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EXPERIMENTAL ANALYSIS OF TURBULENT TRANSVERSAL FLOW ON TWO FIXED PARALLEL CYLINDERS WITH OSCILLATORY AND ROTATIONAL FREEDOM

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Abstract. *This paper presents an experimental study of the bistability phenomenon that occurs in the simplified geometry of two tubes arranged side by side submitted to a turbulent cross flow. In the analysis we consider the condition of fixed tubes and with a degree of freedom (rotational), submitted to different numbers of Reynolds. The experimental technique consists in the measurement of flow rate fluctuations through the aerodynamic channel hot wire anemometry and the evaluation of the stresses of the flow on the tubes with the use of a load cell. The data obtained from the measurement in the channel are treated with the use of statistical, spectral and wavelet tools. In the experimental results we observe the presence of bistability and note the non-simultaneous behavior of the phenomenon along the cylinders. The asymmetric formation of the wakes is also studied and attributed to the interaction between the vortices from wakes behind the cylinders, since, initially, the wake detachments is symmetrical. In the evaluation of the forces by means of the extensimetry technique, the steps of conditioning and acquisition of the signal were elaborated and the results of mechanical deformation presented similarity with the phenomenon observed in the experimental anemometry. For a Reynolds number of 27635 a force of 26.1 mN was found with a torque developed in the load cell of 84.95 Nmm.*

Keywords: *Bistable flow, Hot wire anemometry, Turbulence, Load cells, Experimental analysis.*

1. INTRODUCTION

The phenomenon of bistability, shown in Fig. 1, has very interesting characteristics and many of them are still not fully understood. This ignorance of the mechanisms that act on the flows on two cylinders positioned side by side is the main motivation of the present study, being that the inscience of the reasons and the means of the event of the bistable phenomenon is the central interest of the analyzes.

In bistability there is a narrow mat downstream of one of the tubes and a wide mat downstream (Fig. 1a and 1b). This phenomenon generates two predominant frequencies of vortex detachment, each associated with a treadmill: the narrow treadmill is associated with the highest frequency, and the wide treadmill is associated with the less frequent detachment. Through the slit, the flow is diverted towards one of the cylinders, forming the narrow mat. Bistable flow is characterized by a change in the flow pattern of the slit from side to side during irregular periods of time. Thus, if the flow velocity is measured, for example, along lines tangent to the external generators of the cylinders, downstream, a pattern of exchange between the modes of the flow may occur as shown in the scheme of Fig. 1c. According to Möller,

2000, this pattern is independent of the Reynolds number and is not associated with possible misalignment between the cylinders or external influences, which suggests to be an intrinsic characteristic of the flow.

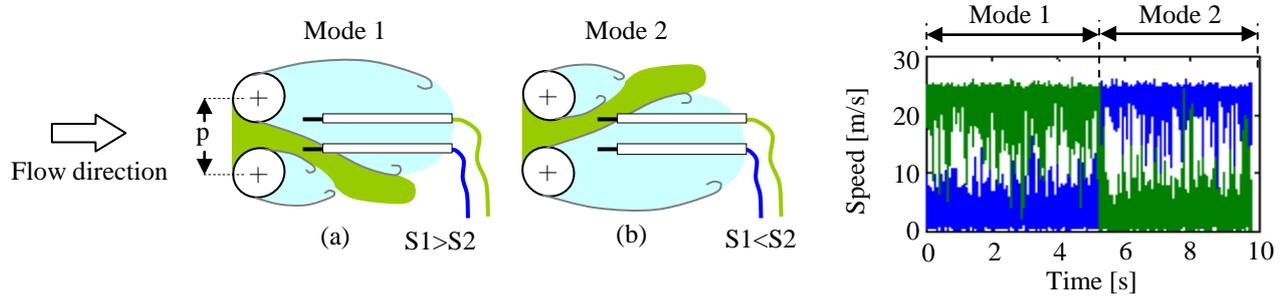


Figure 1. Schematic representation of the bistable flow for (a) Mode 1. (b) Mode 2. Their respective characteristic signals (c).

