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Influence of the geometry of the compound channel in the formation of coherent structures

Jhon N. V. Goulart
Tiago de Melo
Carla T. Anflor
GMEC- Group of Experimental and Computational of Mechanics - University of Brasilia,
PO box 8114, Gama, DF, zip code: 72.405-610, Brazil
E-mail address: jvaz@unb.br, tiago.melomec@gmail.com, anflorgoulart@gmail.com.

Abstract. *Turbulent flow in channels with gap is still a challenge for engineering. The experimental study was performed in a closed compound channel under steady state incompressible air flow. Hot wire probe was employed to measure the time-serie of velocities. Test sections were formed by two parallel plates attached on a side wall of a wind channel, forming a slot with width D and depth P. In this paper 8 test sections were investigated covering P/D-ratio from 3.33 and 5.00, under the same Reynolds number. The main results showed that the dynamical characteristics of the turbulent flow in these structures are not dependent only on P/D-ratio, but the test section's length plays an important role. The Wavelet transform was used for analyzing non-stationary time series, well as PSD (Power Spectro Density Function), in the identification coherent structures in the flow in channel gap.*

Keywords: *Compound Channels, Turbulent Flow, Large Scale Structures, Wavelet Transform.*

1. INTRODUCTION

Compound channels are found in nuclear and process industry, in channels like rod bundles, heat exchangers and coolers of modern electronic devices. This subject has been studied since early 1960s, even though the concept of compound channel has been recently introduced. Compound channels are characterized by the presence of a narrow region of the channel connected to one or more wider regions.

The cross section of a compound channel is formed by a narrow region (gap) connected to a wider one, or, conversely, a narrow region connecting two wider regions. In nuclear reactors, the narrow gap between the rods connects parallel sub-channels. The investigation of the turbulent flow in this channel type show peculiar characteristics in relation to stress distribution and the coefficient of turbulent heat transfer on the region between two channels.

Experimental measurements in a single line rod bundle, showed high values of turbulence intensity for the axial and azimuthal components of velocity in the region of the gap and a strong relationship between the increase in these quantities and decreasing of the distance between the tubes” (Möller, 1991). Fluctuations of the different velocity components showed a quasi-periodic behavior close to gap, exactly as identified previously in Rowe et al. (1974), which suggested that these pulsations of the flow were responsible for the increase in turbulent intensities along the gap. Still, according Rehme 1992, these large-scale structures that cross the cracks are the true source of the increase of the mixing coefficients between the subchannels.

The presence of flow pulsations on very simple geometries is shown in the work of Wu and Trupp, 1993 and Meyer and Rehme, 1994 and 1995. The findings of these studies point to the fact that these instabilities flow could arise on any channel where there was at least one major subchannel connected to a slit and that the mechanisms that give rise to them could be the same that originate pulsations in rod bundles.

Guellouz and Tavolaris, 2000, allege that the formation of these coherent structures in very simple geometries, clearly demonstrates that such structures are not derived asymmetry or any other peculiarity in subchannels, but an inevitable result of instability. Afterwards Goulart et al. (2013) showed, through their results of spectral analysis of the velocity time-traces in a compound channel, that the length of the channel and the width of gap of the slot play an important role on large vortices appearance. At that time the authors concluded that the P/D – ratio is not the only non-dimensional parameter that rules the dynamic of the turbulent flow, and even more, the dynamic of turbulent motion in the slot depends much more on D and L than P/D – ratio itself.

This experimental work was aimed to investigate the dynamic behavior of the turbulent flow in a closed compound channel. The velocities time-series were analyzed through Power Spectral Densities functions – PSD, and Continuous Wavelet Transform – CWT. The main goal is to assess how geometric parameters of the channel are important to large-scale structures formation. The experimental tests were carried out under the same Reynolds number, 7.98×10^4. During the experiments both the gap width and the length of the test section are free to change. The investigation included 2 P/D- ratio, namely 5.00 and 3.33. The dimension P, deepness of the slot, was kept almost constant, while D was raged from 4 and 6 mm. We evaluated results for 04 different test section’s length, 250, 500, 1000 and 1500 mm. The CWT, whose spectrogram provides us the scale-containing energy distribution along the time and frequency, showed us that our phenomenon is prone to unsteadiness and intermittent processes along the time.

