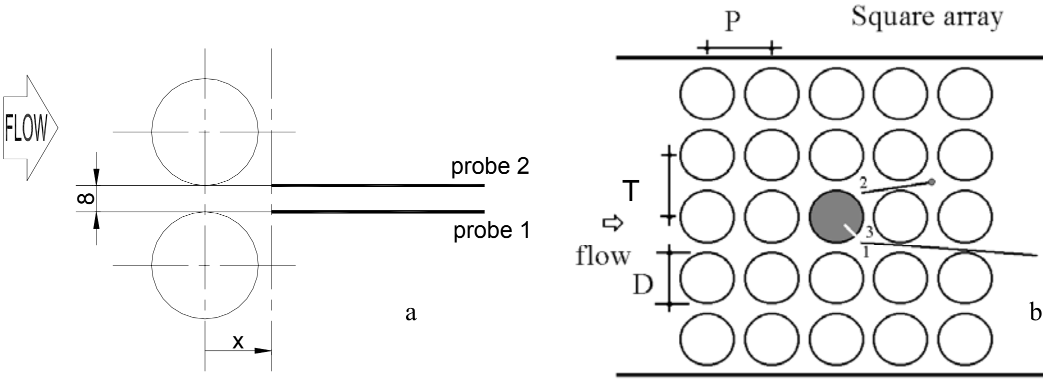


Figure 2 – Tube arrays and measurement probes location.

6. Results

6.1. Two tubes placed side-by-side

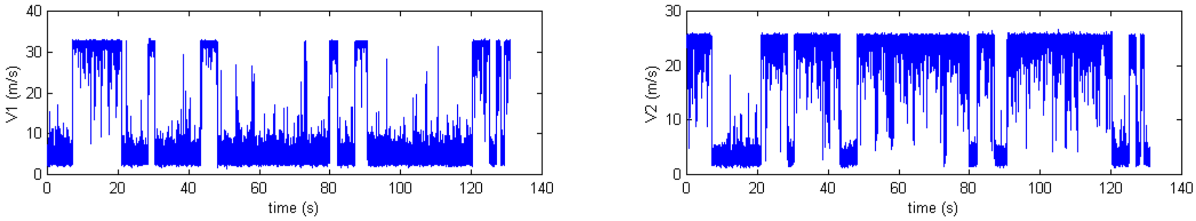
The biased flow effects and bistable phenomenon presence were studied from time series obtained in the wind channel. Table 1 shows three simultaneous acquisitions using two probes for the two tubes side-by-side geometry. The reference velocity during the experiments was 13,8 m/s, corresponding to a value of 3 x 10^4 for the Reynolds number.

Table 1 – Signal characteristics

series	x (m)	x/d	fs (kHz)	t (s)
H0	20	0.62	1	131
H2	30	0.93	8	8.2
H9	70	2.18	1	65.5

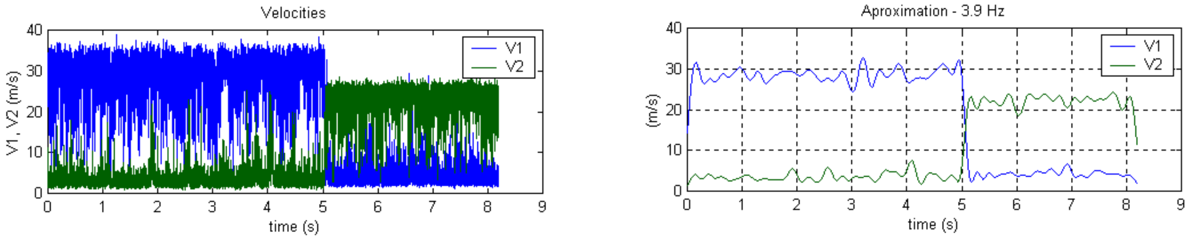
The first signal obtained immediately after the tubes shows the bistable phenomenon presence and the two flow modes just by velocity signal visual inspection from Fig. 3. It can be viewed that for the time 130 s, occur about 15 mode switches.

The H2 signal allows to view the two-flow modes separation presents in the bistable flow, by mean the instantaneous velocity values, Fig.4. In Fig. 4-a, the measured signals from probes 2 and 3 are presented. No particular features can be observed. After applying wavelet filter for a band of frequencies 0-3.9 Hz, Fig. 4-b the velocity signals present the change in the wake mode flow at about 5 seconds.



