24th COBEM - 2017

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0105
VELOCITY LEVELS ANALYSIS IN A CROSS FLOW OVER TWO SIDE-BY-SIDE CYLINDERS AND A ROW OF CYLINDERS

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Abstract. *The present study shows the experimental analysis of cross flow over two cylinders in side-by-side arrangement and a row of cylinders, both cases with P/D = 1.26 and the cylinder diameter is 25mm. The experimental investigation was executed in an aerodynamic channel with Re = $2{,}2x10^4$ based on the diameter and in the free stream velocity. The velocity signals were acquired with hot-wire anemometry technique and the signal analysis was executed with Fourier Transform, Continuous Wavelet applying db20 and nine levels Discrete Wavelet. The velocity data series were acquired in the gap between the cylinders and in the wakes, to investigate the relations between the signals and the indication of a possible bistable trigger generated by a self-excitation in the gap. The objective also includes investigate the behavior, without bistable flow, in the row case. The results from side-by-side configuration show that there is a level change in the gap flow in the same time that the variation on the wakes happen, but analyzing the energy levels in wavelets results and the Fourier Transform they indicate low energies and low influence in the flow. The results from the row do not present the change in the energy level, but maintain higher energy in the wakes. The non bistable behavior in a row of cylinder might be connected to the low frequencies ranges that predominate in the signals.*

Keywords: *experimental**,** turbulent flow, two side-by-side cylinders, bistability, row of cylinders.*

INTRODUCTION

Studies with row of cylinders and with two cylinders side-by-side has been presented with different objectives, the main topic is the asymmetric wakes and the bistable behavior in side-by-side configuration. These asymmetric features change the forces and the structure response to the flow and generates new studies necessity.

Covering the flow over two cylinders and row of cylinders Zdravkovic (1997) executed a review and showed the main characteristics of the flow, as the differences in the wakes and the spacing ratio influence. The author also presented the studies of flow over a row of cylinders indicating that, with external perturbations, the bistable wake modes happen, but without external perturbations the wake mode change is not visible.

The asymmetric configuration on the wakes of two close cylinders and the aerodynamic characteristics in a side-by-side arrangement were investigated experimentally by Alam et al. (2003). The authors focused on the determination of the characteristics of steady and fluctuating fluid forces, wake frequencies and switching phenomena. The authors described that when the gap flow switched from one side to the other, a short duration stable flow pattern persisted in the intermediate time, in which the gap flow was oriented parallel to the free-stream flow and the Strouhal number was almost equal to that of a single cylinder.

Some years after, Wang and Zhou (2005), presented an experimental investigation based on laser-illuminated flow-visualization, particle image velocimetry and hot-wire anemometry measurements. The authors showed that for 1.2< P/D < 2 the flow structure and its downstream evolution are closely linked to the phase relationship between the gap vortex in the wide wake. The author described that in the cases that the gap vortex in the wide wake leads in phase, the two opposite-signed vortices in the narrow wake are pairing and this vortex interaction may act to stabilize the gap flow deflection.

The wake configuration change is linked, in some studies, to the vortices interaction on the wake as showed by Alam and Zhou (2013) the authors showed that due the synchronization vortices in both wakes a new asymmetric configuration happens. This new configuration stabilizes and build a new wake mode, different from the previous one.

de Paula et al. (2013) executed a visualization study showing the characteristics of the wakes behind a row of cylinders and observed that the wakes maintain the same mode during all the acquiring times, even with small P/D. This study also showed a visualization executed in two rows of cylinders applying hot wire anemometry and in this case the wakes after the second row present the mode alternation during the experimental acquisitions.

Islam et al., 2016 executed a two-dimensional numerical study to investigate the effect of gap spacing for flow past five side-by-side rectangular cylinders using the lattice Boltzmann method at a Re= 150. The gap spacing between the cylinders varies and authors indicate that the gap spacing have strong effect on the hydrodynamic interaction of the cylinders wakes. The average Strouhal number and average drag coefficient showed significant variation in each gap spacing. The authors also observed the wake mode characteristic changing in some spacing tested.

Neumeister et al., 2016 executed a study applying pressure fluctuations and velocity in a flow over a row of cylinders and observed the same characteristics that de Paula et al. (2013), where the wake modes do not change the mode during the flow.

The present experimental study objective is to investigate if the presence of a perturbation between the cylinders generate or influence the wakes modes change in a two cylinders side-by-side configuration and observe the possible characteristics that change from a row of cylinders configuration to two cylinders and that allow the bistable phenomenon to occur.