Considering that the flow stresses the solid surfaces, the objective of this work is to carry out a study to determine the interrelationship between the bistability phenomenon in turbulent flow on parallel cylinders arranged side by side with spacing ratio $p/d = 1,26$ and the forces caused by the flow on the cylinders, since bistability can act as an additional source of dynamic instabilities in this geometry.

In this way, the technique of anemometry of hot wire in aerodynamic channel was used in order to measure the medium and floating field of velocities downstream of the tubes, thus obtaining time series of velocity and wavelet. It was analyzed the transient behavior of the flow in the belt regions to better understand the bistable phenomenon and the mechanisms involved in it and to measure the actions of the velocity fluctuations in points of the mats for different numbers of Reynolds.

In order to complement this investigation, measurements of fluctuations of the drag forces and rolling momentum were carried out which are originated by the interaction, fluid (air) and structure (tubes), in the aerodynamic channel with the use of the load cell. This stage of the experimental investigation consists of tests of rigid cylinders mounted on a base, submitted to the permanent flow of air in the channel. This base has a shaft at the top and bottom, with bearing bearings that allowed the rotational movement of the tubes. The results will be able to correlate the vortex detachment modes of the rigid tube bistability phenomenon with those with rotational motion and, consequently, generate torsional moment in the elaborated structure.

2. EXPERIMENTAL PROCEDURE

The experimental study applied in this work consists in measuring the average velocity and the air velocity fluctuations when passing through the tube bank, through the technique of hot wire anemometry in an aerodynamic channel. Thus, time series are obtained that, with the help of the mathematical tools mentioned above, allow a quantitative analysis of the results. A qualitative study of the bistability phenomenon was also carried out through the evaluation of the force with the use of a load cell.

The experiment was performed in one of the aerodynamic channels of the Laboratory of Fluid Mechanics of the Federal University of Rio Grande do Sul, LMF. It is composed of a centrifugal fan Gema with 1 HP of power followed by a grille homogenizer, a beehive and by two screens with 0.001m of internal spacing each. The aerodynamic channel section consists of rectangular shaped acrylic plates resulting in a cross section of 146 x 193 mm, which can vary only the length of the test section for the experiment. Downstream of the test section, outside the aerodynamic channel, a probe holder positioning system is mounted. The reading of the freewheel speed is done with a Pitot tube. The pressure points are connected to an electronic pressure gauge which is connected to the multimeter and indicates the readings in electric current that are converted into pressure.

After the homogenization screens, install the desired test section. The configuration is a test section with two PVC cylinders with a diameter of 25.1 mm side by side and, in this case, the length of the section of 900 mm is used. The locking ratio, presented with the cylinders positioned inside the aerodynamic channel is 26.5%.

In the measurements performed in the present study, probes with a DANTEC 55P11 straight wire sensitive element are applied. The equipment used in the measurements is the DANTEC StreamLine 90N10 Frame that operates with the constant temperature system. The velocity data series are acquired through a 16-bit analog / digital converter (A/D) card, model NATIONAL INSTRUMENTS 9215. According to Olinto et al., 2009, when the flow travels through the interior of a tube bank, a strong vertical component arises. Thus, for this vertical component to be better captured by the probe wires, the experiments are performed with the perpendicular wire positioned horizontally.

For the development of the experimental procedures, a base was constructed that positions the tubes in parallel. Its articulation is by rolling bearings attached to the bottom and top plates of the wind tunnel, which allows it to rotate

along an axis equidistant to both cylinders. Fig. 2a shows the securing base and Fig. 2b an exploded view of all the components used for assembling the tubes in the measurement bench.

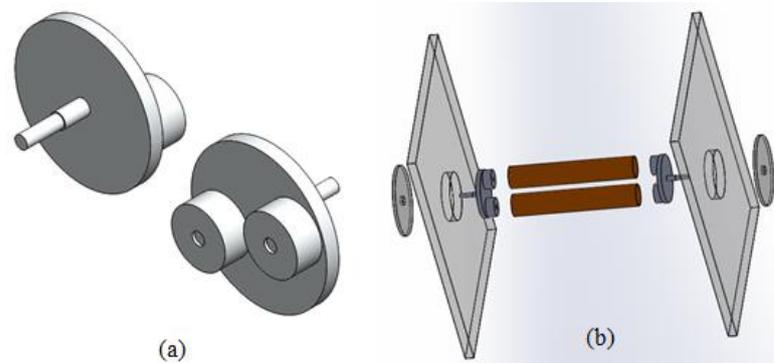


Figure 2. Scheme for articulating the experiment. (a) base. (b) set.