(a) (b)

Figure 3 – Velocities for H0 acquisition. (a) V1; (b) V2.



(a) (b)

Figura 4 – Characteristics of the H2 signal. (a) measured signal; (b) Wavelet filtered signal.

Figure 5 shows the spectrograms obtained by wavelet continuous transform, where the change in the flow mode can be viewed through the large variation in the energy contained from velocity series.

For studing the flow modes, the signals V1 and V2 were separated in two clusters: the mode A and the mode B. The first one is composed by the values measured form zero to 4.1 s, corresponding to cluster with 32,768 elements. The second one with 16,384 elements from 5.5 to 7.6 s. Using this separation, the statistical functions were calculated for each one, as given in Table 2. It can be observed that the switch between the velocities obtained from the probe 1 and the probe 2 carries the statistical characteristics from each mode. This behavior is associated to the switch in the gap flow direction.

The velocity spectra, shown at Fig.6, calculated for the two signals, allow identifying the presence of a mean frequency about 70 Hz for the mode A, and about 60 Hz for the mode B. These frequencies correspond to Strouhal number of 0.16 and 0.14, respectively, calculated with reference velocity. For mode B it is possible to identify another frequency energy peak at 180 Hz for velocity V2, which corresponds to St=0.42. A similar frequency would be expected for the mode A, at velocity V1. Probably it was not identified due the probe location. The values found do not agree with those demonstrated by Alam, 2003. Probably this is due the high blockage ratio used in this experiments. In spite of this two expected bistable mode shedding frequencies were present.

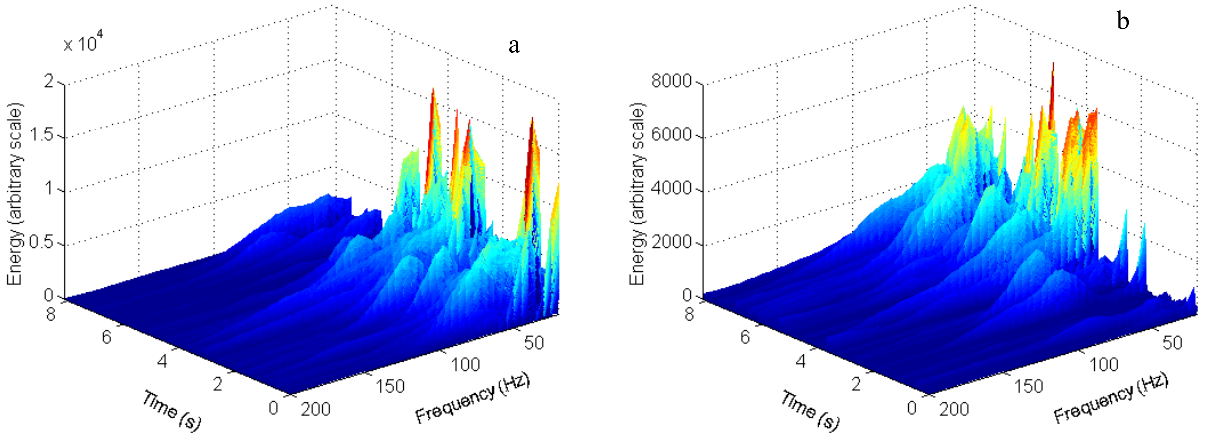


Figure 5 – Velocity signal Spectrograms a) V1 b) V2

Table 2 – Statistical characteristics from signal H2

	mode A		mode B	
	V1	V2	V1	V2
Mean Velocity	28.39	3.59	4.37	22.23
Standard deviation	5.48	2.43	2.62	3.70
Skewness	-1.57	3.60	3.02	-1.83
Kurtosis	5.33	20.40	16.71	6.71

