ANALYSIS OF THE FREE END FLOW ON THE BISTABILITY PHENOMENON AFTER TWO SIDE BY SIDE FINITE CYLINDER WITH MID ASPECT RATIO

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Abstract. *For the purpose of studying the impact of three-dimensional flow on the bistable flow, several flow visualization experiments were conducted around a cylinder with a finite height. The free ends of the cylinder induced a three-dimensional flow which influenced the flow pattern along the height of the cylinder. The bistable phenomenon, in which the flow forms two wakes behind the cylinders (a large wake behind one cylinder and a narrow wake after the other), can occur in circular cylinders placed side by side, and is relevant in many practical engineering situations. This phenomenon results in a flip-flopping wake with a polarized flow that changes at irregular intervals. This can lead to additional sources of dynamic instabilities in the flow. However, the bistable phenomenon in finite cylinders is still not fully understood. In some cases where the bistable phenomenon can occur in infinite cylinders, it may not occur in finite cylinders due to downwash flow from the free end. To address this issue, an experimental study was conducted in a wind tunnel using hot wire anemometry techniques to analyze the flow around circular finite cylinders with a diameter of 0.032 m arranged side by side with aspect ratio 4 and spacing ratio p/d = 1.26. Then, an experimental study with dry ice in a wind tunnel were used to visualize the flow around circular finite cylinders with the same diameter. The vortex shedding frequency is obtained through the auto spectral density function, using hot wire anemometry. The velocity fluctuations in an aerodynamic channel were measured using the hot wire anemometry technique, and the results were compared with those obtained using the dry ice flow visualization technique. The experimental data from the aerodynamic channel were analyzed using statistical tools, spectral and wavelet analysis. The results of the experiment confirmed the occurrence of the bistable phenomenon at the free end in the configuration of finite cylinders with aspect ratio 4.*

Keywords: turbulent flow; hot-wire anemometry; aspect ratio.

1. INTRODUCTION

Recent attention has been focused on the study of finite circular cylinders due to their widespread use in various structures worldwide. Many tall buildings can be simplified as finite cylinders with a free end (Park and Lee, 2000). Unlike infinite cylinders, finite cylinders exhibit distinct characteristics, and the presence of a free end is a significant factor. The flow around a finite cylinder is more complex compared to that around an infinite cylinder, primarily due to the presence of longitudinal vortices and the relatively small aspect ratio of the cylinder's height (h) to its diameter (d) (Park and Lee, 2003).

The bistable phenomenon is a common occurrence when two circular cylinders are placed side-by-side and subjected to turbulent cross-flow. In the literature, bistability refers to the intermittent change in flow mode between the cylinders at irregular time intervals, accompanied by a floppy and random behavior of the gap flow. This phenomenon is considered an intrinsic property of the flow, independent of the Reynolds number, and unrelated to misalignments between the cylinders or any other external influences.

1.1 The Bistable Phenomenon

Sumner et al. (1999) suggest that when two circular cylinders of the same diameter (d) are placed side-by-side, the cross steady flow exhibits different wake modes depending on the distance between the cylinder centers (p). When the pitch ratio falls within the range of 1.2 < p/d < 2.2, the flow forms two distinct wakes behind the cylinders: a larger wake behind one cylinder and a narrow near wake behind the other (Figure 1). These wakes give rise to two dominant frequency vortex shedding phenomena: one associated with the narrower wake and the other with the wider wake. The flow passing through the gap is diverted towards the narrower wake.