It was then analyzed some alternatives of solution to measure forces for these magnitudes and as a way of exploring intermediate values it was decided to implement a load cell with strain gages fixed to the axis of rotation, which would allow the measurement of the deformation of the forces and consequent tensions and mechanical forces. For the assembly of the load cell, a shaft coupling was built and a crimping the wind tunnel structure, between the ends of these two structures was fixed a blade that undergoes deformation, acting as a spring element of the system.

3. RESULTS AND DISCUSSION

In this chapter the results of velocity measurements will be presented for two aerodynamic channel tubes, all performed in the longitudinal median plane. The spacing ratio studied was $p/d = 1.26$, where "p" is the distance between centers of any two tubes and "d" is the diameter of these. The results of measurements of drift and rolling moment fluctuations that are generated by the interaction, fluid (air) and structure (tubes) in the aerodynamic channel with the use of the load cell will be presented.

Aerodynamic channel Reynolds numbers range from $8,979 \times 10^3$ to $2,763 \times 10^4$, based on the average velocity of the undisturbed flow and the diameter of the tubes. The frequencies chosen for acquiring the velocity series depend on the availability of the filters for cutoff frequency, taking into account the Nyquist criterion to avoid bending the high frequencies in the spectrum. Also, they should allow the identification of the main characteristics of the flow. The data acquisition times depend on the number of elements in each sample.

3.1 Two fixed tubes

This section will present the results obtained for two fixed tubes arranged side by side with two positioning configurations of the hot wire probes. For the two configurations, the Reynolds numbers of the experiment range from 8.979×10^3 to 2.763×10^4 and the reference speed from 5.4 m/s to 16.6 m/s respectively with acquisition frequency of 1000 Hz and 2^{17} (131072) points. The motivation for the evaluation in these two conditions was to understand the behavior of the velocity of the flow in different positions of the mat and to observe the existence or not of the bistability in this condition. Fig. 3 shows the geometry of the two tubes disposed side by side and the positioning of the probes used in the first configuration. In the second configuration, $x=45 \text{ mm}$ was considered.

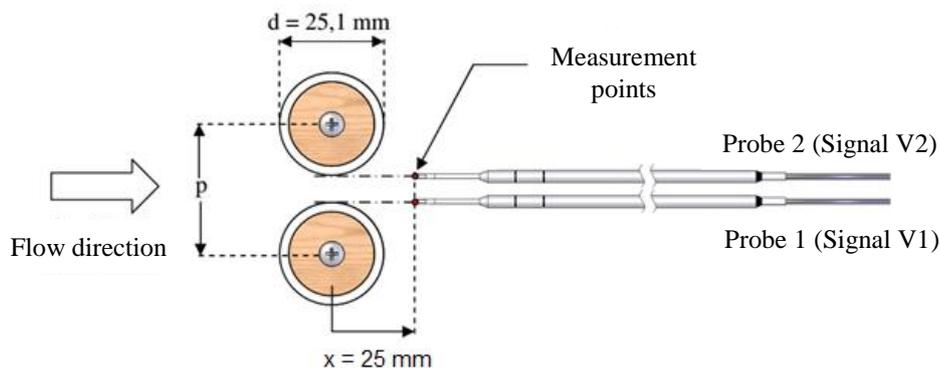


Figure 3 – Geometry of the two tubes and positioning of the probes used in the experiments of the first configuration.

According to Alam et al., 2013, the phenomenon of bistability can be verified in arrangement of two side-by-side tubes submitted to cross-flowing turbulence for a spacing ratio between $1.2 < p/d < 2.2$. In this case, the bistability is manifested by deflecting the portion of fluid emerging from the slit between the two tubes. Thus, one way of experimentally measuring the bistable effect for this configuration is by positioning two straight hot wire probes downstream thereof, aligned to the tangent lines to the internal generators of the tubes.