2. FOURIER AND TIME-FREQUENCY ANALYSIS

2.1 Fourier Transform

The Fourier Transform of a endless time-serie x(t) enable us to represent the spectral behaviour such temporal serie. Following the eq. 1:

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

where $\hat{X}(f)$ are the Fourier coefficients into the periodic function based on frequencies f.

The power of such signal, splitted into bandwidth, can be evaluated through autospectral density function (PSD). PSD is of a random time-serie is the Fourier coefficients squared (Indusiak et al., 2005). It can be evaluated as Following the eq. 2:

$$P_{xx}(f) = \left| X(f) \right|^2 \tag{2}$$

2.2 Wavelets Transform

The Fourier basis is a set of trigonometric functions which are the results from decomposition of original signal. Such sinusoidal functions deal with only amplitude and the frequency, none information on time is provided according to Bueno et al. (2008). Unlikely Fourier analysis, wavelets transformation is a set of coefficients that arisen from dilatation and translation of a mother wave that must present finite energy and null average (Indusiak et al., 2005, De Paula et al., 2013). The energy is then related to a scale (frequency), *a*, and the translation *b*. The translation provide us some information about the time of a certain amount of energy is (Daubechies, 1992).

One of the ways we can evaluated some signal in time-frequency domain is through the Continuous Wavelets Transform (CWT). The CWT of a f(t) function is given by eq. (3)

$$\tilde{X}(a,b) = \int_t X(t) \psi_{a,b}(t) dt \qquad a,b \in R, a \neq 0 \tag{3}$$

Where $\psi(t)$ are the wavelet functions itself and *a* and *b* are the parameters that deal with scale (frequency) and translation. So, the power of the signal assigned to frequency and time at once can be computed as follow eq. 4:

$$P_{xx}(a,b) = \left| \tilde{X}(a,b) \right|^2 \tag{4}$$

while the scale is associated with the frequency as stated in Abry, 1997, Following the eq. 5.

$$f = \frac{F_\psi . F_S}{a} \tag{5}$$

$F\psi$ is a pseudo-frequency that belongs to the wavelet and is the sampling frequency of the data, 3 KHz for all cases.

3. EXPERIMENTAL FACILITIES

The experimental study was carried out in an aerodynamic two meters long channel with cross-section constant 150 × 200 mm. The working fluid was air at room temperature, driven by a centrifugal blower controlled by a frequency inverter. After passing through a diffuser and a set of honeycombs and screens the flow reaches the test sections. After the screens, a Pitot tube is placed on a fixed position responsible for measuring the reference velocity U_{ref}, during the experiments. The reference velocity was assumed constant for all experiments being set up at 9.40 m/s. The Reynolds number was defined using the bulk velocity, U_{Bulk}, the hydraulic-diameter, D_h and the kinematic viscosity as well. The bulk velocity is given by eq. 6.

$$U_{Bulk} = \frac{1}{A}\int_A u\,dA \tag{6}$$

then, the Reynolds number was 7.98×10^4.

Figure 1 (a), presents a schematic view of wind channel. Inside the channel two metal plates with thickness e = 1.2 mm and L [mm] long were mounted onto a side wall to form a canyon like slot with depth “P” and width “D”. The length L could be increased as the other dimensions as well.

