



25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COBEM-2019-0713

HILBERT-HUANG TRANSFORM APPLIED WITH DETERMINISTIC PERTURBATION AND WHITE NOISE ON WAKE SIGNALS FROM CYLINDER WITH TRIPWIRE

Ana Paula Ost

Roberta Fátima Neumeister

Sergio Viçosa Möller

Universidade Federal do Rio Grande do Sul. Rua Sarmiento Leite, 425 – Porto Alegre/RS

ana.ost@ufrgs.br

roberta.neumeister@ufrgs.br

svmoller@ufrgs.br

Abstract. *This study provides an evaluation of the performance of Hilbert-Huang Transform as a tool of analysis for turbulent flows. The method was applied in the analysis of the turbulent wake flow past a single circular cylinder with and without trip wire. The study was conducted in an aerodynamic channel with a 25 mm cylinder located in the test section and Reynolds number of 2.7×10^4 , based on the diameter and free stream velocity of the undisturbed flow. The trip wires present 2.3 mm diameter, representing 9% of cylinder diameter, and were positioned at $\pm 45^\circ$ from the stagnation point. The velocity was obtained with constant temperature anemometer. A deterministic periodic function, of constant amplitude and frequency was added in the velocity signal with the purpose evaluate the flow scale separation of the short period oscillations, and prevent mixing mode from happening. HHT was assisted by Fourier Transform and Wavelet Transform. Results showed that HHT satisfactory separated the short period perturbation and that the addition of the perturbation contributed to avoid mode mixing in the small flow scales.*

Keywords: *Hilbert-Huang transform, Single cylinder, Turbulent flow, Trip wire*

1. INTRODUCTION

The flow over a single cylinder present a series of known characteristics, associated to the boundary layer and the flow regime that the body is imposed, the main changes are observed in the vortex shedding frequency, drag and lift forces. For the Reynolds number between 300 and 200,000 the subcritical state is defined, and present specific mechanisms detailed in Zdravkovich (1997) with patterns of vortex shedding mechanisms. Modification of the flow characteristics over a bluff body can change the vortex shedding and reduce the forces. The force can be reduced changing the geometry or transitioning the boundary layer from laminar to turbulent, creating a delay in the separation point and, as consequence, reducing the pressure difference over the body (Schlichting, 1979). Some studies as Igarashi (1986) presented the flow patterns around the cylinder with a tripwire and showed that the patterns depend, mostly, on the roughness height and on the wire angle.

For the analysis of experimental signals some options on the time domain, frequency domain and time-frequency domain are available, but most of them are generated for linear and stationary data. Since most of the real data is originated from nonlinear and nonstationary systems, the analysis tools are limited, and those nonlinear processes need special treatment. Hilbert-Huang transform is not limited by linearity or stationarity and has an adaptive base, based and derived from the data itself, attempting to learn the detailed dynamics in processes of the data (Huang et al., 1998).

The application of new methods in the analysis of cylinders signals is relevant to validate the method in study and also to identify new characteristics in the signal. The study of flow experimental data applying Hilbert-Huang transform still in evolution and been explored as in the study presented by Franzini et al. (2014) where an experimental investigation of the vortex-induced vibration phenomenon on a long semi-immersed flexible cylinder in constant current profile were carried out at a recirculating water channel facility. Vertical and prescribed monochromatic harmonic motions were imposed to the top, causing eigen frequencies modulations. The Reynolds number range lies within the interval $10^3 < Re < 10^4$. The application of both the Fourier Transform and the Hilbert-Huang Transform allowed identifying subharmonic components and frequency modulation aspects in the data.