The instantaneous velocity signals obtained for the first configuration varied between levels of minimum speeds of 1m/s for Reynolds of 2.76×10^4 and maximums reaching 40m/s in Reynolds 1.39×10^4 . According to Neumeister, 2015, the velocity variation is only influenced by the behavior of the mats that change the point of detachment of the vortices and this alters the speed of the slit. With the reconstruction of these signals by means of a discrete transform of Db20 and level 10, it was observed that during the 131 seconds of the data acquisition, 4 to 18 exchanges between the modes of the flow were verified. The Reynolds flow 8.98×10^3 had the highest number of exchanges and Reynolds 8.98×10^3 had the smallest number of exchanges between modes.

However, if a successive process of measuring instantaneous velocities is performed, this value does not remain constant, showing that the bistable phenomenon does not have a defined natural period.

The spectrograms generated by continuous waveform transformation of the velocity signals were also generated for these evaluations. These spectrograms show the energy distribution of velocity fluctuations in the time and frequency domains simultaneously at 4 Hz frequency ranges in the range of 20 to 200 Hz. It is possible to observe the variation of the energy values at the same times as the trovas happen. The lower the speed, the lower the energy values obtained.

In the second configuration (repositioned probe), the instantaneous speed signals obtained varied between levels of speeds of 1m/s to 23m/s. With the reconstruction of these signals through a discrete transform of Db20 and level 10, it was observed that during the 131 seconds of data acquisition, between 4 and 22 exchanges between the modes of the flow were verified. Being that the greater amount of exchanges was observed again for Reynolds $8,98 \times 10^3$.

Fig. 4a shows the instantaneous velocity signals obtained for the Reynolds number of the experiment is 8.979×10^3 and the reference speed is 5.4m/s. Measurements were performed according to the second set of probes, where the probes were moved away from the tubes. You can clearly observe several speed changes throughout the data acquisition time. There are two levels of visible velocities: one in 1m/s and another in 12m/s in probe 1 and one in 1m/s and another in 10m/s for probe 2. Rebuilding these signals through a discrete wavelet transform (Fig. 4b), it is observed that during the 131 seconds of data acquisition 22 changes between the modes of the flow are verified. Depending on the frequency of acquisition, this reconstruction results in a signal with frequencies up to 0.48Hz, which eliminates frequency fluctuations higher than this value.

It is observed that the velocity obtained by probe 1 does not reach the same levels of the velocities obtained by probe 2. According to De Paula et al., 2013, in order to reach the same velocity levels between the modes of the flow the probes need to be properly calibrated, and positioned symmetrically with respect to the roller conveyors. Poor calibration does not guarantee that when switching between flow modes one of the probes reaches the highest speed range. According to the literature, when the average velocity fluctuates around a higher value, the flow out of the slit is inclined towards the probe, and when the average velocity fluctuates around a lower value, the probe is measuring the speed inside the wide track.

The spectra generated by the continuous waveform transform of the velocity signals of Fig. 4a are shown in Fig. 4c. These spectrograms show the energy distribution of speed fluctuations in the time and frequency domains simultaneously, at 4Hz frequency ranges, in the range of 20 to 200Hz.

3.2 Free tubes to rotate

This section will present the results obtained for two tubes arranged side by side with $p/d=1.26$ and released to rotate or oscillate with respect to the central axis between them. The objective of this experiment is to first evaluate if the bistability acts on the proposed mechanism and to relate this behavior with the fixed tube analysis.

The spacing ratio continues to be $p/d=1.26$, acquisition frequency of 1000Hz and 2^{17} (131072) points. The Reynolds numbers of the experiments range from 8.979×10^3 to 2.763×10^4 and the reference speed from 5.4m/s to 16.6m/s respectively. Using the same probe positioning configuration from the previous experiment, instantaneous velocity signals were acquired, reconstruction of these signals by discrete wavelets and spectrograms.