Furthermore, according to Sumner et al. (2004), in the case of finite cylinders, the flow around the free end of the cylinder may suppress the Kármán vortex shedding process. Instead, arch vortices can form in the near-wake region, interfering with the bistable flow phenomenon.
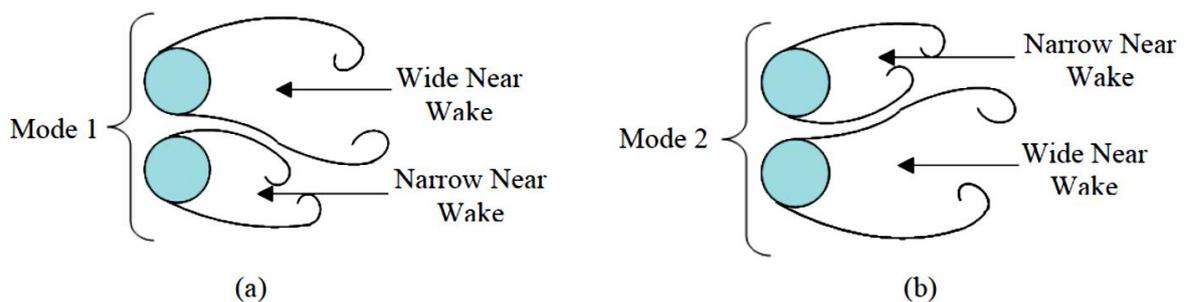

Figure 1. Bistability scheme for (a) mode 1 and (b) mode 2.

In their study, Alam et al. (2003) investigated the flow around two circular cylinders of equal diameter arranged side-by-side in the transverse direction, focusing on the subcritical regime with a Reynolds number of 5.5 x 10^4. The authors noted that the forces exerted on the cylinders were insensitive to changes in Reynolds number within this regime. They also observed different flow modes in the wake vortices.

Alam and Zhou (2007) identified four distinct flow modes in the cross-flow around two cylinders placed side-by-side, specifically for small pitch ratios ranging from 1.1 < p/d < 1.2. For this study, the authors used a Reynolds number of 4.7×10^4.

Olinto et al. (2009) examined the bistable phenomenon in the flow around two cylinders arranged side-by-side in an aerodynamic channel. Their study, conducted at a Reynolds number of 3 x 10^4, revealed a strong presence of bistability in measurements near the cylinders (up to x/d = 0.93), where "x" represents the distance from the probe to the center of the cylinders. However, for greater distance ratios, the bistable pattern was not observed.

De Paula (2008) observed multiple velocity changes throughout the entire data acquisition period in their study on the presence of the bistable phenomenon in two tubes. They investigated pitch ratios of p/d = 1.26 and 1.6, and Reynolds number ranges of 1.85×10^4 to 2.98×10^4.

In this paper, wind tunnel experiments were conducted to study the bistable flow at the free end in two finite cylinders arranged side-by-side. The cylinders had a diameter of 32 mm and aspect ratios (AR) 4. The experiments were performed at a constant Reynolds number of 2.5×10^4.

2. METHODOLOGY

In order to investigate the flow characteristics at the free end of a finite circular cylinder, velocity measurements were conducted using a DANTEC StreamLine hot wire anemometer in an aerodynamic channel. The experimental setup, as illustrated in Figure 2, consisted of a test apparatus with a height of 147 mm, width of 194 mm, and a total area of 28518 mm². The working fluid was air at room temperature, propelled by a 0.75 kW centrifugal fan. The airflow passed through a diffuser, a series of honeycombs, and screens to reduce turbulence intensity in the channel to approximately 1%. The fan speed was controlled by a frequency inverter, allowing for variable flow velocities in the aerodynamic channel ranging from 0 to 15 m/s. A Pitot tube placed before the test section was used as a velocity reference.

The cylinders utilized in the experiment had a diameter of 32 mm and were rigidly mounted in a vertical position inside the channel. The pitch ratio was set at p/d = 1.26, and the Reynolds number for the experiment was Re = 2.5×10^4.

To measure velocity and velocity fluctuations, two single hot wire probes were positioned in the wake region, specifically at a location 10 mm downstream of the cylinder, as depicted in Figures 2(b) and 2(c).