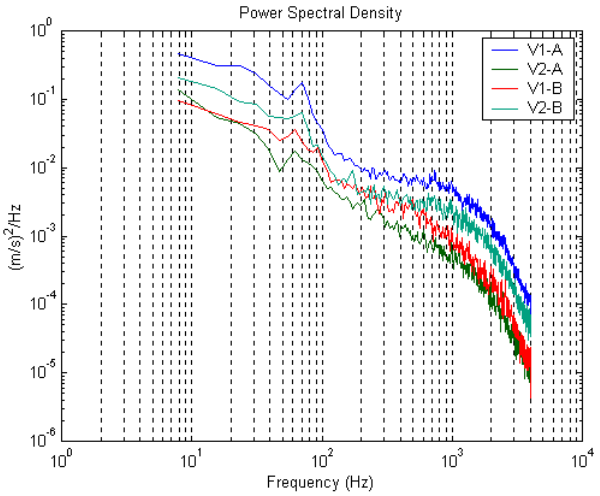


Figure 6 – Power spectral density

The H9 signal obtained in a location more distant relative the tube center line (Fig.7), shows that the bistable effect it was not identified, characterizing, therefore, the single wake flow. This behavior is confirmed using the wavelet discrete transform, at Fig.7 right, and by wavelet continuous transform (Fig.8), where the changing characteristic behavior is not present for the both signals. Thus, one can consider that the two probes are measuring the velocity inside the same wake. For biased gap flow, at this probe location, it is possible to measure velocities only in the wide wake. Thereby, the statistical analysis is made without to divide the signal in its two characteristics modes.

From Tab. 3 one can verify that the measure values in both probes have characteristics related to those wide wake, as expected. At this distance the narrow wake characteristic is already vanished. Figure 9 shows the energy spectrum, where the 70 Hz peak, related with wide wake, is confirmed.

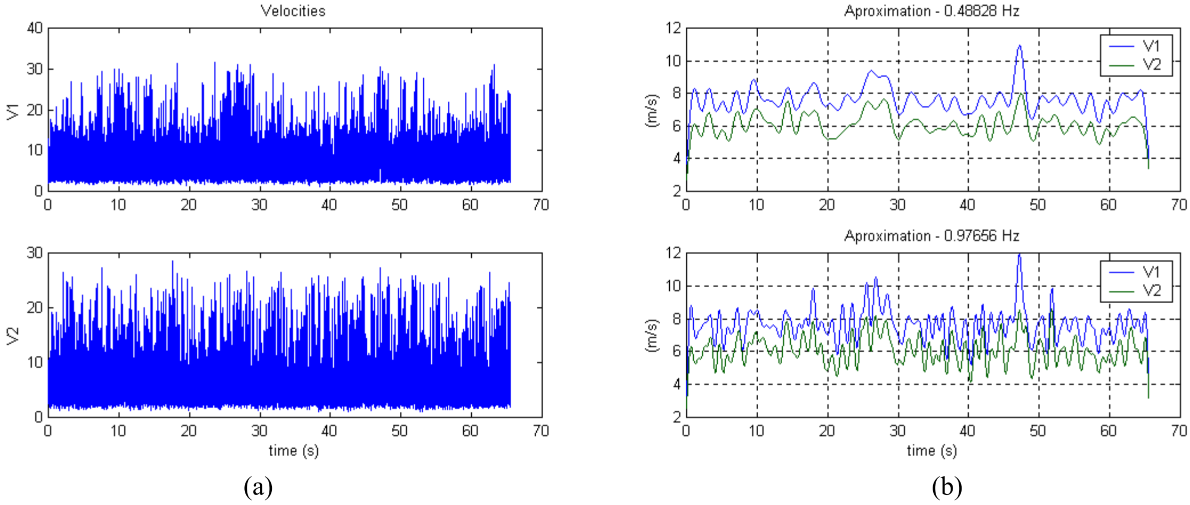


Figure 7 – Characteristics of the H9 signal and corresponding discrete wavelet transforms. (a) measured signals; (b) Wavelet filtered signals.