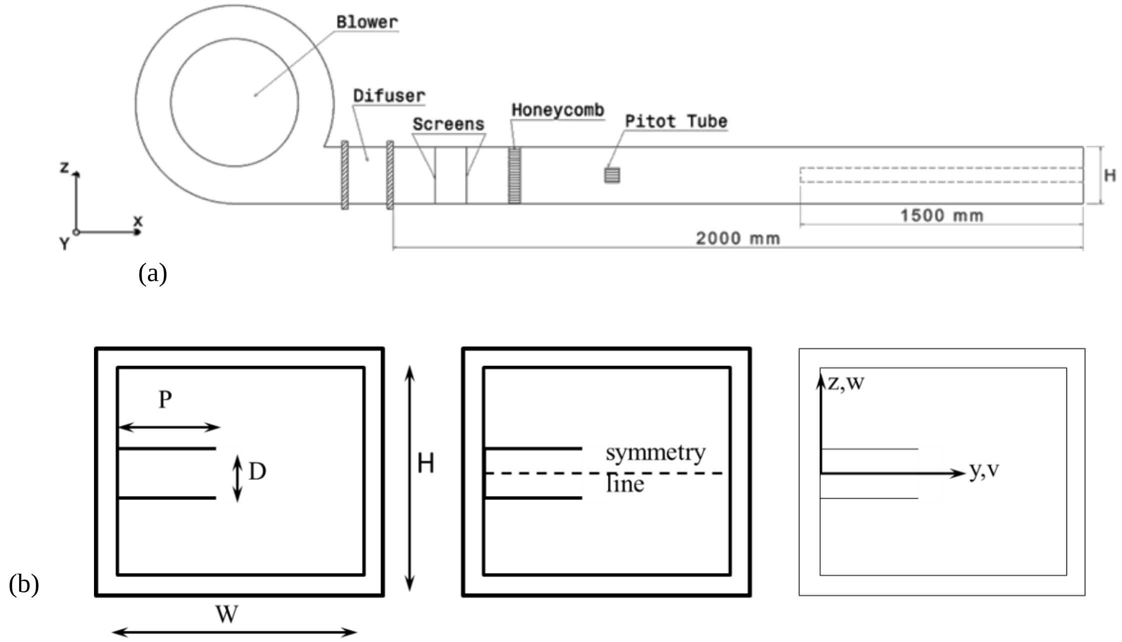


Figure 1. a) Schematic view of the wind channel. (b) cross section of the compound channel, its symmetry line and the axis and their velocity components.

Based on previous works from Meyer (Meyer and Rehme, 1994 and 1995) and Goulart et al., (2013), were adopted 02 different P/D-ratios, 5.00 and 3.33. The slot’s deepness, dimension P, was kept almost constant. To investigate the sensitivity of the turbulent flow patterns related to geometric parameters the slot’s width and length has been changed, producing 8 test sections. All dimensions are stressed on the Table 1. The length of the slot was ranged from 250 mm up to 1500 mm.

Table 1. Test sections configuration

Test Section	**P**	**D**	**L**	**P/D**	**L/P**	**L/D**	**L/D_h**	**Re**
S1	20	4	250	5	12.5	62.5	1.62	$7.98\text{x}10^4$
S2	20	4	500	5	25	125	3.25	$7.98\text{x}10^4$
S3	20	4	1000	5	50	250	6.50	$7.98\text{x}10^4$
S4	20	4	1500	5	75	375	9.75	$7.98\text{x}10^4$
S5	20	6	250	3.33	12.5	62.5	1.62	$7.98\text{x}10^4$
S6	20	6	500	3.33	25	125	3.25	$7.98\text{x}10^4$
S7	20	6	1000	3.33	50	250	6.50	$7.98\text{x}10^4$
S8	20	6	1500	3.33	75	375	9.75	$7.98\text{x}10^4$

Measurements of streamwise velocity and velocity fluctuations were performed by a single hot wire DANTEC Mini-CTA 54T30. Measurements were performed 20 mm before channel’s outlet.

