ANALYSIS OF THE BISTABLE FLOWS IN TWO SIDE BY SIDE FINITE CYLINDERS WITH MID ASPECT RATIO

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Abstract. *The bistable flow on circular cylinders placed side-by-side presents occurs depending on distance between the cylinders. In addition to the occurrence of the bistable phenomenon, in finite cylinder there is interference in the bistable flow due to the downwash flow of the free end. Thus, this paper presents an experimental study about the bistable phenomenon in two side-by-side finite cylinders with aspect ratio AR=3 and 4. The cylinders have 32 mm diameter and the Reynolds number of this experiment is 25000 constant. The experimental study consists of measuring velocity fluctuations in aerodynamic channel using the hot-wire anemometry technique. Experimental data from the aerodynamic channel are treated with the use of statistical tools, spectral and wavelet analysis. Results confirm the occurrence of the bistable phenomenon in finite cylinders. For high aspect ratio, there is a greater influence of the free end in the bistable flow because the downwash flow is increased.*

Keywords: *turbulent flow; hot-wire anemometry; bistability; finite cylinder.*

1. INTRODUCTION

The study with finite circular cylinder has recently attracted greater attention due several structures in the world use cylinders in its composition and many tall buildings can be simplified as a finite cylinder with a free end (Park and Lee, 2000). The finite cylinder has different characteristics from the infinite cylinder and the free end of a finite cylinder is a significant factor. The flow around the finite cylinder is more complicated compared to the case of the infinite cylinder and the main cause for the flow three dimensionality is the presence of longitudinal vortices and small aspect ratio of cylinder height *H* to diameter *D* (Park and Lee, 2003).

The bistable phenomenon is a typical phenomenon that occurring when two circular cylinders placed side-by-size are submitted to a turbulent cross-flow. In the literature, bistability is the phenomenon where a floppy and random behavior of the gap flow changes intermittently the flow mode, from one cylinder to other at irregular time intervals. This phenomenon is considered an intrinsic property of the flow, it is independent of Reynolds number, and it is not related to misalignments between the cylinders or any other external influence.

1.1 The Bistable Phenomenon

According to Sumner *et al.* (1999), the cross steady flow through circular cylinders of same diameter (d) placed side-by-side presents a wake with different modes depending on distance between the centers of the cylinders (p). For intermediate pitch ratios (1.2 < p/d < 2.2) the flow to form two wakes behind the cylinders, a large wake behind a cylinder and a narrow belt after another, Figure. 1. The presence of these wakes make two dominant frequency vortex shedding are derived: one related to the higher narrow wake, and another is associated with lower wide wake. The flow passing through the slit is deviated toward the wake narrower. Furthermore, for Sumner *et al.* (2004) in finite cylinders, the flow around the free end may suppress the Kármán vortex shedding process, and arch vortices may form in the near-wake interfering with the bistable flow.

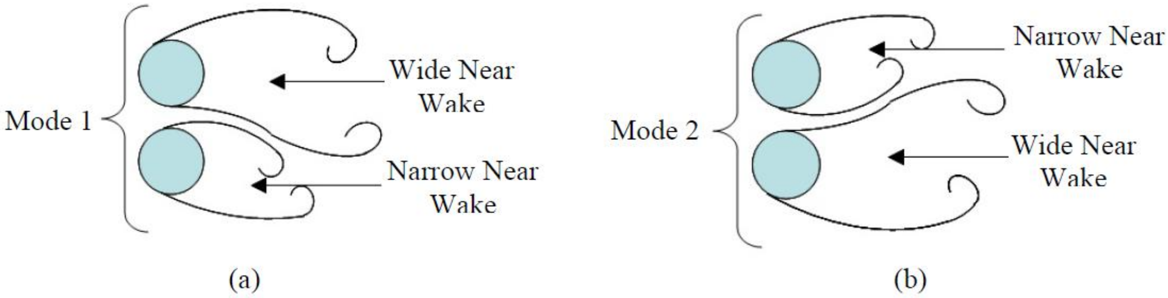


Figure 1. Bistability scheme for (a) mode 1 and (b) mode 2.