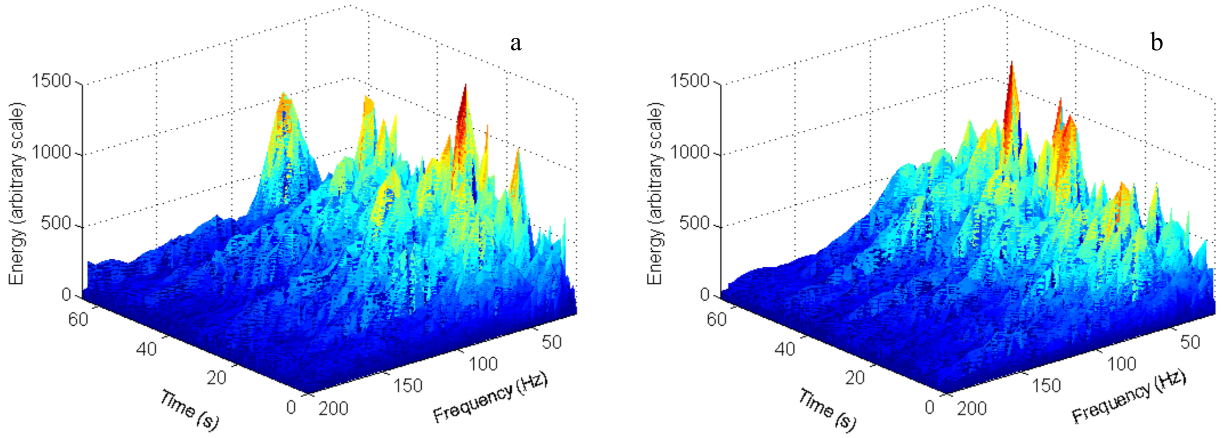


Figure 8 – H9 signal Spectrograms a) velocity V1 b) velocity V2

Table 3 – H9 signal statistical characteristics

	V1	V2
Mean velocity	7.65	6.10
Standard deviation	3.84	3.52
Skewness	1.40	1.81
Kurtosis	6.23	7.32