Mironov et al. (2017) studied the formation and evolution of fluctuations, mostly non-stationary, generated by flow over obstacles. To analyze such experimental data Hilbert-Huang transform was applied. Time series analyzed were obtained in experiments on fluctuations measurements behind a circular cylinder in two different wind tunnels at

different speeds but close Reynolds number ranges. Amplitudes of fluctuations behind a cylinder were found to have some specific behavior in each case. Comparison with wavelet transform on test signal with instantaneous change of frequency of a signal showed higher temporal resolution of HHT, however some difficulties of application of HHT are related by the authors. One of them is separation of fluctuations of interest into different IMF. The authors suggested that Hilbert-Huang spectrums should be plotted based on all IMFs and results should be analyzed carefully.

Neumeister et al. (2018) studied the influence of the trip wire in a cylinder applying Fourier transform, wavelets transform and Hilbert-Huang transform. Reduction in the vortex shedding frequency and wake characteristics were observed. The HHT showed agreement with Fourier and Wavelet transform, but the authors suggest additional studies with HHT.

Based on these previous results the purpose of the present study is to evaluate the performance of the Hilbert-Huang transform in identifying and separating short and long period perturbations in a turbulent wake of a circular cylinder with and without trip wire. The method is complemented with Fourier analysis and Wavelet transform.

2. EXPERIMENTAL TECHNIQUE

The aerodynamic channel is made of acrylic glass, with a rectangular test section of 0.146 m height, width of 0.193 m and 0.9 m length, as shown in Fig. 1 a). The flow driven by a centrifugal fan with 1HP, passes through two honeycombs and two screens, to reduce the turbulence intensity less than 1% of the free stream. The cylinders have 25mm diameter, with and without two tripwires with diameters of 2.3mm. The blockage ratio is 13% and the trip wire represent 9% of the cylinder. The reference velocity is measured with Pitot tube upstream the test section. The Reynolds number is 2.7×10^4 .

The velocity of the flow and its fluctuations are measured by means of a DANTEC StreamLine constant hot-wire anemometry system. The measurements are executed with 3kHz of acquisition frequency and with 1kHz low pass filter to avoid aliasing. The error associated with velocity measurements is about 5%. The cylinder was positioned in channel center and 645mm from the last homogenizer screen. The hot wire probe was positioned aligned with the cylinder side and 45mm from the cylinder center. The trip wires represent 9.2% of the cylinder diameter. The wires were positioned 45° from the stagnation point and the details of the cylinder with the wires are presented in Fig. 1 b).

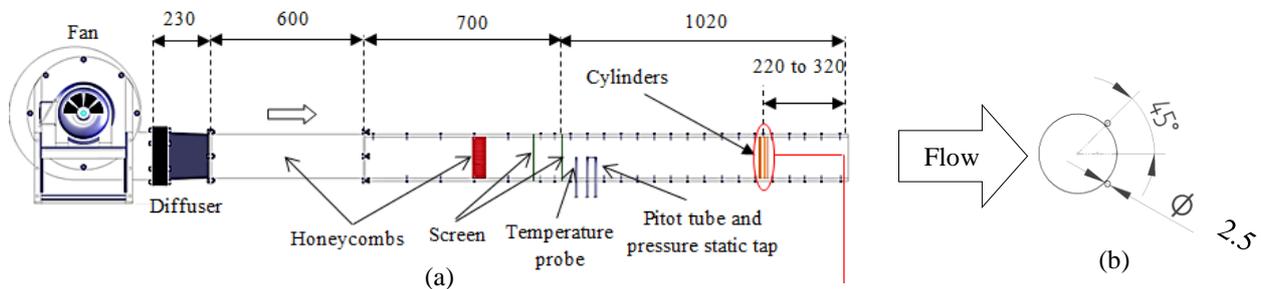


Figure 1. Schematic view of a) the aerodynamic channel and b) the cylinder with trip wires.

2.1 Hilbert-Huang transform

Hilbert-Huang transform is applied in the analysis of data emerged from non-linear and non-stationary systems, consisting in a combination of the empirical mode decomposition (EMD) and the Hilbert spectral analysis (HSA). The empirical mode decomposition (EMD) is an adaptive method, with *a posteriori*-defined basis from the decomposition method, based on and derived from the data (Huang and Shen, 2005). The method identifies empirically the intrinsic oscillatory modes by their characteristic time scales in the data, and then decomposes the data accordingly. Each of these oscillatory modes is represented by an intrinsic mode function. 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.

