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ANALYSIS OF THE SWITCHING FLOW AFTER TWO CYLINDERS SIDE-BY-SIDE SUBMITTED TO A HIGH TURBULENCE IMPINGING FLOW

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Abstract. *Bistability describes a phenomenon which, under the same conditions, presents distinct stable behaviors, where two different flow modes are present and remain in a stable configuration, during a certain period of time until a second flow mode is assumed. An experimental study, about the influence of the turbulence intensity on a bistable flow, were the flow through two cylinders side-by-side is studied in an aerodynamic channel with two turbulence intensities, lower than 1%, and about 7.5%, was performed. Usually, this phenomenon is investigated using Wavelets and Fourier Spectral Analysis. This work suggests the use of Hilbert-Huang Transform as a method that enables the analysis of non-stationary and non-linear turbulent signals. The experiment was performed with two rigid cylinders with an arrangement of pitch-to-diameter ratio (p/d) of 1.26. Hot wire anemometry technique was used for the experimental analysis. The results show that the Hilbert-Huang Transform can improve significantly the analysis of turbulent data, revealing the main characteristics of signal by obtaining its instantaneous frequency.*

Keywords: *turbulent flow, bistability, turbulence intensity, Hilbert-Huang Transform*

1. INTRODUCTION

When two cylinders of equal diameter, placed side-by-side, are submitted to a transversal flow, the resulting wake can present peculiar characteristics: due to the interaction of the wakes, the resulting flow can be deviated to the back of one or the other cylinder, depending on the pitch to diameter ratio p/d, being "d" the diameter of the cylinder and "p" the pitch, or distance from the cylinders centers.

A comparison between Fourier Spectral Analysis, Wavelets and Hilbert-Huang Transform for the analysis of the shedding process of a single cylinder in turbulent flow was presented by Silveira and Möller (2012). The results showed that the Hilbert-Huang Transform was more effective than Wavelets, once it is directly decomposed from the original data, and the physical characteristics are shown clearly in the Intrinsic Mode Functions (Huang and Shen, 2005).

De Paula and Möller (2013) presented a study of bistability for two cylinders. Using the double well energy models, the authors suggest the existence of more than two flow modes, with no evident time correlation between the changes.

Horszczaruk and Möller (2013) analysed the bistable phenomenon around two circular cylinders with two P/D in turbulent flow, using Hilbert-Huang transform as an alternative analysis tool together with Wavelets. They concluded that Hilbert-Huang transform promoted a better visualization of the behaviour of the IMF's components. They found no relation between the spectrogram with HHT and with continuous wavelet transform.

This paper presents the study of the bistable flow on two side-by-side cylinders, with P/D = 1.26 in an aerodynamic channel with two turbulence intensities, lower than 1% and about 7.5%. This work applies Hilbert-Huang transform as a tool of analysis of nonstationary and nonlinear turbulent data.

2. BACKGROUND

Data-analysis methods are traditionally based on linear and stationary assumptions. It is also known that the bistable phenomenon is nonlinear and nonstationary and methods as Fourier analysis and Wavelet transform may not provide complete and physically meaningful results. The combination of the empirical mode decomposition and the Hilbert spectral analysis is known as the Hilbert-Huang transform (HHT). The HHT enables the analysis of nonstationary and nonlinear turbulent signals.

2.1 Hilbert transform

For an arbitrary time series, *X*(t), it's Hilbert transform, *Y*(t), is obtained by

$$Y(t)=\frac{1}{\pi}P\int_{-\infty}^{\infty}\frac{X(t')}{t-t'}dt' \tag{1}$$

Where, *P* indicates the Cauchy principal value. It is a convolution of *X*(t) with 1/t; hence, the transform emphasizes the local properties of *X*(t). *X*(t) and *Y*(t) form a complex conjugate pair by definition, so it is possible to have an analytical signal, *Z*(t) as in Eq.(2),

$$Z(t)=X(t)+iY(t)=a(t)e^{i\theta(t)} \tag{2}$$

in which

$$a(t)=[X^2(t)+Y^2(t)]^{1/2} \tag{3}$$

$$\theta(t)=\arctan\left(\frac{Y(t)}{X(t)}\right) \tag{4}$$

where *a*(t) is the instantaneous amplitude, and *θ*(t) is the phase function. Based on the Hilbert transform, the instantaneous frequency can be defined as:

$$\omega(t)=\frac{d\theta(t)}{dt} \tag{5}$$

At any time, it is possible that the signal may involve more than one oscillation mode, and consequently the signal has more than one local instantaneous frequency at a time (Huang & Shen, 2014).