Alam *et al.* (2003) studied the flow around two circular cylinders of equal diameter, arranged side-by-side in the transverse direction of the flow and these studies were developed using the Reynolds number in the subcritical regime, 5.5 x 10^4. According to the authors, the forces exerted on the body are insensitive against variations of Reynolds number in this regime. Furthermore, the studies shows that the wake vortices have different modes of flow.

Alam e Zhou (2007) identified four distinct flow modes in the flow around two cylinders placed side-by-side on the cross-flow, for small pitch ratios ($1.1 < p/d < 1.2$), with a Reynolds number of 4.7 x 10^4.

Olinto *et al.* (2009) studied the bistable phenomenon in flow in aerodynamic channel on two cylinders arranged side-by-side, with Re = 3 x 10^4. The author found the strong presence of bistability in measurements near to the cylinders (until x/d = 0.93), where "x" is the distance of the probe to the center of the cylinders. For a greater ratio distance did not identify the bistable standard.

De Paula (2008) found several changes of velocity were observed during the entire period of data acquisition. The author studied the presence of the bistable phenomenon for two tubes, for pitch ratios p/d = 1.26 and 1.6, and Reynolds number range of 1.85 x 10^4 and 2.98 x 10^4.

In this paper, wind tunnel experiments were conducted to study of the bistable flow in two side-by-side finite cylinders. The cylinders have a diameter of 32 mm with aspect ratios *AR* =3 and 4 and it were tested at a Reynolds number of 25000 constant.

2. METHODOLOGY

Velocity measurements were made with DANTEC StreamLine hot wire anemometer in an aerodynamic channel to investigate the flow along the height of the finite circular cylinder. The test apparatus, shown on Fig. 2, with 147 mm height, width of 194 mm an total area of 28518 mm². Air, at room temperature, is the working fluid, driven by a centrifugal fan of 0.75 kW, passed by a diffuser and a set of honeycombs and screens, which reduce the turbulence intensity in the channel to about 1%. A frequency inverter controls the fan speed, where the flow velocity in the aerodynamic channel can be varied from 0 to 15 m/s. To measure the velocity reference a Pitot tube fixed before to the test section is used.

The cylinders have a diameter of 32 mm and are rigidly mounted in vertical position inside the channel. The pitch ratio p/d=1.26 and the experiment was performed with a Reynolds number *Re* = 2.5 x 10^4.

For the measurement of velocity and velocity fluctuations, two single hot wire probes were placed at the wake region in a location x=10mm downstream of the cylinder as shown in Figure 2(b) and 2(c).

Data acquisition was performed with a 16-bit A/D-board (NATIONAL INSTRUMENTS 9215-A) with USB interface through software DANTEC StreamWare 3.4 , with a sampling frequency of 1000 Hz and a low pass filter at 300 Hz.