2. MATHEMATICAL

The mathematical approach in the present study applies the Fourier transform of a function, which represents the ratio using the mean square variation and the frequency of the same function. Where the function of frequency, *x(f)*, is indicated in Eq.(1) and the function in time, *x(t),* is indicated in Eq. (2). The power spectrum of the function is indicated in Eq. (3) and represents the signal energy level in the frequency domain, considering the total time. In these analysis the signal approximation is a seno or cosseno curve (Bendat and Piersol, 1986).

$$x(f) = \frac{1}{2\pi}\sum_{-\infty}^{\infty} x(t)e^{-ift} \tag{1}$$

$$x(t) = \sum_{-\infty}^{\infty} x(f)e^{-ift} \tag{2}$$

$$P_{xx}(f) = |x(f)|^2 \tag{3}$$

Due the signal non-ergodic behaviour, the Wavelet analysis allows a time - frequency domain evaluation and indicates the energy levels observed in the signal. The wavelet uses a window of frequency and time, where Wavelet functions with a specific characteristic are applied. These functions are finite energy function, ψ(f), have zero average and satisfies the condition in Eq. (4) (Percival and Walden, 2000).

$$C_\psi = \int_0^\infty \frac{|\psi(f)|^2}{f} df < \infty \tag{4}$$

The ψ(f) is the Fourier Transform of the wavelet. The function base is generated by translations and dilatations, the values a and b are, respectively, scale and positions coefficients.

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right), a,b \in R, a > 0 \tag{5}$$

The wavelet application presents many possibilities and does not have a rule to indicate which is the best wavelet, but studies conducted by Indrusiak (2004) and Indrusiak et al. (2005) indicated that the wavelet Daubechies 20 (db20) presents the best description of a turbulent flow signal. The Wavelet analysis can be continuous, where a frequency range is studied in a continuum form or discrete Wavelet form where bands of frequencies are used.

The Continuous Wavelet Transform (CWT) represents the signal linear convolution by the base wavelet, indicated in Eq. (6) and the continuous wavelet spectrum represents the absolute square convolution, as indicated in Eq. (7), in this analysis the energy level in the time-frequency domain (Percival and Walden, 2000).

$$Wx(a,b) = \int x(t)\psi_{a,b}(t)dt \tag{6}$$

$$P_{xx}(a,b) = |Wx(a,b)|^2 \tag{7}$$

The discrete wavelet analysis is a division in dyadic scales from the continuous wavelets, as indicated in the Eq.(8) and the discrete wavelet spectrum is the absolute square discrete value presented in Eq. (10). The transformation depends on the series size (Percival and Walden, 2000). The scale and positions coefficients, m and j, are dyadic and sample of a and b. Applying the values a = 2m and b=j2m and the adjusts to apply in Eq.(8) are:

$$D(m,j) = \sum_t x(t)\psi_{m,j}(t) \tag{8}$$

$$\psi_{m,j}(t) = 2^{-\frac{m}{2}}\psi(2^{-m}t - j),\ m, j \in N \tag{9}$$

$$P_{xx}(m,j) = |D(m,j)|^2 \tag{10}$$

3. EXPERIMENTAL PROCEDURE

The experimental study was executed in the aerodynamic channel in UFRGS with rigid smooth cylinders with 25mm diameter and placed in an aerodynamic channel with P/D = 1.26. The aerodynamic channel is made of acrylic glass, with a rectangular test section of 0.146 m height, width of 0.193 m and 0.89 m length, as shown in Figure 1 a). The airflow is driven by a centrifugal fan with 1HP, and passes through two honeycombs and two screens, to reduce the turbulence intensity less than 1% of the free stream velocity in the test section. Upstream the test section, placed in one of the side walls, a Pitot tube measures the flow reference velocity, this considered as the average velocity in the channel. The velocity of the flow and its fluctuations are measured by means of a DANTEC StreamLine constant hot-wire anemometry system. The measurements are executed in a configuration with two cylinders side-by-side and with a row of cylinders applying 3kHz of acquisition frequency with 1kHz low pass filter to avoid aliasing. The error associated with velocity measurements are about 5%. The statistic applications are executed in Matlab©.