2.2 The Ensemble Empirical Mode Decomposition

The empirical mode decomposition (EMD) is a method to deal with nonstationary and nonlinear data. It is an intuitive, direct and adaptive method, with *a posteriori*-defined basis from the decomposition method, based on and derived from the data (Huang & Shen, 2014). The method identifies the intrinsic oscillatory modes by their characteristic time scales in the data empirically, and then decomposes the data accordingly. Each of these oscillatory modes is represented by an intrinsic mode function (IMF). The Intrinsic Mode Function (IMF) is a class of functions so that the instantaneous frequency can be defined everywhere based on the local properties of the data.

The decomposition is based on the following assumptions (Huang et al., 1998):

1) The signal has at least two extrema, a maximum and a minimum;
2) The characteristic time scale is defined by the time lapse between the extrema;
3) if the data were totally devoid of extrema but contained only inflection points, it can be differentiated once or more times to reveal the extrema.

The decomposed data *X*(*t*) represented in terms of IMFs, $c_{j,}$ i.e.,

$$X(t)=\sum_{i=1}^{n}c_i+r_n \tag{6}$$

As useful as EMD proved to be, it still has some problems unresolved. One of those drawbacks, is the frequent appearance of mode mixing, defined as a single IMF either consisting of signals of widely disparate scales, or a signal with a similar scale residing in different IMF components. Mode mixing is usually a consequence of signal intermittency (Wu and Huang, 2009).

To successfully deal with the scale separation problem, a noise-assisted data analysis method was proposed, called the Ensemble EMD (EEMD). The approach is based on the studies of the statistical properties of the with noise (Wu and Huang, 2004), which showed that the EMD is effectively an adaptive dyadic filter bank when applied to white noise.

The concept of the EEMD is based in the following observations (Wu and Huang, 2009):

1) A collection of white noise cancels each other out in time-space ensemble mean, surviving and persisting only the final noise-added signal ensemble mean.
2) Finite amplitude white noise is necessary to force the ensemble to exhaust all possible solutions; the finite magnitude noise makes the different scale signals reside in the corresponding IMF, dictated by the dyadic filter banks.
3) The true physically meaningful answer to the EMD is not the one without noise, it is designated to be the ensemble mean of a large number of trials consisting of the noise-added signal.

The EEMD principle is quite simple: adding white noise to populate the whole time-frequency space uniformly with the constituting components of the different scales. By adding the signal to this uniformly distributed white background, the bits of signal of different scales are automatically projected into the proper scales of reference. Each individual trial may produce very noisy results, each of the noise-added decompositions consisting of signal plus the added white noise. The noise is canceled out in the ensemble mean of enough trials, and the ensemble mean is treated as the true answer, for in the end, the only persistent part is the signal.

2.3 Hilbert spectral analysis

After obtaining the intrinsic mode functions (IMF), one can apply the Hilbert transform to each IMF component, and compute the instantaneous frequency using Eq. (1) to (5). The original data, after the Hilbert transform can be expressed as the real part $\Re$

$$X(t) = \Re\left\{ \sum_{j=1}^{n} a_j(t) \exp[i \int \omega_j(t) dt] \right\} \tag{7}$$

With the IMF expansion, the amplitude and the frequency modulations are also clearly separated. This frequency-time distribution of the amplitude is designated as the Hilbert spectrum $H(\omega,t)$. although the Hilbert transform can treat the monotonic trend as part of a longer oscillation, the energy involved in the residual trend representing a mean offset could be overpowering (Huang & Shen, 2014).

3. EXPERIMENTAL PROCEDURE

The flow velocity and its fluctuations are measured by means of a DANTEC StreamLine constant hot-wire anemometry system, with a single hot wire probe (type DANTEC 55P11), with a single wire perpendicular to the main flow. The aerodynamic channel used in the experiments, Fig. 1, is made of acrylic glass, with a rectangular test section of 0.146 m height, 0.193 m width and 1.02 m length. The air flow is driven by a centrifugal blower of 0.64 kW, and passes through two honeycombs and two screens, that homogenises the flow and reduce the turbulence intensity to about 1% in the test section.