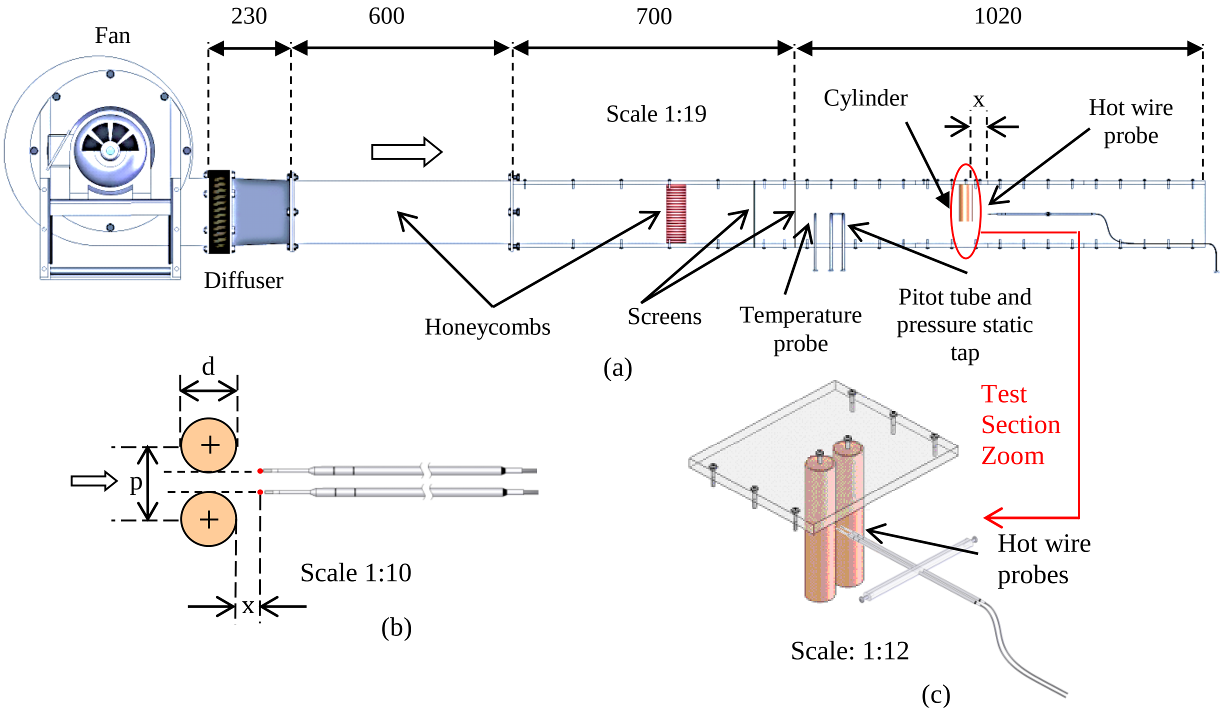


Figure 2. Schematic view: (a) the aerodynamic channel, (b) probes positions and (c) test section (measures in mm).

3. MATHEMATICAL TOOLS

Analysis of the results of time series obtained from the experiment was performed by means of Fourier and Wavelet techniques. Computations of the Fourier transform and wavelet transform were performed using the Matlab R2012a software. Continuous wavelet transforms are used in this study. The mathematical analysis was made with using the toolboxes for the signals, statistical, spectral and wavelet analysis.

3.1 Fourier and Wavelets Transforms

In this paper, the analysis was made by Fourier transform and the Fourier spectrum, with the aim of obtaining a frequency domain analysis. The spectral (or frequency domain) analysis can be done through the power spectral density function (PSD). While the Fourier transform uses trigonometric functions as basis, the bases of wavelet transforms are functions named wavelets, with finite energy and zero average that generates a set of wavelet basis.

In the wavelet spectrum, the energy is related to each time and scale (or frequency), Daubechies (1992). This characteristic allows the representation of the distribution of the energy of the signal over time and frequency domains, called spectrogram.

The velocity signals were analyzed using wavelet transforms to obtain the energy distribution of the turbulent flow over time-frequency domain. The Continuous Wavelet Spectrum (CWS) was obtained through continuous wavelet transform.

4. RESULTS

In this study the flow for two finite cylinders side-by-side, 32 mm diameter, pitch ratio p/d = 1.26 was analyzed. "p" is the distance between the centers of two cylinders and “d” is the diameter. The height of the finite cylinder is related to aspect ratio, so for *AR* =3 the height is equal to 96 mm and *AR*=4 the height is equal to 128 mm. In the figures, original data signal and Wavelet analysis are presented for all configurations studied. Through the original data signal, it is possible to identify the bistable phenomenon when there are few changes. Through the Discrete Wavelet Analysis (DWA), it is possible to identify changes and quantify them and through the Continuous Wavelet Spectrum (CWS), it is possible to observe the concentration of energy and it is to confirm the existence or not of the phenomenon.

4.1 Results for *AR*=3

For this aspect ratio, the bistable phenomenon were identified in the finite cylinders. Figure 3 shows the original data signal of probe 1 and 2, where the bistability is clearing seen in the signals of probes that changes of mode are observed. In this case, four changes of mode occurred in the flow. Figure 4a 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 less influences the free end, therefore the downwash flow is weak and it does not interfere significantly with the changes of mode. The energy distribution of the velocity signals are displayed in spectrograms made from the Continuous Wavelet Transform, Fig. 4b. 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.