Data acquisition was performed using a 12 bit National Instruments 6023E A/D converter board, with a sampling frequency of 3 KHz and a low pass filter set at 1 KHz. Temporal series were 43.69 s long. For test sections P/D-ratio 5, named S1, S2, S3 and S4, the temporal series were 21.85seconds long. Despite this change low pass filter and sampling frequency were kept constant.

4. RESULTS

4.1 Power Spectral Density Function Analisys - PSD

The high shear flow, that takes place in compound channels, gives rise to the strong vorticity field between slot and main channel (Möller, 1991). The vorticity is basically represented by a turning point in the velocity profile, therefore. Such singularity in the flow introduces disturbances that depending on the flow state rolling vortices, travelling along streamwise direction, may appear. Large eddy structures have been known to cause quasi-periodic flow patterns in the flow. Such periodic behavior can be seen through spectral analysis of the time-traces of velocity fluctuations.

In the Figures 2 and 3, the spectral analyses of streamwise velocity fluctuations were displayed. The spectral functions were computed using 128 blocks of 1024 elements, yielding a bandwidth of 2.93 Hz and a statistical error of 8.83 %.

For the test sections S1, S2, S3 and S4, the auto spectral densities functions stressed in Fig. 2. As the gap width is 4 mm it is possible to gather the velocities time-trace at dimensionless position y/P = 1.00. It can be observed: the absence of periodical patterns in the time-trace velocity for the shortest section and the peaks appearance as the slot becomes longer. The both gap width and length seem to produce different effects in the dynamic behavior of velocity time-trace. The frequency was not remained constant for all tests sections studied and a displacement towards the higher frequency was noticed, starting at 30 Hz. Furthermore, broad peaks are displayed in Figure 2 (b) and (c), suggesting that vortices of different scales (time, velocity and length) are dominating the flow (Rehme, 1992). Such broadness of the peak in the spectrum may indicate an unsteadiness of the phenomenon, and this behavior seems to be ruled by the gap width much more than the slot's length. Surprisingly the broadness of the peak is much more pronounced in test section S3 that is 1000mm long than S2 which length is only 500mm.

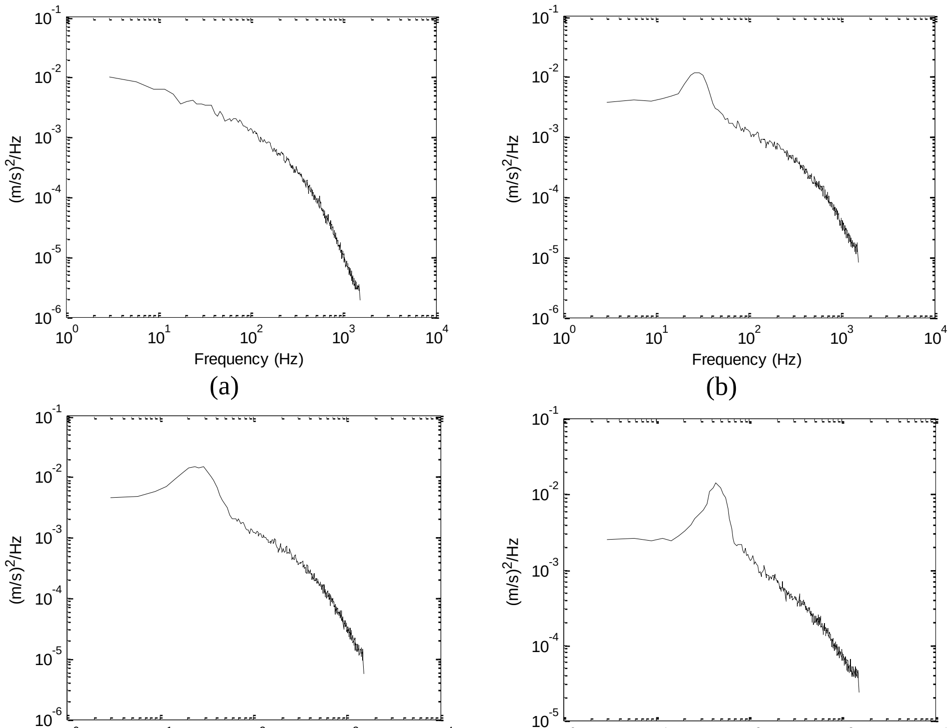


Figure 2. Auto spectral density functions for P/D = 5.00, gap width 4 mm. a) Test section S1, L=250 mm, b) Test section S2, L=500 mm, c) Test section S3, L=1000 mm, d) Test section S4, L=1500 mm.