Fig. 5a shows the instantaneous speed signals obtained for Reynolds number of $8,979 \times 10^3$ and the reference speed is 5.4m/s. It is possible to observe a large initial velocity peak followed by a series of oscillations. From half of the experiment onwards, the velocity curiously stabilizes at a higher level than the one presented when it oscillated. This behavior is still not clearly understood, having relation to the difference of the tangential velocities of the cylinders in relation to the velocity of the incident flow.

The spectra generated by the continuous waveform transform of the velocity signals of Fig. 5a are shown in Fig. 5c. These spectrograms show the energy distribution of speed fluctuations in the time and frequency domains simultaneously, at 4Hz frequency ranges, in the range of 20 to 200Hz.

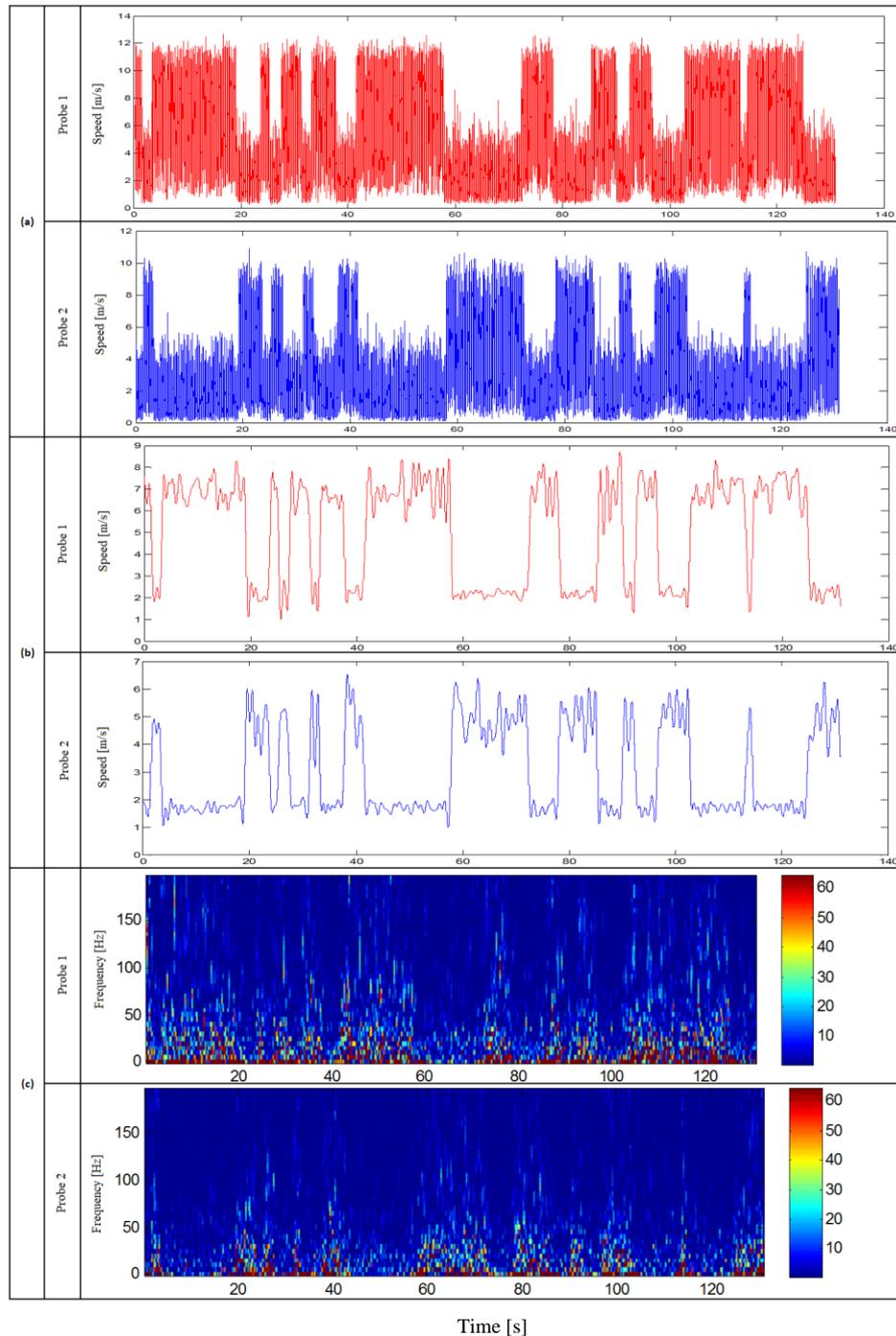


Figure 4 – (a) Signals of instantaneous speeds. (b) Reconstruction of signals of instantaneous velocities through discrete wavelet transform. (c) Spectrograms of the instantaneous velocity signals.