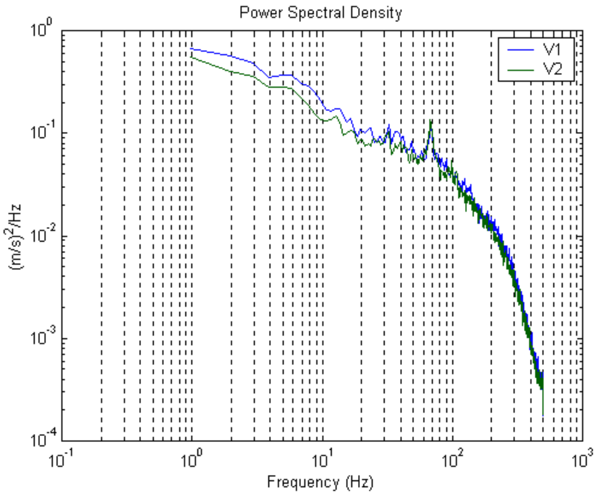


Figure 9 – Power spectrum density

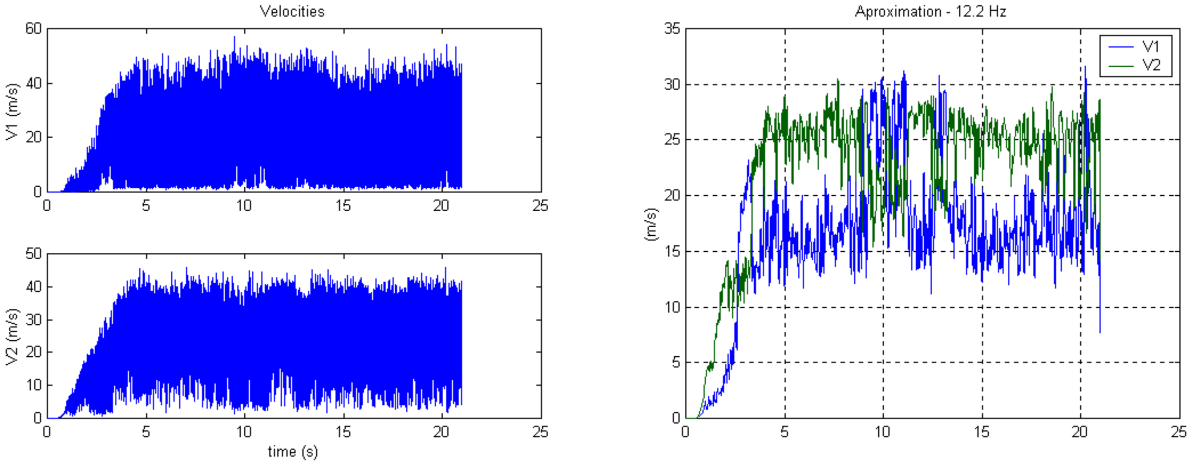
6.2. Tube bank

For studying the bistable phenomenon inside tube bank, velocity time series behind the center tube of the third row were obtained, according Fig. 3-b. The first one, acquired by 21s at acquisition frequency 25 kHz during a starting transient, is shown in Fig. 10, where the wavelet discrete transform is also shown. When the velocity signal graphic is analyzed isolate, it is not possible to identify the flow switches. Nevertheless, looking the wavelet transform graphic, it is possible to see the switching, identified by the mean velocity variations. Figure 11 shows the spectrograms for the velocities first 5 second, corresponding to the transient part. This spectrograms show the switches shown at Fig. 10-b repeat as energy fluctuations.

An acquisition where the bistable phenomenon is present was selected for the study of the mode characteristics (Fig. 12). In the wavelet discrete transform, it is possible to identify the moment when the mean velocity V2 changes. It is also possible identify that this change is associated with a positive pressure jump at the same time location. This occurs for all cases, include two tubes side-by-side, not showed in this paper due to reasons of space.

In the spectrogram generated near the time location of the flow mode switch, Fig. 13, one can verify that for velocity V1, no changing occurs, since no flow variation can be observed. For the velocity V2, the spectrogram shows a variation on the energy, at 19 s, where a jump velocity occurs.

In order to characterize the two-mode flow, the steady part of the signal was divided into two groups: mode A from 8 s to 16.2 s, and mode B from 22 to 30.2 s. Their statistical characteristics are shown at Tab. 3 and Fig. 14 shows the probability density function. The reference velocity measure upstream at Pitot tube was 7.24 m/s.



(a) (b)

Figure 10 – Instantaneous velocities (a) and corresponding wavelet discrete transform (b).

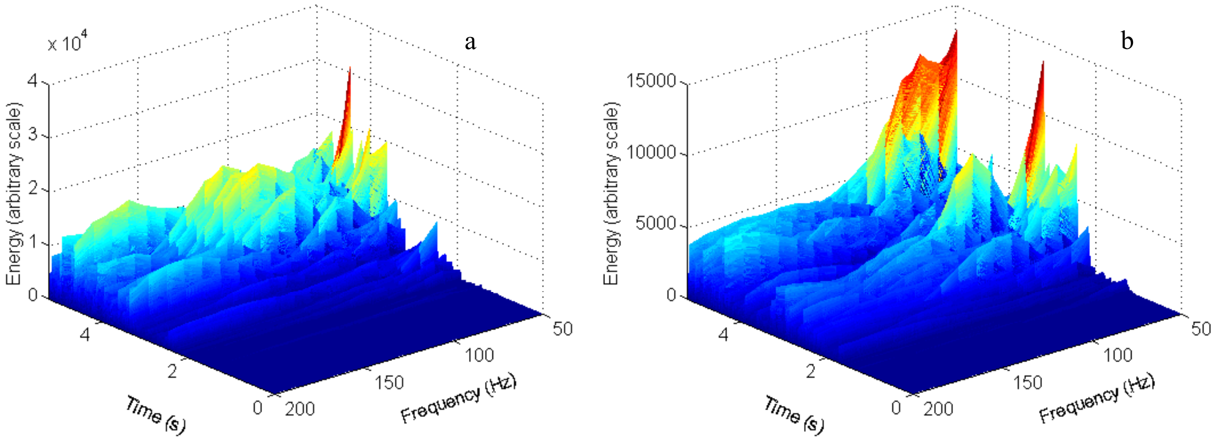
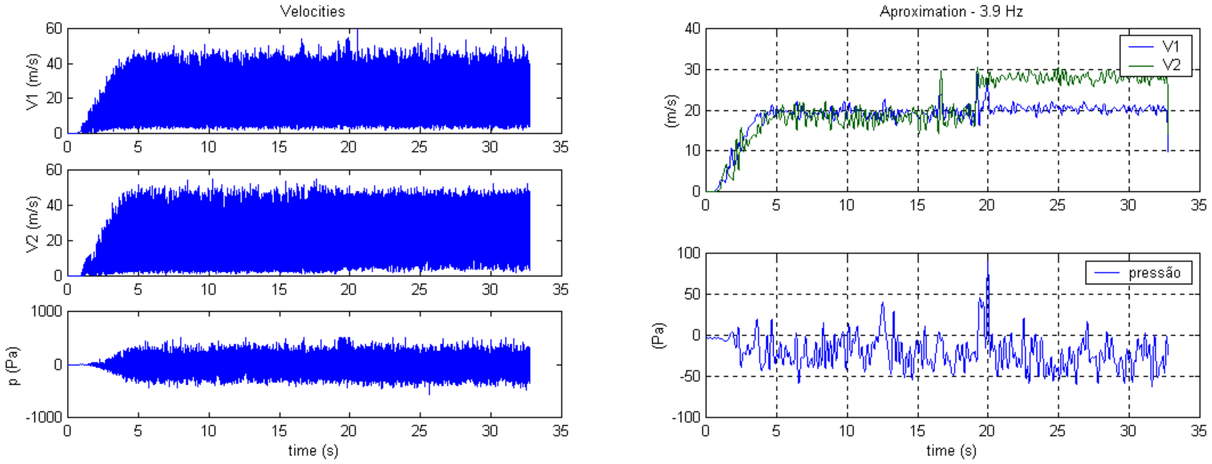