In Figure 3 the auto spectral analysis is computed for P/D = 3.33. Now the gap is wider than preceding ones, 6 mm, and the role played by the gap is even more evident. Here we can observe that the Fourier analysis was not able to show any trace of periodicity in the time-series of velocity for test section S5 and S6, L= 250 and 500 mm, respectively.

In comparison with tests section S2 which so far have shown quasi-periodic time-traces of velocity the increased of the gap width to 6 mm was enough to die out the sinusoidal characteristic of the velocity time-trace. For test sections S7 and S8 periodic traces were found through spectral analysis, however both sections presented broad peaks in the spectra. In both cases the fundamental frequency takes place at 20 Hz.

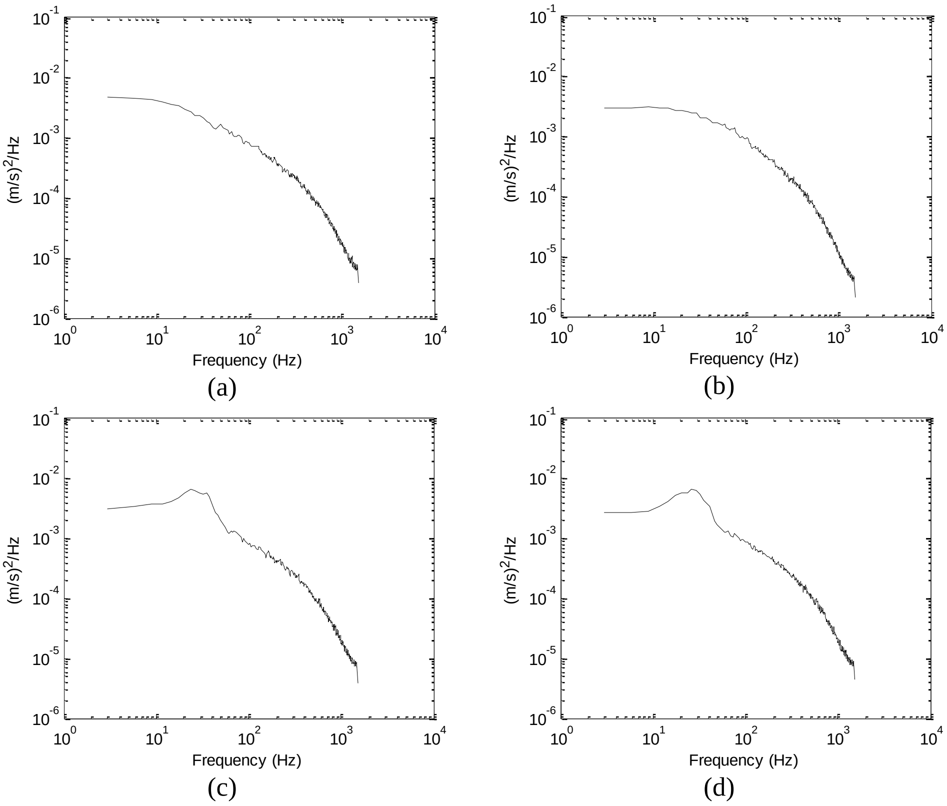


Figure 3. Auto spectral density functions for P/D = 3.33. a) Test section S5, L=250 mm, b) Test section S6, L=500 mm, c) Test section S7, L=1000 mm, d) Test section S8, L=1500 mm.