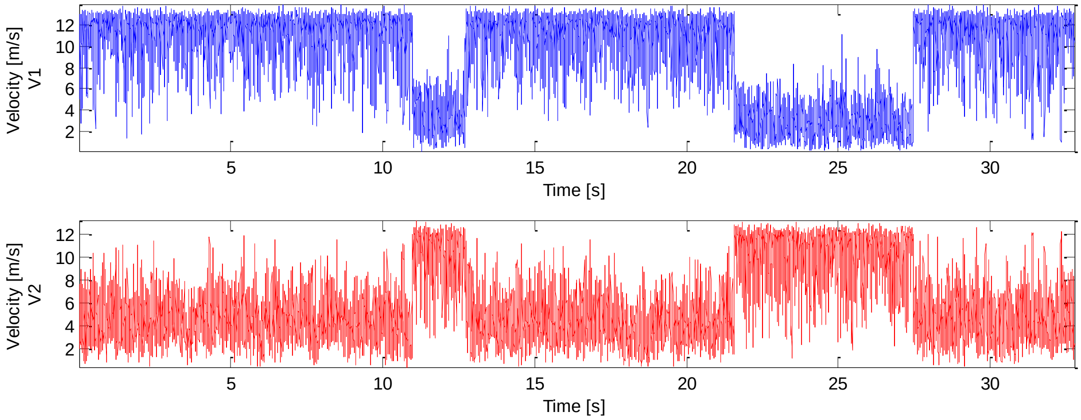


Figure 3. Signal Velocities for finite cylinders with Aspect Ratio=3 and Re = 2.5 x 10^4.
Probe 1 – V1, Probe 2 – V2.

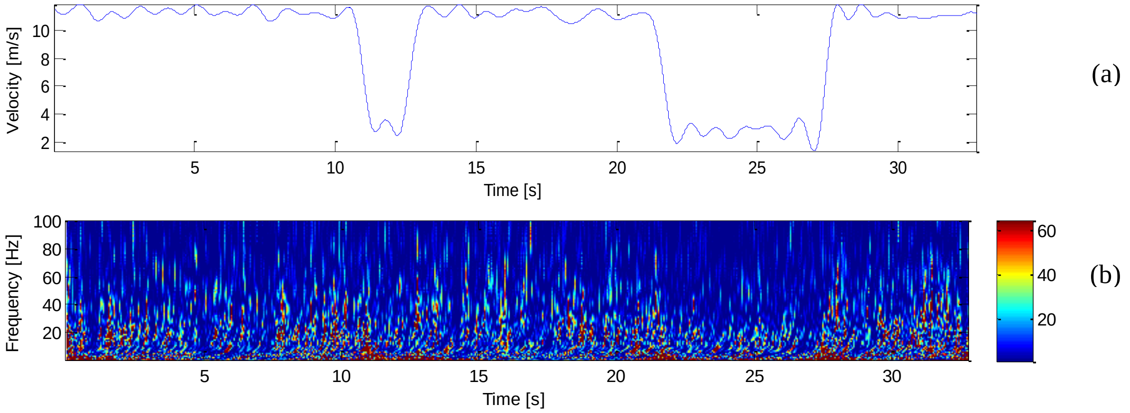


Figure 4. Reconstruction for signals and spectrograms of finite cylinders with Aspect Ratio=3 and Re = 2.5 x 10^4 Probe 1 – V1.

4.2 Results for *AR*=4

For a higher aspect ratio, the bistable phenomenon also were identified in the finite cylinders, but the changes of mode were increased. In Fig. 5 the original data signal of probe 1 and 2 shows that occurs the bistability because changes of mode are observed. Figure 6a shows reconstructions of the signals processed by Discrete Wavelet Analysis for probe 1 where it is possible to observe that have occurred 16 changes of mode in the flow.