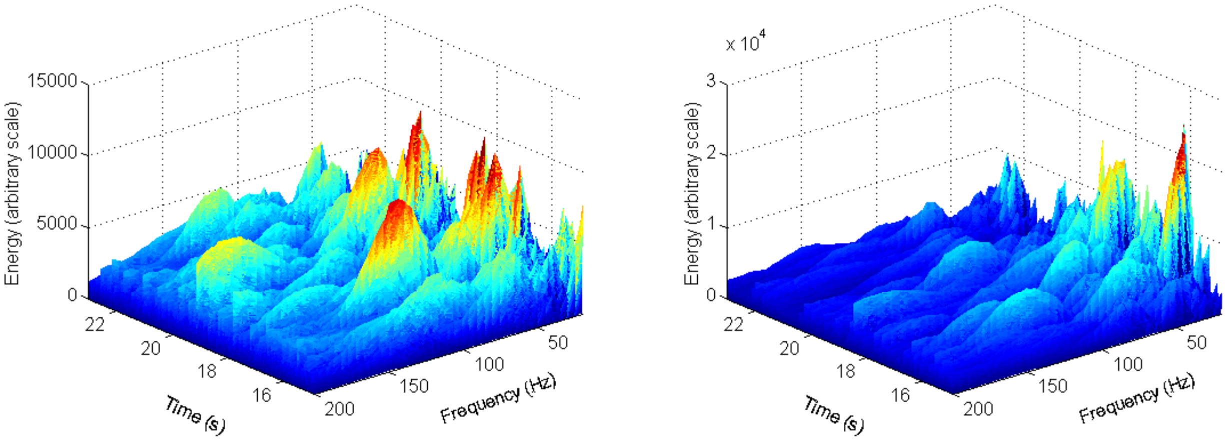
Figure 11 – Spectrograms a) V1 b) V2



(a)

(b)

Figure 12 – Instantaneous velocities and pressure (a) and corresponding wavelet discrete transform (b).



(a)

(b)

Figure 13 – Wavelet continue transform: (a) V1; (b) V2.

Table 3 – Mode A and B statistical characteristics in the tube bank

	mode A			mode B		
	V1	V2	p	V1	V2	p
Mean velocity	19.22	18.28	-16.46	20.36	28.02	-29.02
Standard deviaton	8.76	9.81	108.84	8.12	8.53	113.80
Skewness	0.48	0.65	0.28	0.39	-0.43	0.14
Kurtosis	2.49	2.64	3.25	2.73	2.73	3.19