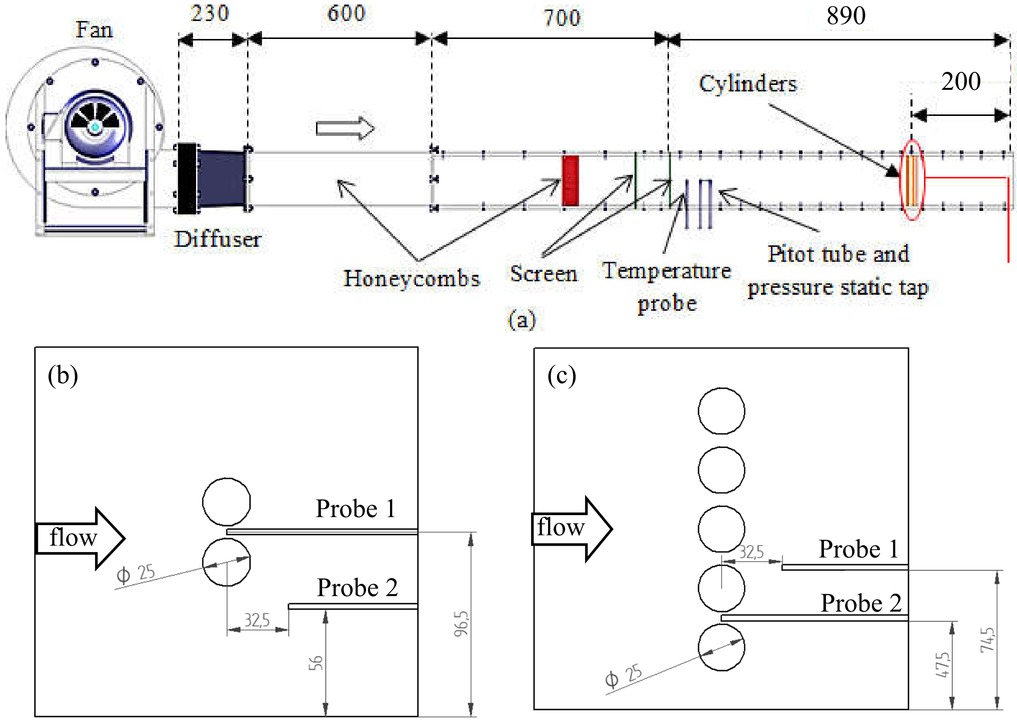

Figure 1 – a) Aerodynamic Channel, b) Probes positions for two side-by-side cylinders configuration and c) Probes positions for a row of cylinders.

The cylinders were positioned in the configuration side-by-side, as indicated in Fig. 1 b) and the probes were positioned inside the gap, aligned with the cylinders centre, and in the wake, the positions are indicated in Figure 1 b).

The cylinders were positioned in the configuration of row, as indicated in Fig. 1 c) and the probes were positioned in the gap and in the wake. The position was selected to observe the same characteristic of higher velocity in the gap and lower in the cylinder side.

4. RESULTS AND DISCUSSION

This section presents the discussion around the results and is divided in the analysis with two cylinders side-by-side and with a row of cylinders.

4.1 Two cylinders Side-by-side

The signal acquisition was simultaneous with two probes, as indicated in Fig. 1 b), in a flow with Re = 2.2×10^4, using a sampling frequency of 3 kHz. The signal from the probe 1, in the gap, is presented in Fig. 2 a) and the results from the probe 2, in the wake, is presented in Fig. 2 b), in both signals the presence of a velocity level change is visible between 4s and 8s. Two instabilities are also visible around 29s and 34s, but with a duration smaller than 1s. The level change in the gap has low difference in the mean value.

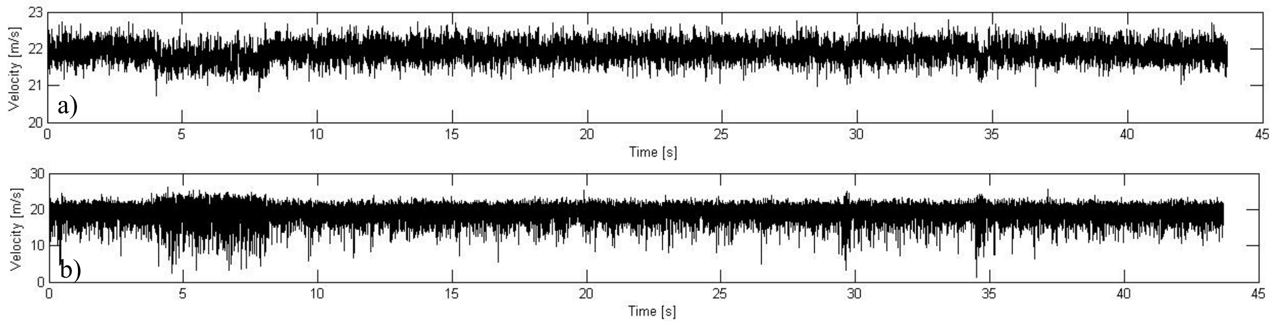

Figure 2 – Experimental velocity signal a) from the gap position and b) from the wake behind the cylinder.

The Fourier Transform, detailed from Eq.(1) to Eq.(3), was applied in both signals, as presented in Fig. 3, the data from the gap, in Fig. 3 a), presents two frequency peaks, with the first one at 67.38 Hz and the second at 202 Hz, where the last peak represents the first peak third harmonic. The first peak indicates the vortex shedding with a Strouhal Number of 0.125 and the energy level is low. The signal from the wake, in Figure 3 b), presents one peak with high energy in 67,38Hz, coincident with the first frequency in the gap and is due the vortex shedding. The energy levels linked to the signal from the wake are higher than the results from the gap signal, due the higher fluctuation. The frequency band is 2.93Hz and the error about 9%.