For increasing the turbulence intensity in the test section, a grid made with eight horizontal parallel bars of 6 mm of diameter equally spaced was used. For this experiment the test section was enhanced in 0.3 m, to properly accommodate the turbulence grid.

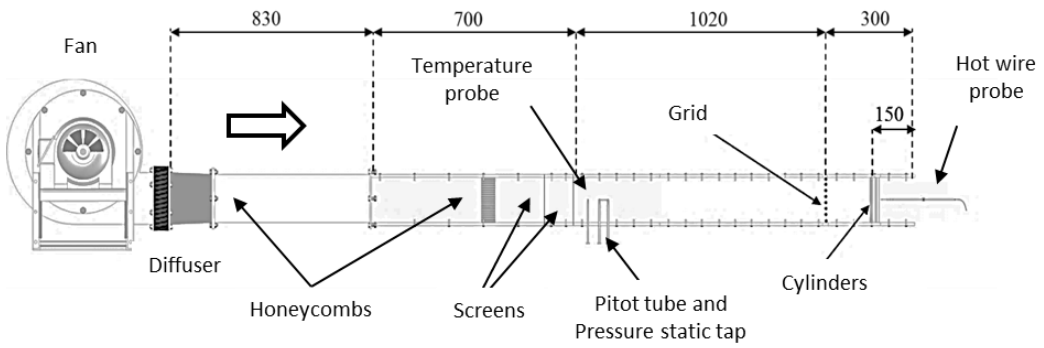

Figure 1. Schematic illustration of the aerodynamic channel and the turbulence grid positioning.

Data acquisition was performed with a 16-bit A/D board, with USB interface, with a sampling frequency of 1000 Hz, and a low pass filter at 300 Hz. The data set was acquired at the same velocity value, in steady state flows.

Fourier, and Hilbert-Huang transform were performed using the Matlab © software.

4. RESULTS AND DISCUSSION

In this study two sets of turbulent data were considered. Both obtained by measurements of turbulent flow after two cylinders side by side, pitch-to-diameter ratio p/d = 1.26, and two turbulence intensity conditions, lower than 1% and 7.5%. "p" is the distance between the centers of two cylinders and "d" is the diameter. The Reynolds number was in the range of $1,0633 \times 10^4$ and 1.3860×10^4.

4.1 Results for lower turbulence intensity

Figure 3 shows the instantaneous velocity signal obtained from a measurement with a single hot-wire probe, for turbulence intensity (*Ti*) lower than 1%. For this pitch-to-diameter ratio, the occurrence of the bistable phenomenon is clearly observed.

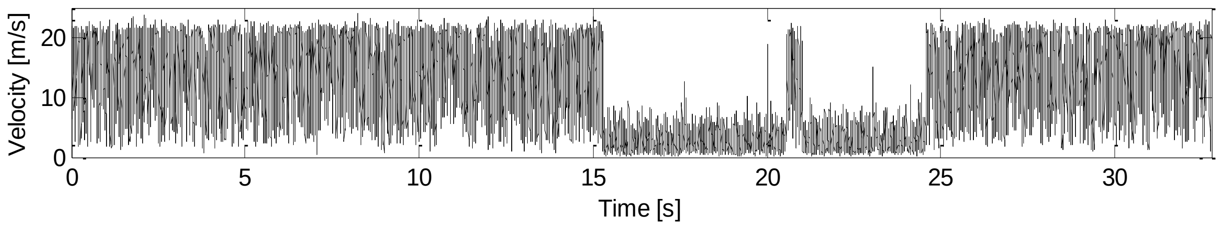

Figure 2. Instantaneous velocity signal for p/d = 1.26; Ti < 1%; Re = $1,0633 \times 10^4$.