Data acquisition was performed using a 16-bit A/D-board (NATIONAL INSTRUMENTS 9215-A) with a USB interface and DANTEC StreamWare 3.4 software. The sampling frequency was set to 1000 Hz, and a low pass filter at 300 Hz was applied.
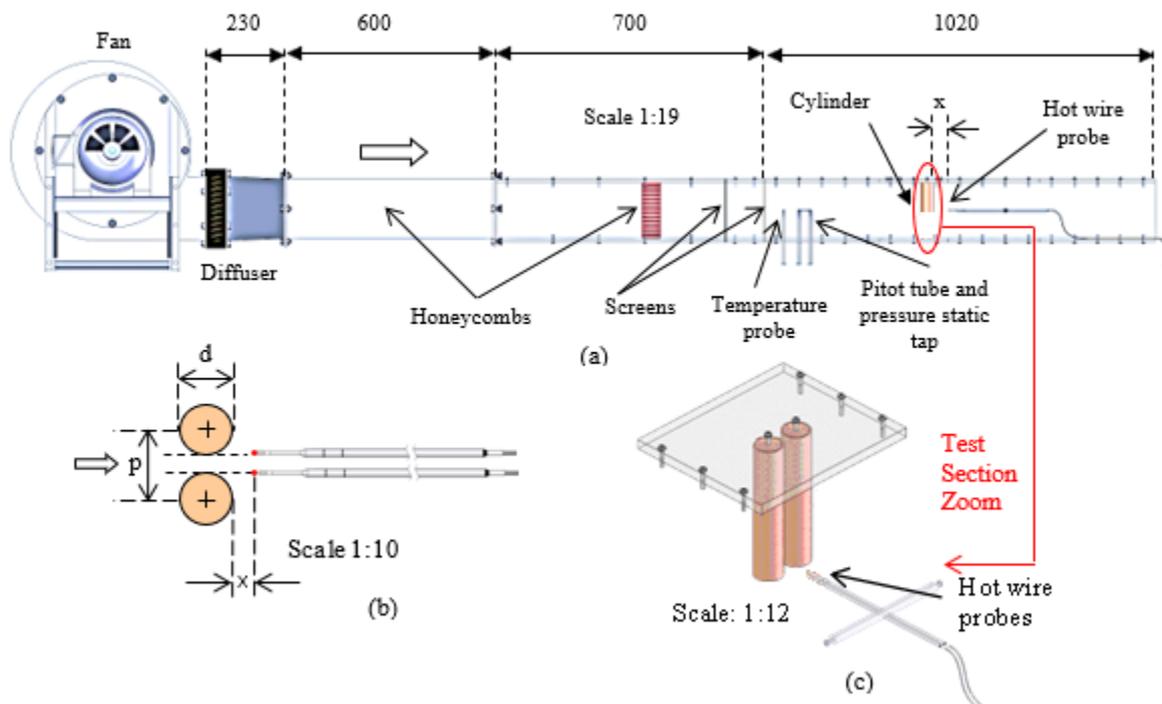
Figure 2. Schematic view: (a) the aerodynamic channel, (b) probes positions and (c) test section (measures in mm).

In the flow visualization technique, Figure 3, dry ice was used in combination with a laser, in order to verify the existence or not of the bistability phenomenon in finite cylinders arranged side by side at the free end. The study consisted of adding a 5 mW laser light source through a laser diode with a wavelength of 532 nm, emitting a beam with a thickness of about 3 mm, where through a optical system, this beam is enlarged in a conical shape completely illuminating the test section in the wind tunnel strictly capturing dry ice in a flat way, as the flow is stabilized by hives. In this way, the dispersion particles of the mixture of dry ice and water were visualized, and the images recorded by a video camera.
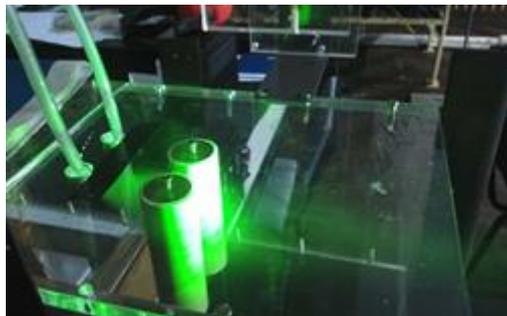

Figure 3. Flow visualization technique.