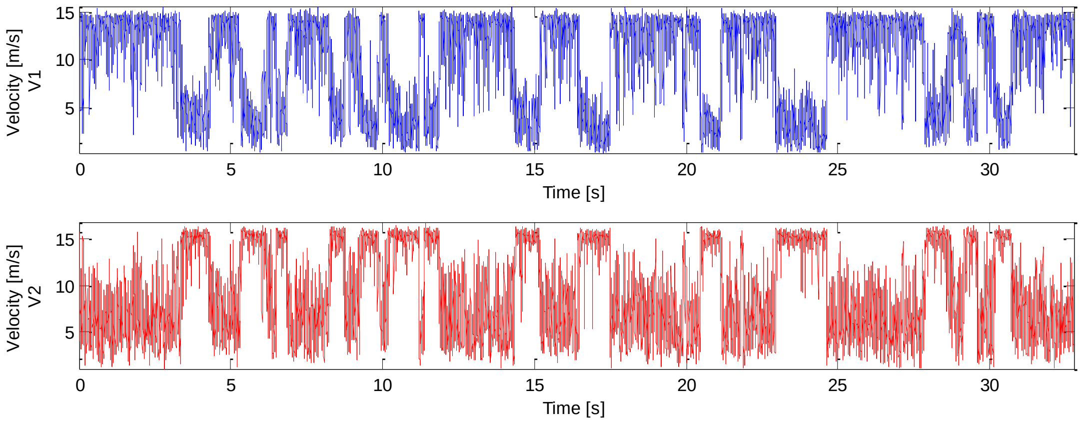


Figure 5. Signal Velocities for finite cylinders with Aspect Ratio=4 and Re = 2.5 x 10^4. Probe 1 – V1, Probe 2 – V2.

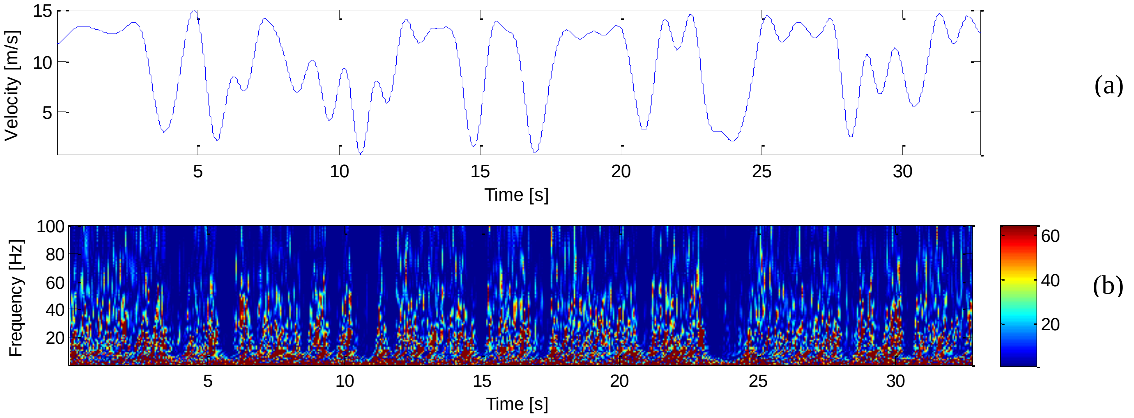


Figure 6. Reconstruction for signals and spectrograms of finite cylinders with Aspect Ratio=4 and Re = 2.5 x 10^4 Probe 1 – V1.

Figure 6b shows the energy distribution of the velocity signals through spectrograms made from the Continuous Wavelet Transform. Through this analysis, it appears that the behavior is similar for an infinite cylinder, but as the height of the cylinder is equal to 128 mm, relatively close to the top of the aerodynamic channel, there is high influence of the free end in the bistable flow. In this case, the downwash flow is strong and it descends in greater velocity. It causes a recirculation region that affects the bistable flow between the cylinders. The crossflow affect change of mode, and the length of time between modes as seen between 8 and 12 seconds. Thus, the bistable flow has quick-change of mode and consequently less time in each mode.