The Ensemble Empirical Mode Decomposition (EEMD) was performed upon the signal, leading to 14 IMF's plus a trend. Figure 3 shows the resulting IMF's of the signal. A significance test, proposed by Wu and Huang (2004) was performed upon the IMF's to analyze which ones have significant components and which ones contained noise. This analysis showed that the fist IMF can be discarded as noise. The second IMF contains the short period components, which represents the very small scales in the turbulent flow. Form IMF's 3-9 it is possible to identify the characteristics wave modulations of the signal, the bistable behavior of the original velocity signal is visible in those intrinsic mode functions. From IMF 10 -14 we have the small frequency and long period components, which include the large scales. The last IMF's can be rejected as trend.

The Fast Fourier Transform (FFT) of the velocity signal gives the power spectral density, Fig. XX, were one can see a frequency peak at 66.4 Hz, that corresponds to the a Strou vortex shedding frequency of the experiment. Comparing with the Fourier spectrum of the IMF's the 66.4 Hz appears in the third IMF. The first IMF shows an almost flat spectrum, consistent with noise. The second IMF shows a frequency range about 93 and 200 Hz, the high range of the frequency spectrum may be caused by the difficulty in measuring appropriately the small scales.

After one has the EEMD performed, the Hilbert Transform is applied on the resulting IMF's. The Hilbert energy spectrum, Fig. 5, shows the energy of each IMF. For the Hilbert spectrum the first and last IMF's where left out, owing to the first being noise and the latter trend. As expected IMF's 2-4 have the higher frequencies and consequently the smaller energy content. The higher amounts of energy are concentrated in the small frequencies, towards those are related to the large scales and the higher amplitudes.