4.2 Strouhal Number

Meyer and Rehme (1994 and 1995) carried out spectral velocity analysis in several types of compound channels. The papers were aimed to understand the main mechanisms behind the large scale structures formation, further, the authors also tried to connect the main frequency to a velocity and length scale as well. According to Meyer's findings a Strouhal number could be developed by using as length and velocity scales the square root of the product between the deepness, P, and the width of the slot, D, and the edge velocity, U_e, eq.7.

$$Str = \frac{f\sqrt{PD}}{U_e} \tag{7}$$

The edge velocity U_e, is the velocity that takes place at y/P = 1. Despite the good agreement between the correlation and the experimental values, some flaws were detected. Firstly, the Strouhal number was function of channel's shape. The authors also reported that the correlation did not work for deeper slots $P/D \geq 7$. The frequency associated with the phenomena was twice than that predicted by the correlation.

In the present case we are expecting this value ranging 0.08 ± 0.01, based on the Meyer's results (Meyer and Rehme, 1995).

Figure 4 shows the Strouhal number as a function of dimensionless distance L/D_h. The uncertainty associate with the Strouhal number ranged from 3 up to 7 %. In the picture it is possible to identify a clear asymptotic tendency of the Strouhal number to reach the value predicted by Meyer's correlation as L/D_h increases. The Strouhal numbers get closer each other soon after L = 6.50 D_h. Furthermore, the relationship between the hydraulic-diameter and the Strouhal number is even more significant once we have joined local scales coming from small subchannel as $U_e, f, \sqrt{PD}$ and macro scales of the flow such L and D_h.

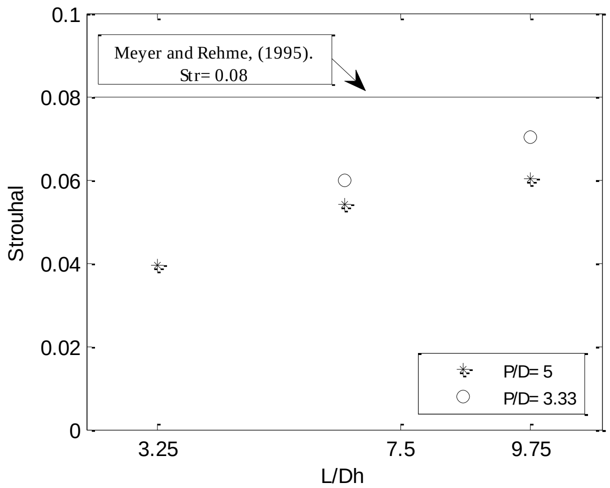


Figure 4. Strouhal number as a function of L/D_h – ratio.

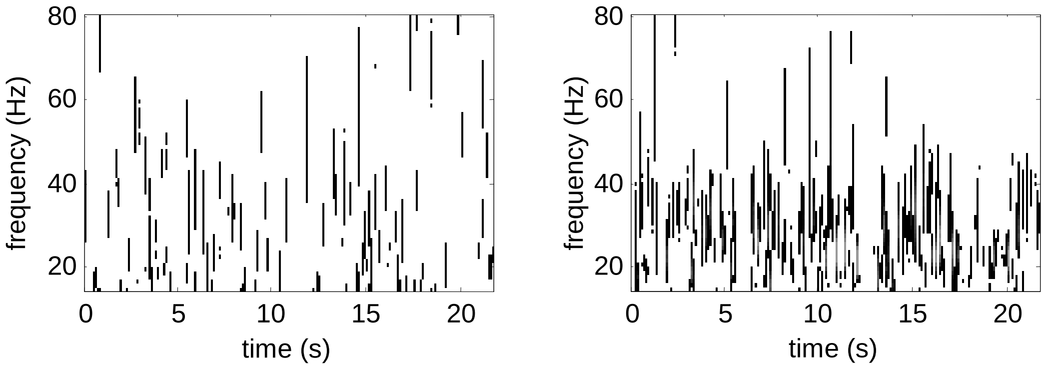
4.3 Continuous Wavelets Transform - CWT

Continuous Wavelet Transform of the signals from all test sections wasere performed and are displayed in Figures 5 and 6. The CWT was calculated using the Morlet wavelet functions. Based on our previous results of the auto spectral density functions we computed CWT transform to comprise a range of frequencies from 5 Hz up to 80 Hz and the bandwidth was 2.93 Hz.