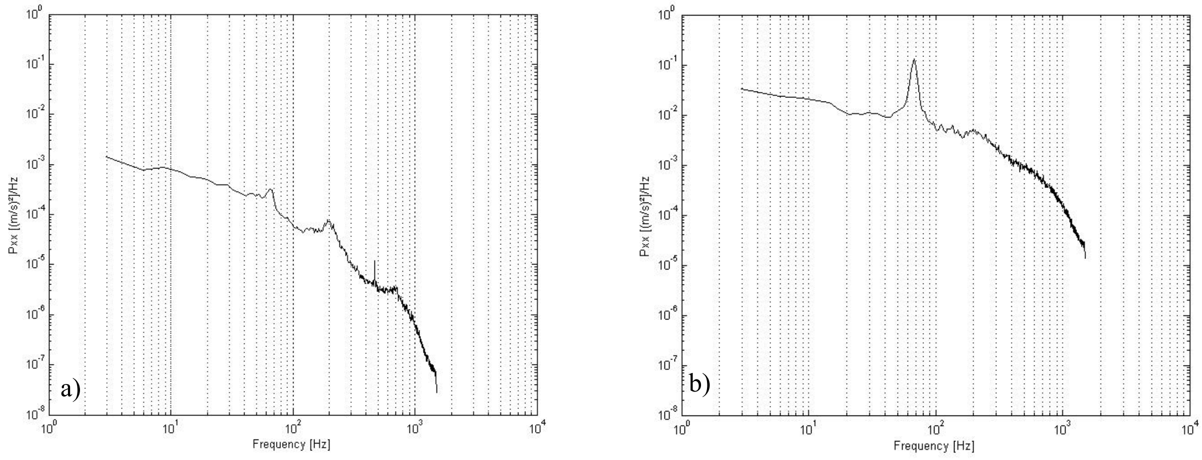

Figure 3 – Fourier Transform from the velocity signal a) from the gap position and b) from the wake behind the cylinder.

To detail the signals, the Continuous Wavelet Transform (CWT), defined in Eq.(6) and Eq.(7), was applied with the db20 wavelet in the band from 1 to 350 Hz. The results for each signal are presented in Fig. 4, where Fig. 4 a) presents the result from the gap signal, with low energy in all times. This range do not correspond to the peaks from the Fourier Transform and do not indicate variation in the energy along the series, as expected in the level velocity change. The result from the wake signal is also presented from 1 to 350Hz and in this case a region with higher energy is observed between 4 and 8s with higher energy in all the range observed. Some peaks are observed between 50Hz and 80Hz that are linked to the vortex shedding indicated in 67.38Hz in the Fourier transform. The energy levels are higher in the mode change between 4s and 8s and in the instabilities around 29s and 34s. The higher energy levels are visible up to 120Hz, but indicate peaks up 300Hz.

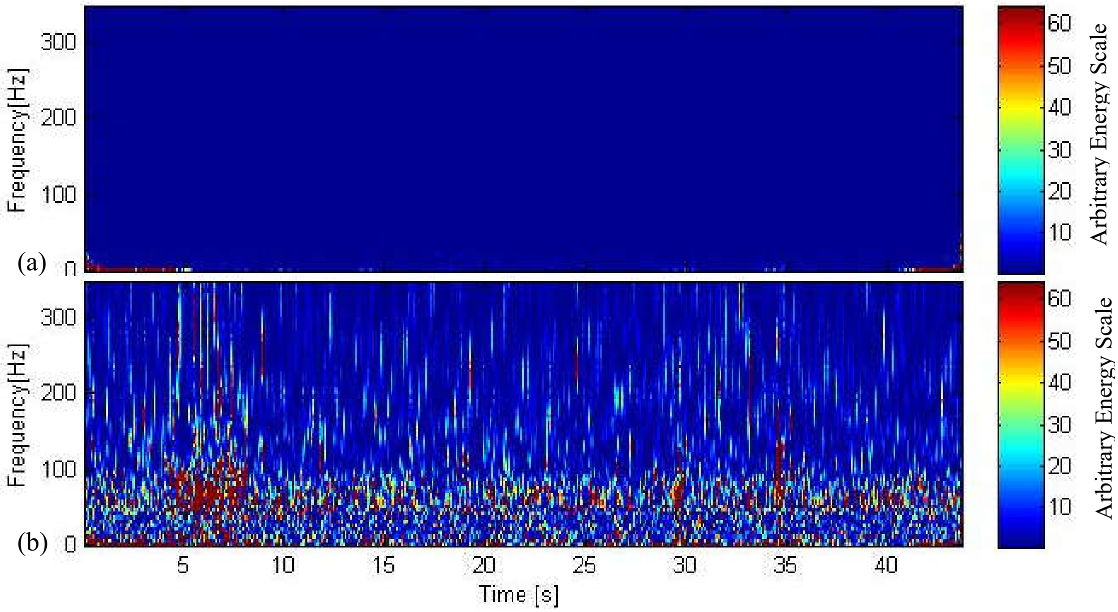

Figure 4 – Two cylinders side-by-side a) Gap signal Continuous wavelet spectrum and b) Wake signal Continuous wavelet spectrum.

The Discrete Wavelet Transform (DWT), defined in Eq.(8) to Eq.(10), is applied in the raw signals with band of 2.93Hz. The signal is analysed in nine level decomposition and one approximation as indicated in Table 1, each decomposition presents a frequency range and allow the observation of predominating ranges. The results for both probes are presented in Fig. 5.