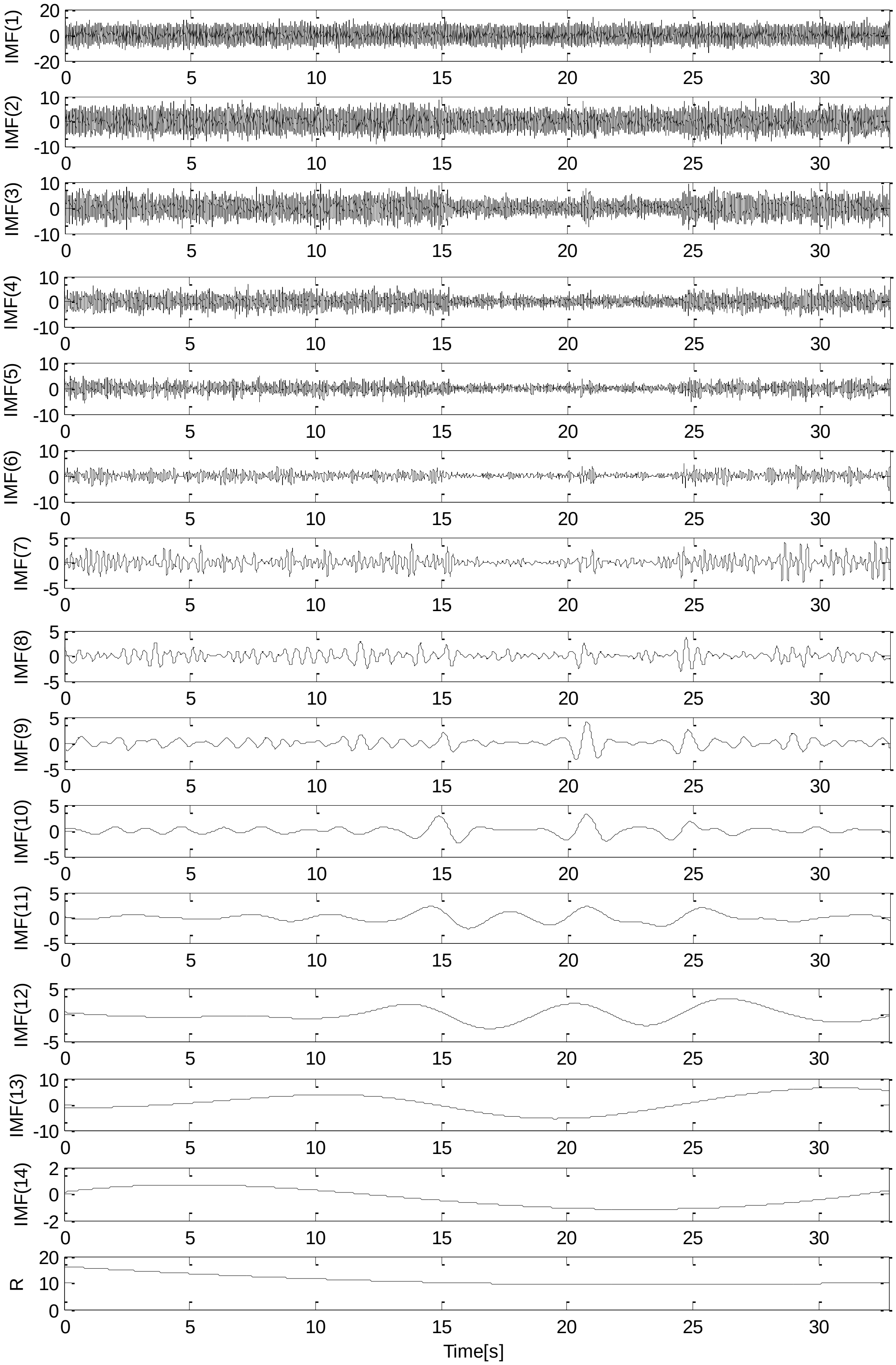

Figure 3. Intrinsic mode functions (IMF's) and trend (R) for Ti < 1%.

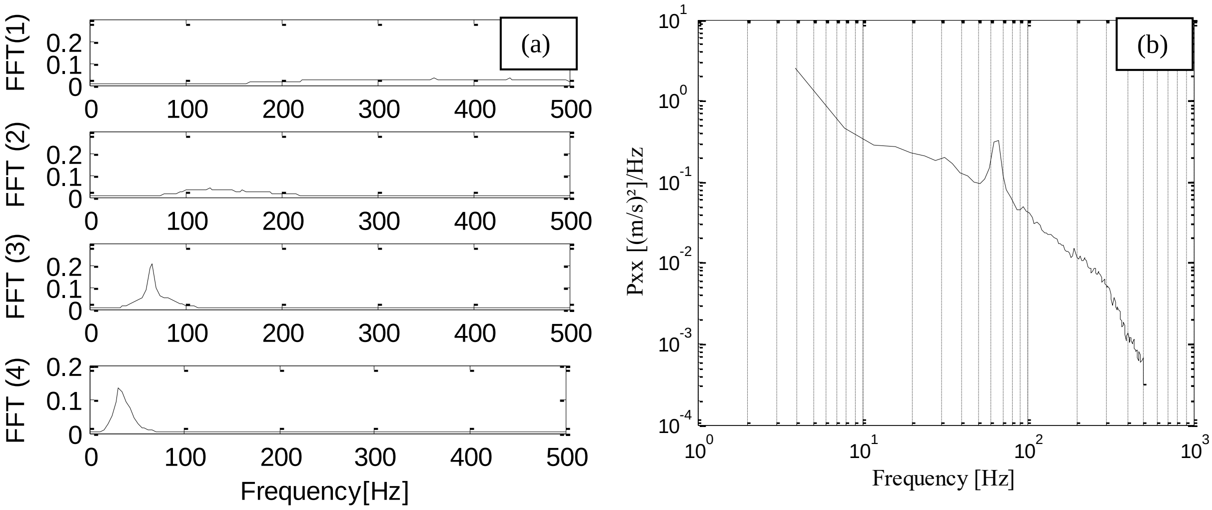

Figure 4. a) FFT of the four first IMF's of the signal and b) power spectral density of the velocity signal. for Ti < 1%.