From CWT it is possible to have some insight how the scale-containing energy are distributed along the time. In general form higher frequencies than those marked in the spectra are excited in the turbulent flow, regardless the dimensions of the channel, P, D or L. we filtered the matrix of the wavelet coefficients of the CWT from the test sections. The main goal here is to provide a better visualization on how higher coefficients are distributed in time-frequency space. To attain such goal we need setting a threshold, below that the coefficient will be zero. We made some attempts to find out the best threshold and we chose the standard deviation of the wavelet coefficients for each time.

For narrower peaks, as shown in Fig. 5 (a) test section S1, the bandwidth of scale-containing energy is marrow and comprises frequencies from 20 up to 40 Hz. However, some excursions can be seen towards upper levels of this range. The same path is stressed for CWT applied to test sections S3, S4, S7 and S7. The energy contained in different scales seems to wander around different frequencies as the time passes, indicating that the broadness of the peak in the spectrum is most likely caused by unsteadiness of the phenomenon. This fact implies that the PSD might not be the safest spectral analysis tool to assess the frequencies of large vortices found in compound channels. Furthermore, the intermittent events can be straightforward observed through CWT plots. In Figures 5 (c), (d) and 6 (c), (d), test sections S4 and S8, it is noteworthy the changes occurred in the wavelets coefficients along the time. In the former case (S4) some disrupt in the coefficients seems to take place at 8 and 18 seconds evidencing a short intermittence.

However, in In the second case, test section S8, lower energy picture is even more marked. The wavelet coefficients can be observed nearly 5s, when the strongest intermittency seems to occur. After this time the highest coefficients are seen to wander between 30 and 40 Hz along the time.



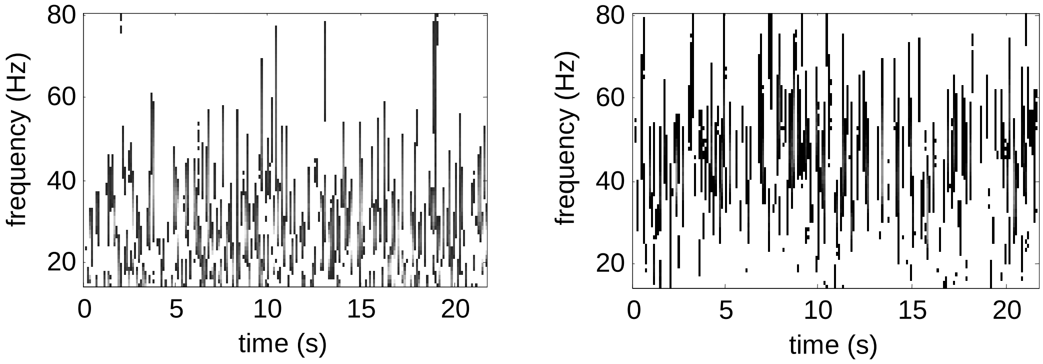


Figure 5. Filtered wavelets coefficients for test different test sections: a) test sections S1 b) test sections S2. c) test sections S3 d) test sections S4.