In Figure 5 a) the results from the gap signal present the velocity level change in the approximation but without any visible characteristics in the decompositions. The signal from the gap present main frequencies between 23 and 375Hz with ergodic signals and the amplitude is low, as the energy observed in CWT and Fourier Transform. The results from the wake signal are presented in Fig. 5 b) and in this case, a variation is observed in the approximation mostly between 4 and 8s, but strong characteristics are presented between 45 and 750Hz. An emphasis in the velocity level change is observed in d_5 that presents frequencies between 46,88 and 93,75 Hz, the mode changes are present between 4 and 8s, the instability in 29s and 34s are also visible. The frequency range englobe the vortex shedding frequency observed in Fig. 3 b) and Fig. 4b).

The signals analyzed in Fig. 5 a) and 5 b) do not present similarities, even the frequencies band that contributes for each signal are different indicating that the level change observed in the gap signal is a consequence of the wake behaviour and not the cause.

Table 1 – Frequency bands used in the discrete wavelet analysis.

a_9	0 -2,93Hz
d_9	2,93 – 5,86Hz
d_8	5,86 – 11,72 Hz
d_7	11,72 – 23,44 Hz
d_6	23,44 – 46,88 Hz

d_5	46,88 - 93,75 Hz
d_4	93,75 – 187,5 Hz
d_3	187,5 – 375 Hz
d_2	375 – 750 Hz
d_1	750 – 1500 Hz

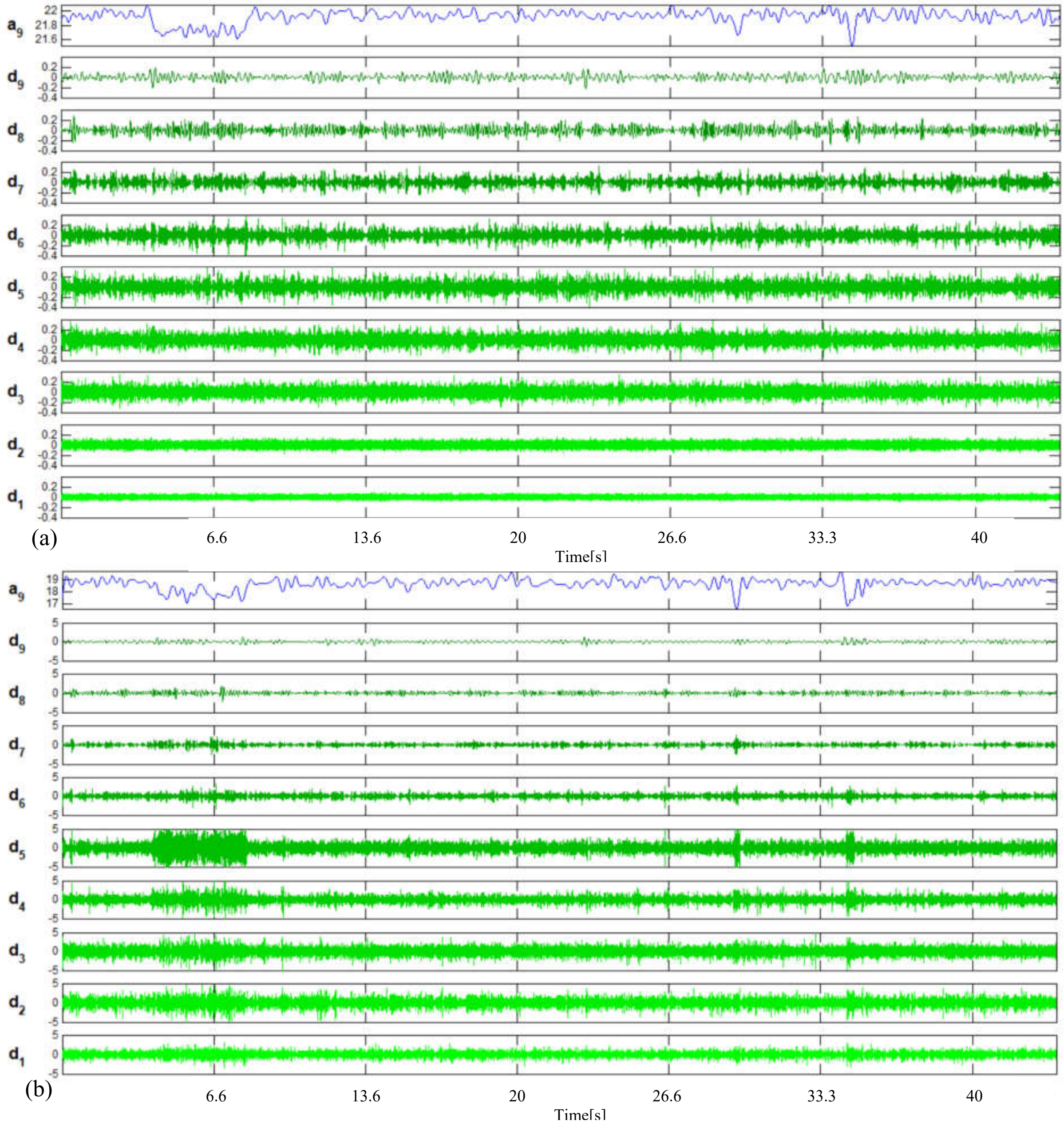

Figure 5 -Two cylinders side-by-side a) Gap signal Continuous wavelet spectrum and b) Wake signal Continuous wavelet spectrum.