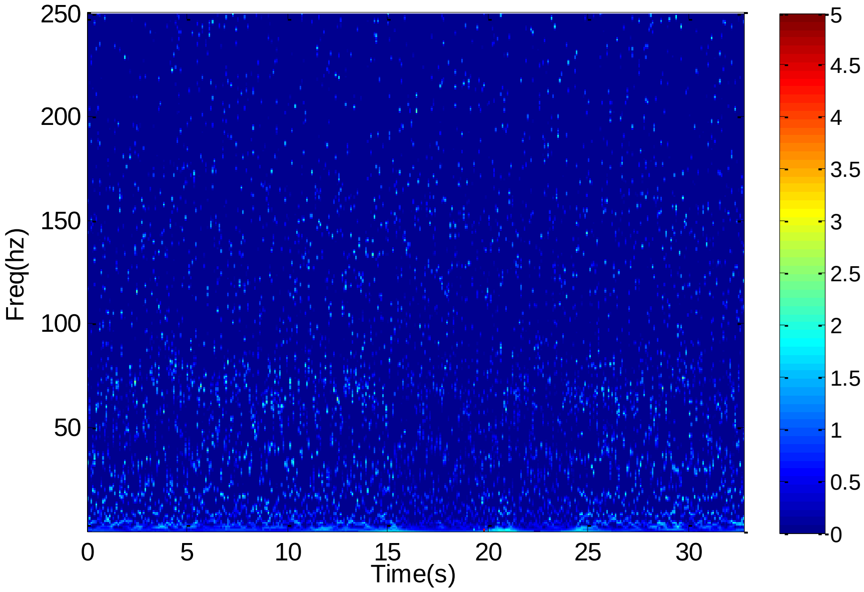

Figure 5. Hilbert Energy Spectrum from IMF's of velocity signal for p/d = 1.26; Ti < 1%; Re = 1,0633x10^4.

4.2 Results for higher turbulence intensity

Figure 6, shows the instantaneous velocity signal for the 7.5 % turbulence intensity. The increasing turbulence intensity enhance the near-wake switching in the bistable phenomenon. The pseudofrequency of the switching in the low turbulence was 0.148 Hz, while in the turbulence intensity of 7.5 % it was 0.498 Hz, which represents an enhancement of 3.36 % in the mode changing. Therefor the bistable behavior is no longer clearly visible in the measured signal, and the flow may be characterized as a flip-flop.

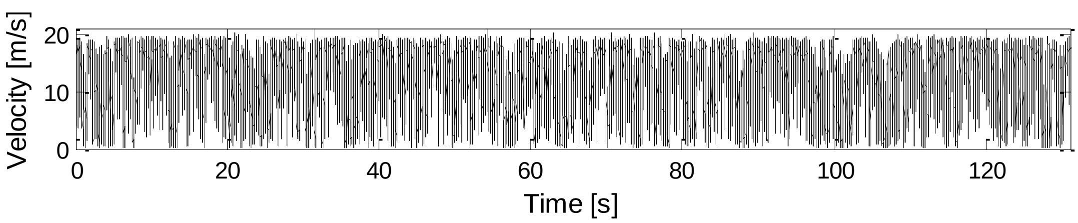

Figure 6. Instantaneous velocity signal for p/d = 1.26; Ti =7.5%; Re = 1.3860x10^4.