4.3 Comparing the Aspect Ratios

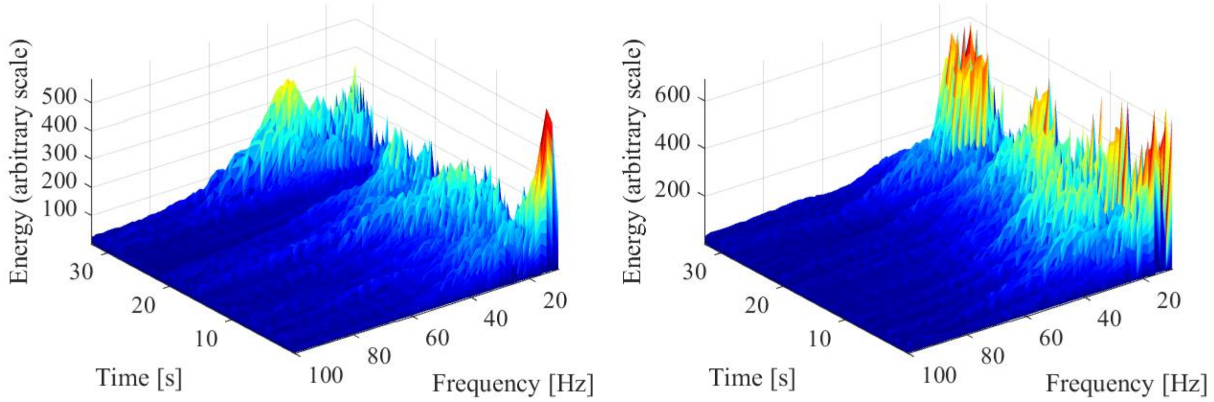
The measurements were performed at the mid height of the cylinders, where may occur influences the free end depending on the aspect ratio, more visible in the spectrograms. Fig. 6b compared to Fig. 4b shows the influences the free end due to high aspect ratio. In the figures, the signals analyzed showed the change of mode, characterizing the bistable phenomenon, but in Fig. 6b the bistability is more visible, due to the high energy in the period. The experimental data indicates that the flow between two finite circular cylinders is more complicated compared to infinite cylinder.

Javadi and Kinai (2014) analyzed and identified numerically the presence a downwash flow above the free end into the near wake region. Park and Lee (2000) reported that the downwash flow are caused by the counter-rotating vortices that interacts with the flow between the cylinders. It causes a recirculation region that affects the bistable flow between the cylinders. The downwash flow becomes stronger with high aspect ratio and this causes increase of changes of mode because the energy is high in the period as shown in Fig. 6b. Due to high energy and energy peaks in the period, the change of mode is fast. The energy increases and decreases several times, indicating difficulty in maintaining one of the modes of bistable flow.

Kawamura *et al.* (1984) also detected the presence of counter-rotating trailing vortices at Re= 3.2×10^4. The authors reported that these vortices originate on the rear surface of the cylinder from a rolling up of the downwash flow over the end.

3D energy analysis shows that the energy is initially concentrated in the first instants of time of the experiment due to the passage of flow between the cylinders. After this energy is low and remains low for the remaining time with fluctuations related to changes of mode. This means that when starting the experiment the energy accumulate quickly, and then partly dissipated in one of the modes. Once again accumulates energy to enable the change of mode. As there is less energy intensity during the experiment, it is clear that the changes of mode are slower (Fig. 7a).

In Fig. 7b, the energy is stronger and distributed throughout the period indicating various changes of mode. By having greater intensity of energy peaks, the changes are faster. As the bistable flow has more influence of the free end it is observed more accumulated energy due to downwash flow.



(a) (b)

Figure 7. Spectrograms 3D of finite cylinders with (a) AR=3 and (b) AR=4 and Re = 2.5×10^4
Probe 1 – V1.

5. CONCLUSION

This paper presents a study of the bistable flow in two side-by-side finite cylinders subjected to turbulent flow. The cylinders diameter is 32 mm with aspect ratios *AR* =3 and 4 and it were tested at a Reynolds number of 25000 constant. Measurements of the velocity fluctuations in the aerodynamic channel were made using the hot wire anemometry technique. The results from hot wires were filtered by means of wavelet transform.

The bistable phenomenon was observed in both cases studied. For finite cylinders with aspect ratio equal to 3, it were possible to observe that have occurred 4 changes of mode in the flow. For finite cylinders with aspect ratio equal to 4, it were possible to observe that have occurred 16 changes of mode in the flow in the same time period.

The analysis shows a high influence of the free end in finite cylinders with aspect ratio equal to 4. In this case, there are quick changes of mode and less time in each mode because the downwash flow becomes stronger and it affects the bistable flow.

For aspect ratio equal to 3 the influence of the free end is smaller because the downwash flow is lower due to the larger spacing between the cylinder and the top of the aerodynamic channel. Thus, there is not significant interference in the bistable flow.

6. ACKNOWLEDGEMENTS

Authors are gratefully indebted to the CNPq National Council for Scientific and Technological Development, for the financial support.

Marcos Woyciekoski thanks CAPES Ministry of Education, Brazil, for granting him a fellowship.

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