4.2 Cylinders Row

In the study with a row of cylinders the signal acquisition was simultaneous with two probes positioned as indicated in Fig. 1 c), in a flow with $Re = 2.2 \times 10^4$, using the sampling frequency of 3 kHz. The signal from the probe in the gap is presented in Fig. 6 a) and the results from the probe in the wake are presented in Fig. 6 b). Comparing the signals, a mean value difference is observed, with higher velocity in the gap, but without a change in the level along the series even considering that in this case the velocity in each side of the cylinder is different.

Applying the Fourier Transform, defined from Eq.(1) to Eq.(3), in each signal some frequencies peaks are observed. In Figure 7 a) the result for the signal from the gap is presented and peaks in 55.65Hz, 70.31Hz and 293 Hz are visible, but the energy linked in each frequency is low. The frequency around 70Hz is the same observed in the cylinder side-by-side case, Fig. 3, generating a Strouhal number of 0.12. In Figure 7 b) the signal from the cylinder wake is presented and the frequency of 70.31Hz is also visible and is linked to the vortex shedding, a small peak is also visible in 29.3 and another one in 293Hz. The results were presented with frequency band of 2.93Hz and error of 9 %.

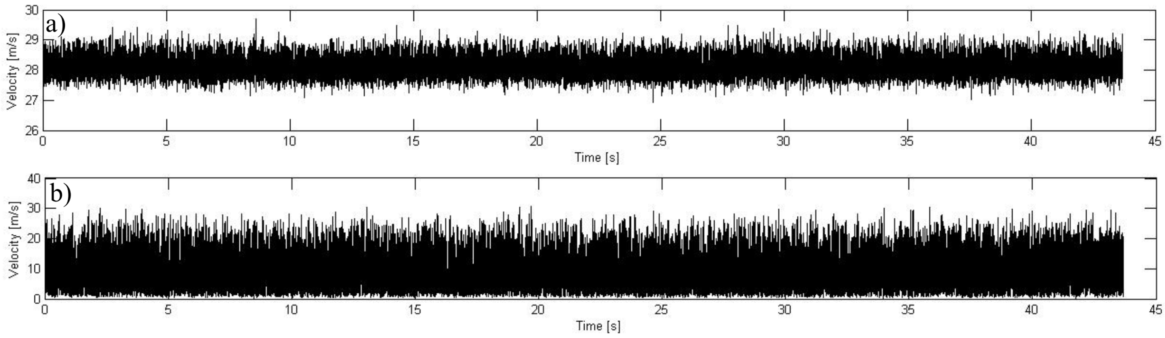

Figure 6 – Experimental velocity signal a) from the gap position and b) from the wake behind the cylinder.

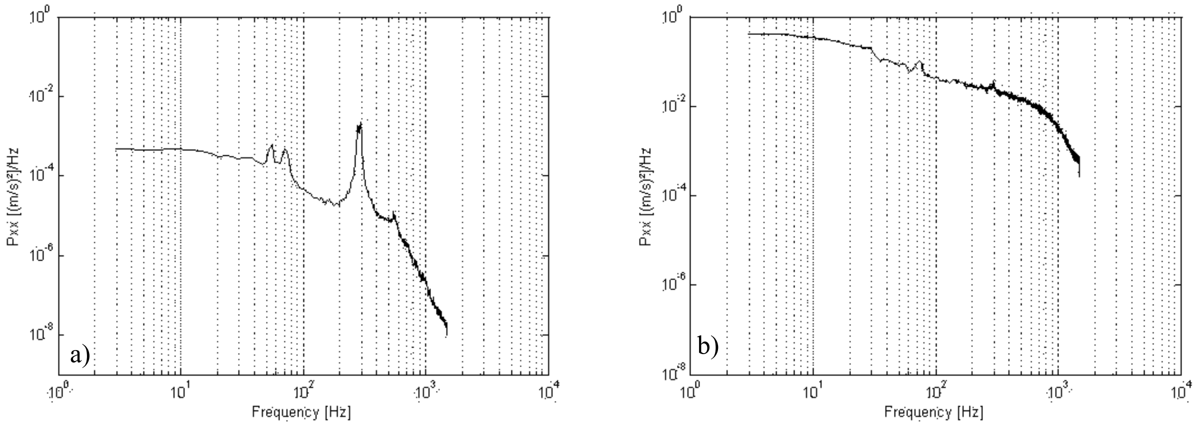

Figure 7 – Fourier spectrum from the velocity signal a) from the gap position and b) from the wake behind the cylinder.