3. MATHEMATICAL TOOLS

The analysis of the experimental time series results was carried out using Fourier and Wavelet techniques. The computations for Fourier transform and wavelet transform were conducted using Matlab R2012a software. Continuous wavelet transforms were utilized in this study. The mathematical analysis was performed using toolboxes specifically designed for signals, statistical, spectral, and wavelet analysis.

3.1 Fourier and Wavelets Transforms

In this study, the analysis was conducted using Fourier transform and Fourier spectrum to perform a frequency domain analysis. The power spectral density function (PSD) was utilized for spectral (or frequency domain) analysis. Fourier transform employs trigonometric functions as the basis for analysis, while wavelet transforms utilize wavelet functions as the basis. These wavelet functions are characterized by finite energy and zero average, and they generate a set of wavelet bases.

The wavelet spectrum provides information about the energy distribution of a signal across both time and scale (or frequency) domains, as described by Daubechies (1992). This characteristic allows for the representation of energy distribution in the signal, known as a spectrogram, which illustrates the signal's behavior over time and frequency.

For the analysis of velocity signals in this study, wavelet transforms were employed to obtain the energy distribution of turbulent flow in the time-frequency domain. The Continuous Wavelet Spectrum (CWS) was obtained through the continuous wavelet transform.

4. RESULTS

In this study, the free end flow around two finite cylinders placed side-by-side was analyzed. The cylinders had a diameter of 32 mm, and the pitch ratio (p/d) was set at 1.26. The term "p" represents the distance between the centers of the two cylinders, and "d" represents the diameter of the cylinders. The height of the finite cylinders is related on the aspect ratio (AR), where AR=4 corresponded to a height of of 128 mm.

The figures presented in the study include the original data signal and the Wavelet analysis for the configuration examined. The flow visualization allows verifying the behavior of the flow from the free end to the base of the finite cylinder. The original data signal allows for the identification of the bistable phenomenon through the observation of minimal changes. The Discrete Wavelet Analysis (DWA) enables the detection and quantification of these changes. The Continuous Wavelet Spectrum (CWS) reveals the concentration of energy and serves to confirm the presence or absence of the bistable phenomenon.

4.1 Experimental study with dry ice in a wind tunnel

The bistable phenomenon was identified at finite cylinders placed side-by-side. The visualizations were carried out for a fixed Reynolds number of 2.50×10^4. With the methodology used in the visualizations, through the footage analysis it is not possible to count each exchange between the flow modes due to the flow velocity and the videos recording speed. However, it is possible to observe at the images sequence in Figure 4, the formation of a narrow wake behind the upper cylinder and a wide wake behind the other cylinder. After a few moments of time, the flow starts the mode change process, where the wake in the two cylinders appears to be the same, until the previous pattern changes and the mode change occurs, that is, the cylinder that presented the wide wake now has a narrow wake and vice versa. For this spacing ratio, during the entire duration of the film, which is 2 minutes, several changes between the flow modes are observed.
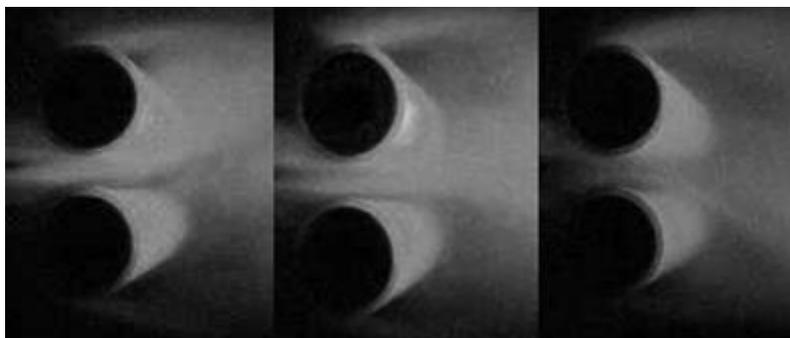

Figure4. Flow visualization technique demonstrating bistable phenomenon.