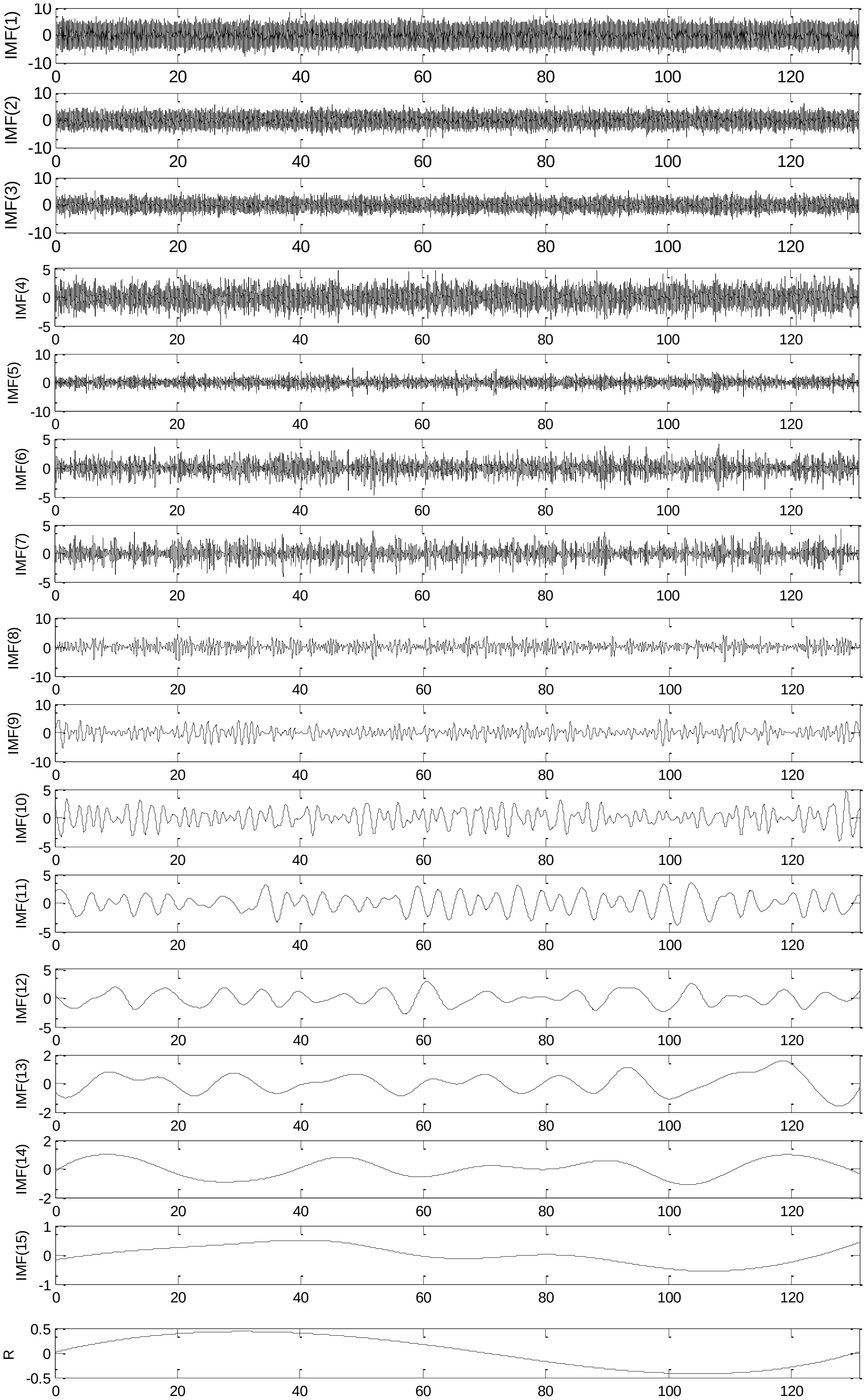

Figure 7. Intrinsic mode functions (IMF's) and trend (R) for Ti = 7.5%.

The EEMD was once more performed in the velocity signal and resulted in 15 IMF's and a trend. Figure 7 shows the resulting IMF's, again the first IMF can be discarded as noise. Duo to the characteristics of the original signal, the switching feature is harder to identify in the IMF's, althought it is possible to identify the wave modulations in IMF's 4 to 11.

The FFT was performed in the velocity signal and on the resulting IMF's. No predominat frequency is identified in the power spectral density of the original signal, Fig. 8b). Figure 8a) shows the FFT of the first four IMF's. The FFT of the first IMF confirms once more the noise features. The second FFT shows a frequency range from 90 to 200 Hz consistent with the small scales. In the FFT of the third and four IMF's the frequencies of 66.4 and 31.25 Hz appear, those frequencys also appeared in the lower turbulence intensity condition in the same scale range. On the other side, those frequencies don't appear as peaks in the power spectral density as a consequency of the signal characteristics.