3.3 Drag force and rolling moment

In this section, the measurements of fluctuations in drag and momentum are shown, which are generated by the interaction, fluid (air) and structure (tubes) in the aerodynamic channel. The experimental investigation consists of tests of rigid cylinders mounted on a base, submitted to the permanent flow of air in the channel. This base has an upper and lower shaft, with bearing bearings that allow rotational or oscillating movement of the tubes. The objective is to correlate the vortex detachment modes of the rigid tube bistability phenomenon with those with rotational motion and, consequently, generate torsional moment in the elaborated structure.

The spacing ratio of $p/d=1.26$, acquisition frequency of 1000Hz and 2^{17} (131072) points is maintained. The Reynolds numbers of the experiments range from 8.979×10^3 to 2.763×10^4 and the reference speed from 5.4m/s to 16.6m/s respectively. For the acquisition of the results, for each number of Reynolds used, 2 minutes were waited until

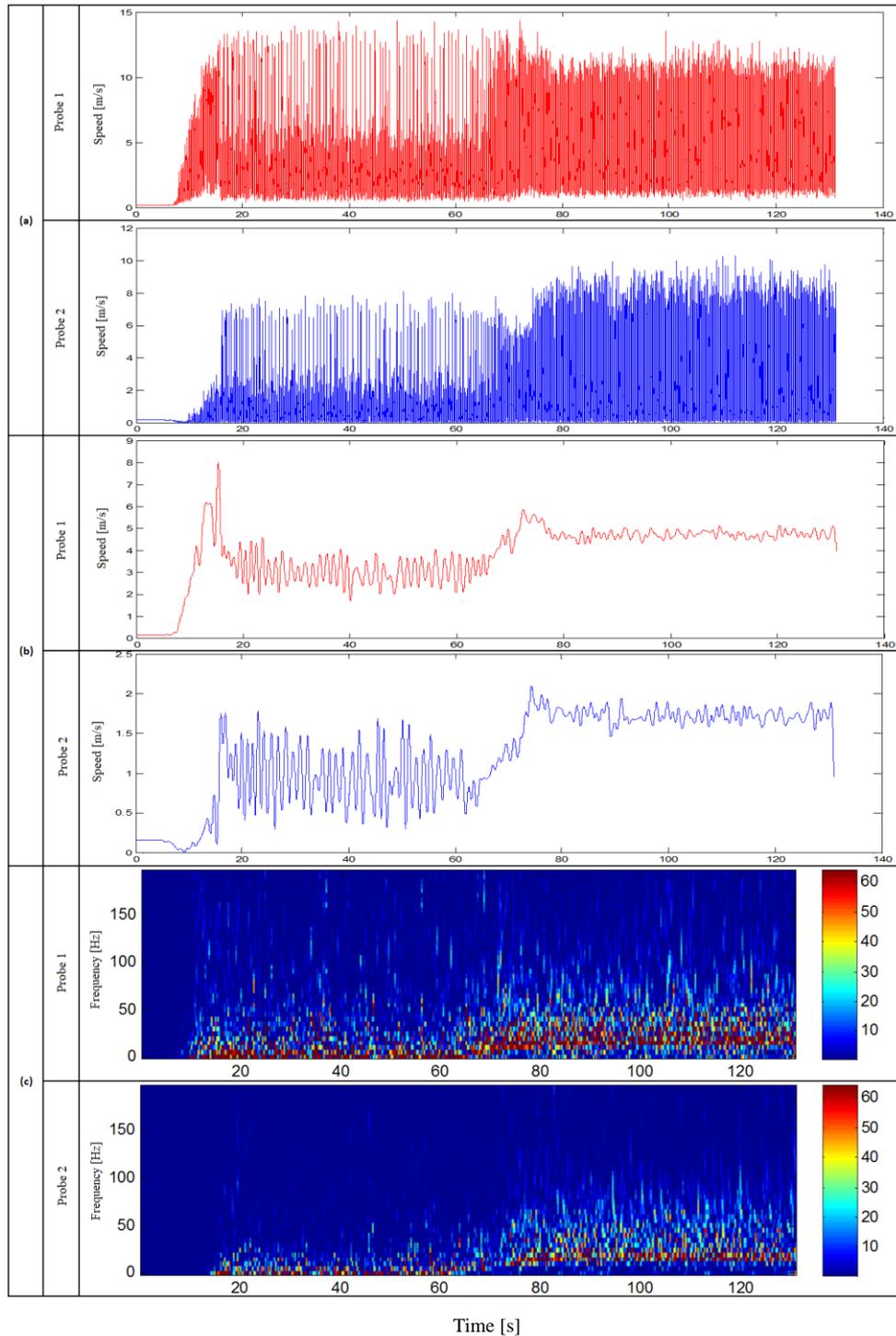


Figure 5 – (a) Signals of instantaneous speeds. (b) Reconstruction of signals of instantaneous velocities through discrete wavelet transform. (c) Spectrograms of the instantaneous velocity signals.

the homogenization of the flow.

Fig. 6 shows the results of force as a function of time and the reconstruction of these signals through discrete wavelet transform for the two free tubes to rotate coupled in the load cell. Being: Fig. 6a for Reynolds 1.80×10^4 and velocity equal to 10.8m/s; Fig. 6b for Reynolds 2.30×10^4 and velocity equal to 13.86m/s; Fig. 6c for Reynolds 2.74×10^4 and velocity equal to 16.48m/s;

It is possible to observe that for the two smaller Reynolds numbers, the flow appears not to be strong enough to present the bistable behavior. The behavior is not oscillatory. For Reynolds 2.74×10^4 the bistable behavior is noticed in the force variation. Very similar to that presented in the results with anemometry.