If we analyze the free end of finite cylinders arranged side by side, the bistability phenomenon is also identified, but with other phenomena involved. According to the images sequence in Figure 5, it can be seen that there is a tendency for a downward flow to occur and this flow goes quickly towards the base without encountering resistance, because according to Adaramola et al., 2006, there may be a possible absence of the structures of vortices at the base, thus favoring the downward flow and consequently not interfering with the bistable flow even at the top of the cylinder.

When the vortex wake opens in one of the finite cylinders, the flow at the free end becomes a downward flow and thus follows towards the base of the finite cylinder forming horseshoe vortices, which alternate between the cylinders causing recirculation of vortices at the base.

In the images sequence in Figure 6, it can be seen that after recirculation at the base of the finite cylinders, there is an upward flow towards the free end. This phenomenon occurs while the wake of one of the cylinders is wider. As the wake changes between the cylinders, the rising and falling phenomena also alternate between the cylinders, depending on the opening of the vortices in each cylinder.

In this study it was not verified that the bistability between the finite cylinders is influenced by the ascending and descending phenomena, however the opening of one of the wakes allows these phenomena to occur in each cylinder.

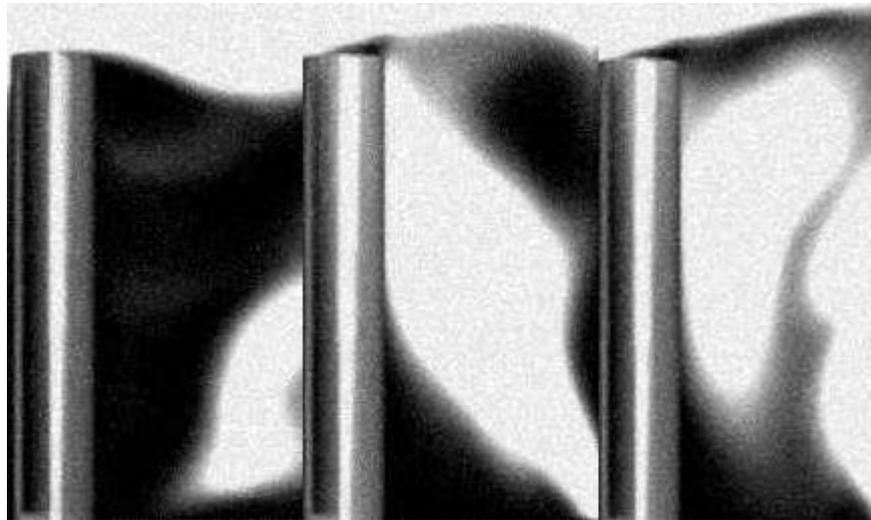Figure 5. Flow visualization technique demonstrating downward flow.

Figure 6. Flow visualization technique demonstrating upward flow.