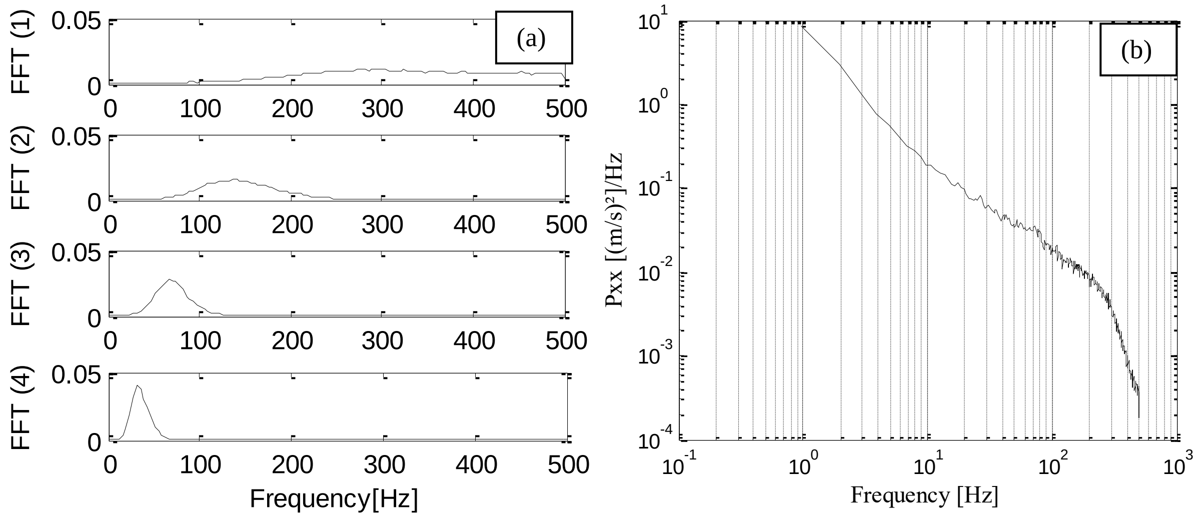

Figure 8. a) FFT of the four first IMF's of the signal and b) power spectral density of the velocity signal. for Ti = 7.5%

The Hilbert Energy Spectrum for the IMFs show that the energy in the small scales seems to be smaller when compared to the low turbulence intensity, most likely because the increased turbulence enhance the mixing. The lower frequencies though contain the largest amount of energy, as expected.

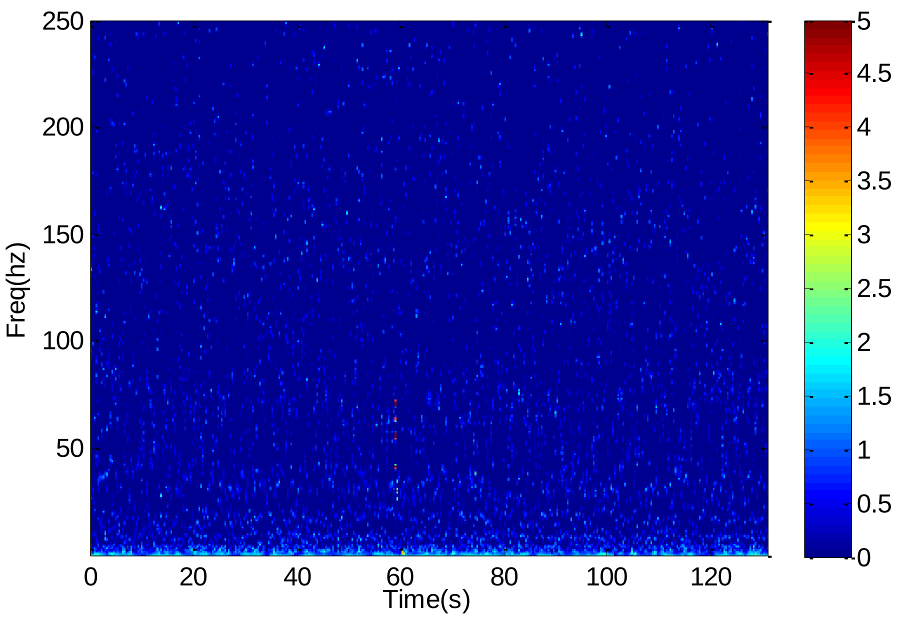

Figure 9. Hilbert Energy Spectrum from IMF's of velocity signal for p/d = 1.26; Ti = 7.5%; Re = 1.3860x10^{4}.

5. CONCLUSIONS

The present experimental study was executed with cross flow on two cylinders side-by-side. The tested flows had 1% and 7.5% of turbulence intensity. The analysis and comparisons of the two flow behaviors was made by means of Fourier and Hilbert-Huang transform.

The Hilbert-Huang transform give the instantaneous frequency distribution over the time and the behavior of each IMF component from the EEMD method. The study of turbulent data of phenomenon like bistability, may become more comprehensive with the aid of the Hilbert-Huang transform to other methods like wavelet and Fourier analysis.

6. REFERENCES

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