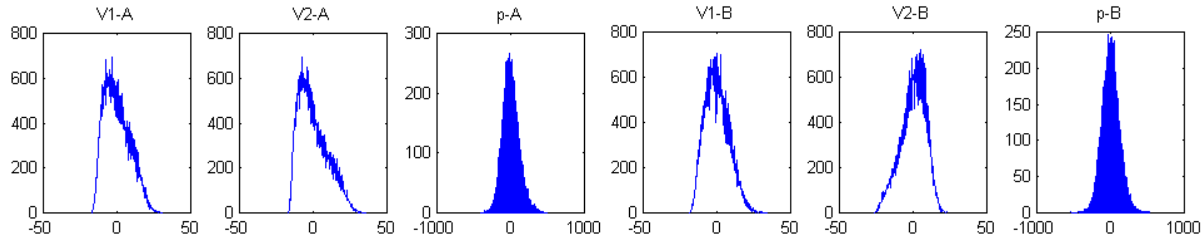


Figure 14 – Probability density function

In contrast to the side-by-side tube array, two mode statistical features does nor changes. The most important change is the mean velocity jump at velocity V2. The mean velocity variation is associated to local pressure variation, thus, drag coefficient variations are expected. This is responsible for the dynamic response on the tubes. In this experiments the measurements of tube pressures cannot be used to calculate the drag coefficients, being only reference values to identify the presence of the bistable phenomenon. Therefore, it is important to perform new pressure field measurements around the tubes to study the dynamic response caused by this kind of the instabilities.

At the velocity and pressure spectra shown in Fig. 15 no important peaks can be observed. According to Ziada, 1989, this is the behavior expected inside in line tube banks, especially after the third row.

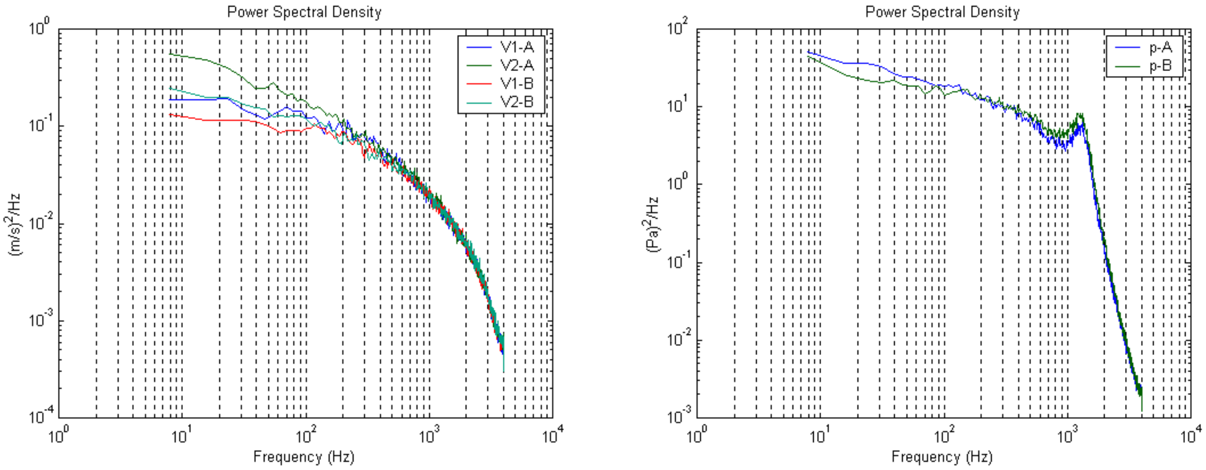


Figura 15 – Densidade espectral de potência

Additional data acquisitions were made inside the tube bank, changing the initial conditions and introducing flow disturbances. In some cases, new flow modes were generated, in other cases, the original flow mode did not change. In all the cases investigated, a rigorous evaluation was performed to identify the presence of instabilities. The results are yet not conclusive and therefore not shown in this paper. The observation and identification of the instabilities by using hot wire technique, however, was only possible by means of the application of the wavelet transforms, either continuous or discrete.

7. Conclusions

In this paper a review of mean characteristics about the phenomenon named bistable flow is presented. This phenomenon has been found at two side-by-side cylinders classical geometry, and more recently at aligning tube banks geometry. This two kind of arrays were experimented in a wind channel and studied by statistical and spectral tools.

Periodic and random phenomena can be an important dynamic instabilities generator, since they alternate the lift and drag coefficients, alternating the structure dynamic response. Thus, should be take special care for the Strouhal number range where these instabilities can occur. New studies are necessary to understand better the bistable phenomenon inside tube banks, especially on the firsts row.

It is also important to evaluate the need of use analytical tools where it is possible to identify this kind of phenomenon, since the spectral analysis using Fourier on all time series, for any cases, it is not able for identify this phenomenon. Every time intermittent phenomena can be present on no stationary series. In these cases, the wavelet transforms is a very suitable tool.

8. Acknowledgements

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