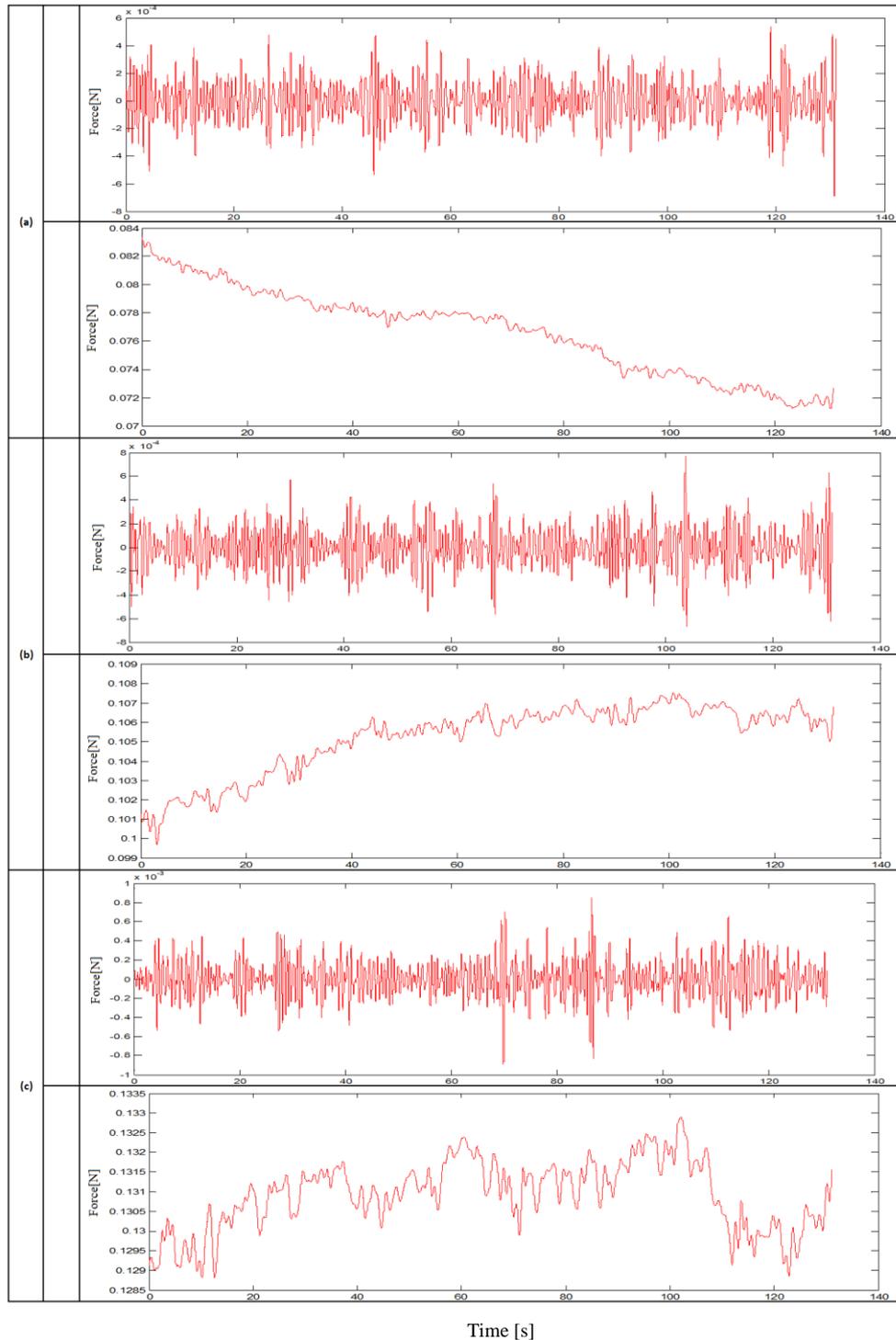


Figure 6 – Signals of Force and the reconstruction of the signals through a discrete transform of waveforms.
(a) $Re: 1,80 \times 10^4$, (b) $Re: 2,30 \times 10^4$, (c) $Re: 2,74 \times 10^4$.

4. CONCLUSIONS

In this work, different techniques are employed in the analysis of experimental time series derived from a highly non-stationary phenomenon: bistability. It was investigated the behavior of the flow on two parallel cylinders with spacing ratio of 1,26. The mechanisms of exchange of treadmill modes in the occurrence of bistability, asymmetric formation of mats and the behavior of speed fluctuations were evaluated. The different techniques employed aim to obtain conditions to better understand the non-stationary behavior of the phenomenon, where classical approaches do not allow a complete description of bistability.

The variation of the velocity levels observed at the point of monitoring between cylinders, during the bistable exchange, was verified experimentally. The results of the analysis of the experimental series studied show that the flow, when established in one of its modes, presents well preserved probabilistic characteristics throughout the time in which this mode is established. This behavior is visible in the series containing the averages and speed fluctuations. The velocity variation is only influenced by the behavior of the mats that change the point of detachment of the vortices and this alters the speed of the slit.

The waveform transformations are useful tools in the analysis of this phenomenon. The use of the discrete wavelet transform assists in the analysis of the data through the reconstruction up to a specific band of frequency, serving as low-pass filter. Through the continuous transformation of waveforms the energy content of the signals can be analyzed. The results show an increase in the energy of the velocity series at time instants where the mean velocity is higher, with a relative spread of the frequencies. When the slit flow changes direction to the lower average speed threshold, there is a decrease in the energy content of the signal accompanied by a higher concentration of the frequency range and also lower fluctuation values. This behavior indicates that the wide vortex mat has a higher concentration in frequency, but with lower total energy.

The data collected by the force measurement system demonstrate a high amplitude frequency close to 8Hz for high Reynolds number flows can be compared with the vortex drop frequencies. The mechanism was effective in measuring the forces originated by vortex detachments and will allow the development of other studies for comparison and optimization of the system as well as the simultaneous measurement of speeds with hot wire anemometry.

5. ACKNOWLEDGMENTS

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