4.2 Analysis of the free end flow

The bistable phenomenon was identified at the free end of finite cylinders. Figure 7 shows the original data signal of probe 1, where the bistability is clearing seen in the signal of probe where several changes of mode are observed. Figure 7a shows reconstructions of the signals processed by Discrete Wavelet Analysis for probe 1 where it is possible to quantify the changes of mode. For this aspect ratio, there is little influence of the free end, so the downward flow does not significantly interfere with mode changes. The energy distribution of the velocity signals is displayed in spectrograms made from the Continuous Wavelet Transform, Fig. 7b. The energy is minimal in almost all the period, keeping the bistable flow. The signal analyzed showed the changes of mode, characterizing the bistable phenomenon were regions that concentrate more energy are related to higher velocities. Consequently, lower velocities are associated with regions whose energy is lower. The Wavelet function Db20 level 9 was used, with frequencies between 0 and 2.93 Hz.
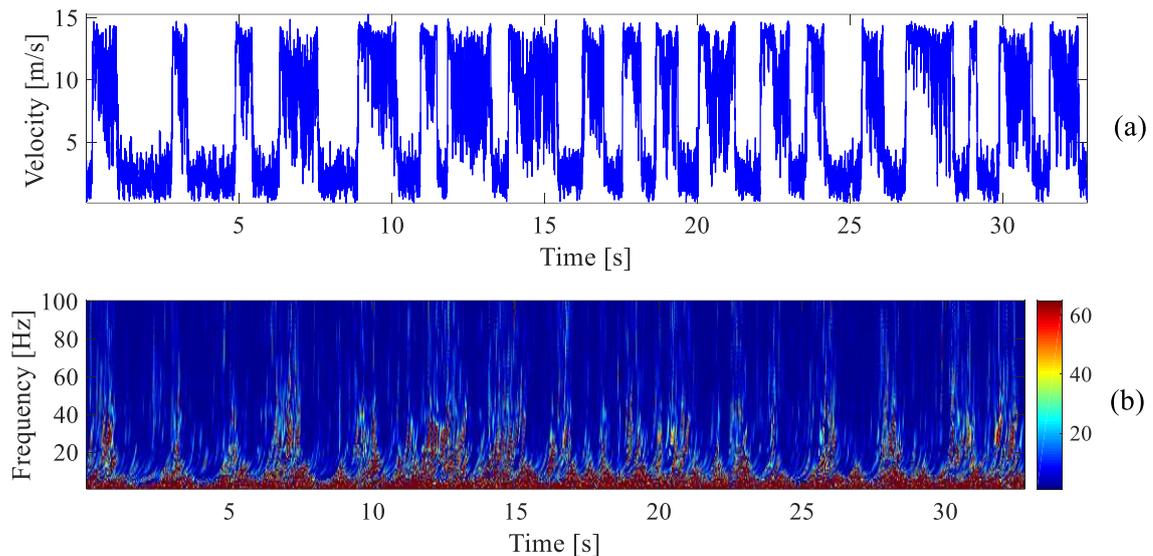
(a)

(b)

Figure 7. Reconstructions of the signals processed by Discrete Wavelet Analysis (a) and spectrograms made from the Continuous Wavelet Transform (b).

5. CONCLUSION

This paper focuses on analysis of the free end flow on the bistability phenomenon after two side by side finite cylinder with mid aspect ratio exposed to turbulent flow. The cylinders have a diameter of 32 mm and aspect ratios of AR = 4, and they were tested under a constant Reynolds number of 2.5 x 10^4. Visualization flow technique were used withe dry ice to verify the behavior of the flow at the free end of finte cylinders. Velocity fluctuation measurements in the aerodynamic channel were performed using hot wire anemometry, and the obtained results were filtered using wavelet transform.

The bistability phenomenon was observed at the free end of the studied finite cylinders. When one of the wakes is wider, the recirculation from the top of the finite cylinders is taken to the base through a downward flow, not interfering with the bistability between the finite cylinders. At the base of the finite cylinders, horseshoe vortices are formed, and a recirculation tends to return to the top of the cylinders through an upward flow. This phenomenon occurs while the wide wake is formed in one of the cylinders. When the wide wake occurs in the adjacent cylinder, the downward and upward flow also alternate for this cylinder with the wide wake.

The analysis reveals that there is no influence of the free end on the phenomenon of bistability in finite cylinders with aspect ratio 4. In this case, rapid mode changes occur at the free end indicating a downward and upward flow while the bistability phenomenon occurs in the extension of the finite cylinder.

6. ACKNOWLEDGEMENTS

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