The analysis using CWT is presented in Fig. 8. The Fig. 8 a) shows the results from the gap signal and it is observed that the energy levels are low, without visible energy peaks. The Fig. 8 b) presents the result from the wake signal, applying the same parameters, and the energy level is high with a range in maximum energy up to 50Hz. Some regions with high energy are visible around 70Hz, a highlight region happens around 190Hz that is not present in the Fourier Transform, Fig. 7, and a new range in 290Hz but in this case lower energy is observed. The high energy range maintain values under 100Hz, agreeing with the peaks observed in the Fourier Transform.

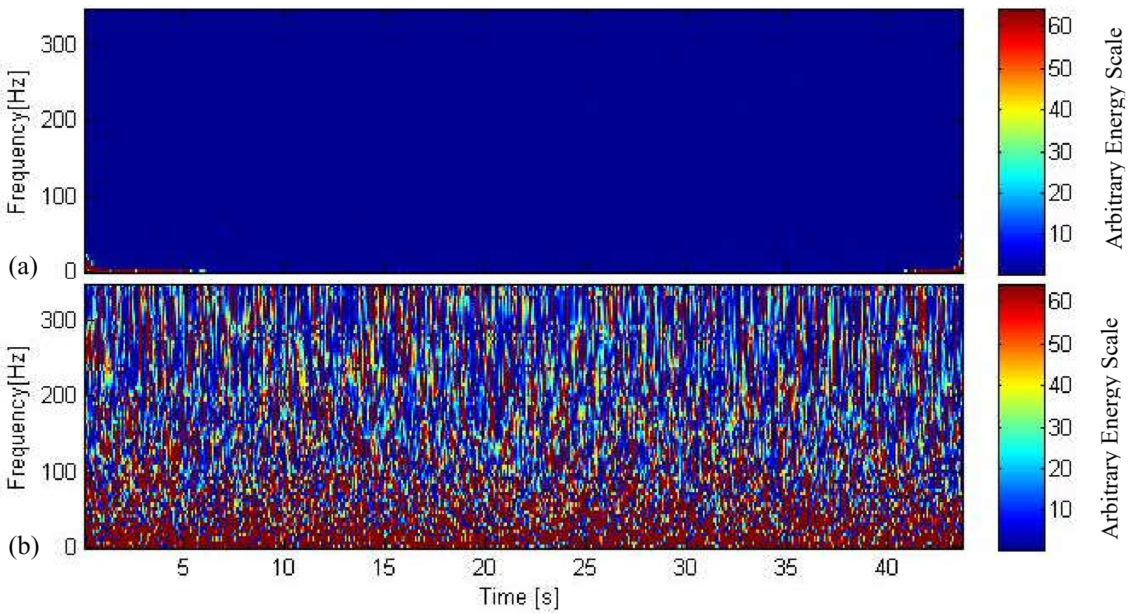

Figure 8 – Row of cylinders a) Gap signal Continuous wavelet spectrum and b) Wake signal Continuous wavelet spectrum.

The DWT is applied in the signal from the gap and the result is presented in Fig. 9 a), the amplitude of the signal in the decomposition d_3 is emphasized in relation to another frequency ranges. The decomposition represents frequencies from 187,5 – 375 Hz and can be linked to the peak in 293Hz observed in the Fourier Transform and in the CWT, but in both cases a small energy linked to the frequency range.

The result of the discrete wavelet transform applied in the signal from the wake is presented in Fig. 9 b) and is visible the amplitude difference in each decomposition, with higher values in frequency ranges over 93,75Hz, but in this case without a clear definition of main range.