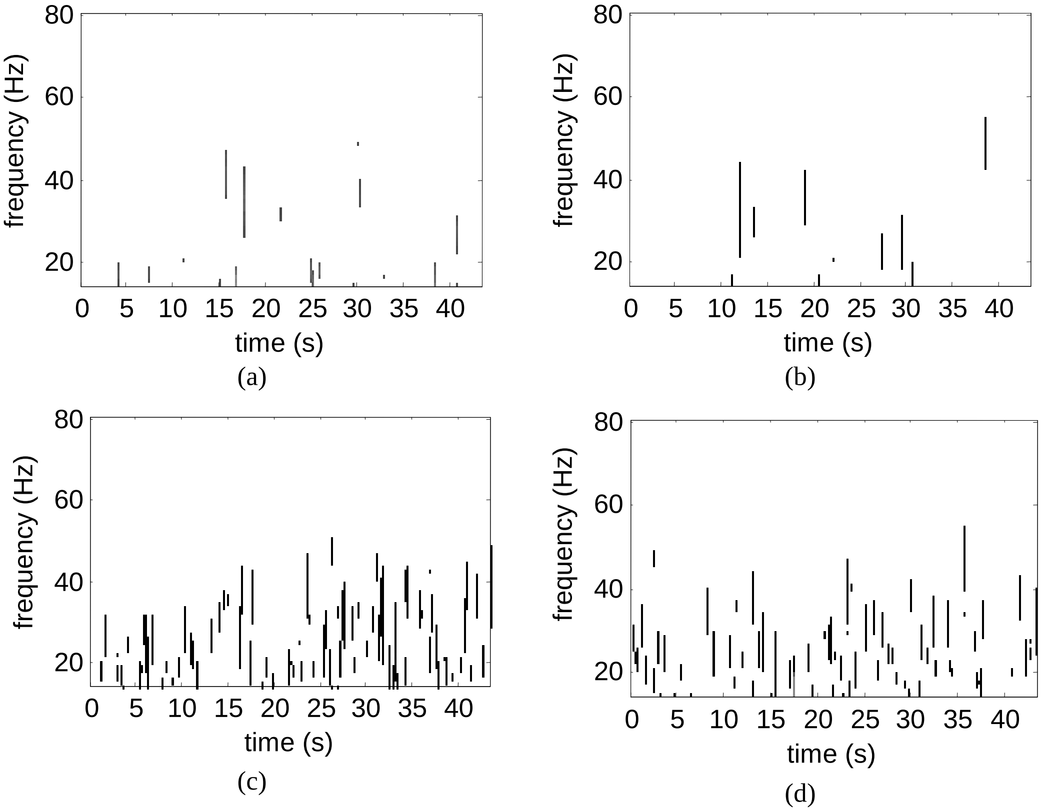


Figure 6. Filtered wavelets coefficients for test different test sections: a) test sections S5 b) test sections S6. c) test sections S7 d) test sections S8.

5. CONCLUSIONS

In this paper we studied the dynamic characteristic of velocity fluctuation in a closed compound channel. The influence of the channel's length and the geometric parameter D of the small channel were target of our study.

The length of the channel and the gap's width seems to be different influence on the dynamic of the turbulence in compound channels.

The gap width plays an important role in the large vortexes appearance. As gap width becomes wider the broadness of the peak in the spectrum is more pronounced. This fact suggests that different frequencies in the spectrum are excited, in other words, vortexes of different sizes might be dominating the flow in the small subchannel vicinity. The combination between a wider gap and a short channel vanishes completely the sinusoidal pattern of the flow.

The Strouhal number was computed as suggested by Meyer and Rehme, 1994. We did not succeed to reach the same Strouhal number calculated by the authors, who performed his experiments in a wind channel 7000 mm long. In this work the Strouhal number ranged from 0.03 up to 0.072. However, we could see as the channel becomes longer the

Strouhal number approximates that one stressed by Meyer and Rehme, 1994 and 1995, showing that the problem is still under development .

The Continuous Wavelet Transform gave us some insight on how energy-containing scales are distributed in time domain. Through the pictures we clear realized that broadness of the peak in the spectra is effect of the unsteadiness of the main frequency, whose value seems to wander in time.

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