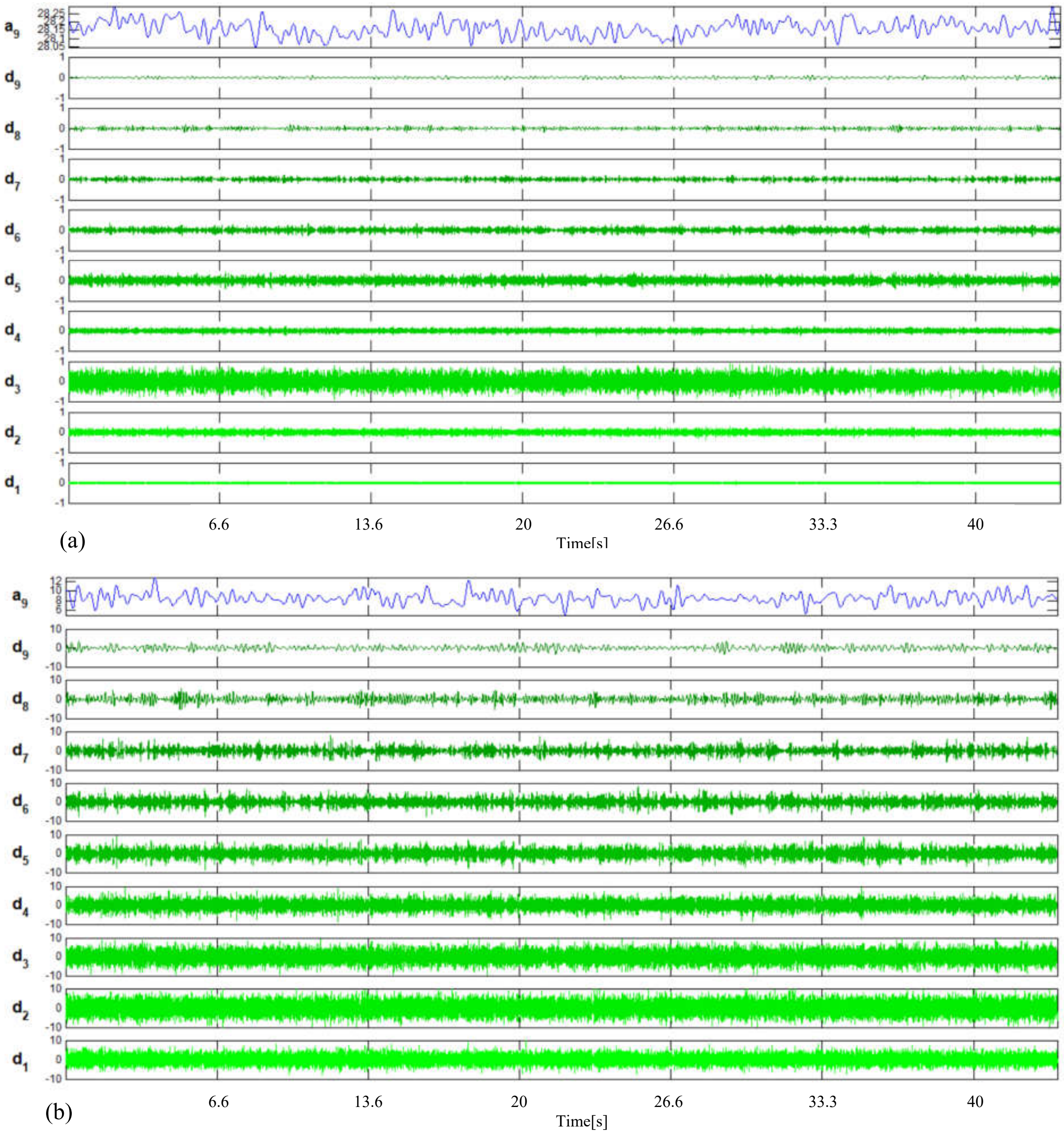

Figure 9 – Row of cylinders a) Gap signal Continuous wavelet spectrum and b) Wake signal Continuous wavelet spectrum.

5. CONCLUSIONS

The present experimental analysis executed over two side-by-side cylinders studied the possible influence of a self-perturbation in the region between the cylinders that could generate a wake change characteristic. The study included an evaluation in a row of cylinders, to observe the characteristics and compare with two cylinders side-by-side. The velocity signals in the gap and in the wake were acquired with hot-wire anemometry and analyzed with Fourier, Continuous and Discrete Wavelet Transform.

The results using the side-by-side cylinders data and applying Fourier Transform showed the same frequency range in both signals, indicating the vortex shedding. The result from the Continuous Wavelet Transform(CWT) presented high energy levels in the wake signal, while no variations happen in the gap signal. The Discrete Wavelet Transform (DWT) results reveal that the signal from the gap presents significant level in the approximation and some visible characteristics in frequencies between 23 and 375Hz, but not a modification in the wake mode. The results from the wake indicate higher energy and there are visible variation in the approximation mostly between 4 and 8s and in the same time between 46 and 750Hz with special emphasis between 46 and 95Hz, also linked to the vortex shedding.

The results from the row of cylinders present low energy in all results from the gap signals, with frequency peaks in the Fourier Transform agreeing with frequencies in the two side-by-side cylinders. In the CWT results from the gap signal there was not change in the energy levels. In the wake results the energy present regions with high values, but without clear separations for the frequency ranges. In the analysis using DWT in the signals from the row of cylinders no modes change are visible. In the gap signal, the amplitude of the signal in the decomposition from 187.5 – 375 Hz is relevant and is visible in the Fourier Transform. For the signal from the wake the high bands decomposition present most of the signal influence.

Comparing the results from both DWT approaches is observed that the signals from the two cylinders side-by-side gap present signal details in a larger band of frequencies, while the row of cylinders results concentrate the main details in one band. The results from the wakes signals are detailed in the higher frequency bands, for both cases. This is the characteristic that can indicate that the wakes change do not occur due an influence/ perturbation in the gap, but in the wake. This characteristic of the gap signals can also justifies the no wake change observed in the row of cylinders in this case the signal has stability, with main characteristics in one frequency band and that is coincident with the vortex shedding band. The low energy in all analysis from the gap indicate that the characteristic observed from these signals are consequences of the wake behaviour and not the opposite.

6. ACKNOWLEDGEMENTS

Authors are gratefully indebted to the CNPq National Council for Scientific and Technological Development, for the financial support. Roberta Neumeister thanks the CNPq for granting her fellowship.

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