However, EMD has some problems unresolved, like 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 EEMD principle consists of adding white noise of finite amplitude to populate the whole time-frequency space uniformly. The effect of the added white noise in EEMD is to provide a dyadic filtering reference frame in the time-frequency space, therefore the added noise collect and combine the portion of the signal of comparable scale in one IMF, significantly reducing the chance of mode mixing (Huang and Shen, 2005). The noise added data is represented by

$$X_i(t) = X(t) + w_i(t) \quad (1)$$

were $w_i(t)$ is a white noise with finite amplitude, and $X(t)$ is the data. The final IMF component is the ensemble mean after a large number of trials of the noise added signal.

$$c_j(t) = \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N [c_{ji}(t) + r_{ki}(t)] \quad (2)$$

The decomposed data $X_i(t)$ is represented in terms of the ensemble mean IMF components as

$$X_i(t) = \sum_{j=1}^n c_j(t) + r_k(t) \quad (3)$$

where $c_j(t)$ are the ensemble mean IMF components and $r_k(t)$ is the ensemble mean of the residues after k^{th} sifting times.

2.2 The perturbation

In a second moment instead of white noise, a deterministic numerical perturbation is added to the signal to work as a filter for the highest frequencies and to evaluate if HHT properly separates the velocity signal from a short period perturbation. The general form of the deterministic perturbation is:

$$p_i(t) = a_p(t) \sin(\phi(t)) \quad (4)$$

were $a_p(t)$ is the perturbation amplitude and $\phi(t)$ is the phase function. The phase function and the perturbation frequency (f_p) are related by

$$\frac{d\phi(t)}{dt} = 2\pi f_p(t) \quad (5)$$

The perturbed signal is represented by the following relation and the EEMD decomposition is applied considering the perturbation instead of the white noise.

$$X_p(t) = X(t) + p_i(t) \quad (6)$$

3. RESULTS

The velocity signals were acquired for single cylinders with and without tripwire at Reynolds number $Re = 2.7 \times 10^4$. Two different analysis situations were considered for analysis. In the first situation the EEMD was performed traditionally, using a finite amplitude white noise to improve the scales separation. The white noise is used due to its dyadic filter bank characteristics. The application of traditional EEMD in each cylinder velocity signal generated a set of 16 IMFs plus a residue.

In the second situation a deterministic periodic function, created numerically, with constant frequency $f_p = 350$ Hz and constant amplitude $a_p = 20$ m/s, was added to the velocity signals. When performing the EEMD in this situation the white noise was omitted. The perturbation is added to evaluate the ability of HHT to separate short period perturbations and to improve even more the scale separation eliminating mode mixing. The frequency of the periodic perturbation was chosen so that it was higher than the vortex shedding frequency and its harmonics, and also not a multiple, so as not to influence the results. The EEMD with the perturbation also generated 16 IMFs and a residue.

The first 8 IMF components for smooth cylinder are represented in Fig. 2.a) for reference signal, using traditional EEMD method, and Fig. 2.b) for perturbed signal. The top plot represents the reference velocity signal and the perturbed-added signal in analysis. The first IMF component, C1, represents the finest scales in the flow and the highest frequencies. In the perturbed signal, this component englobes not just the finest scales, but also the periodic function, since its frequency is higher when compared to the flow frequencies. The frequency contained in each IMF component reduces as the IMF order increases. For IMF components C3 and C4 it is possible to see that the addition of a periodic

perturbation, amplified some characteristic oscillations that were not visible in the traditional EEMD. Also, higher order IMF components in the perturbed signal present a more homogeneous behavior than its equivalent in the reference signal.

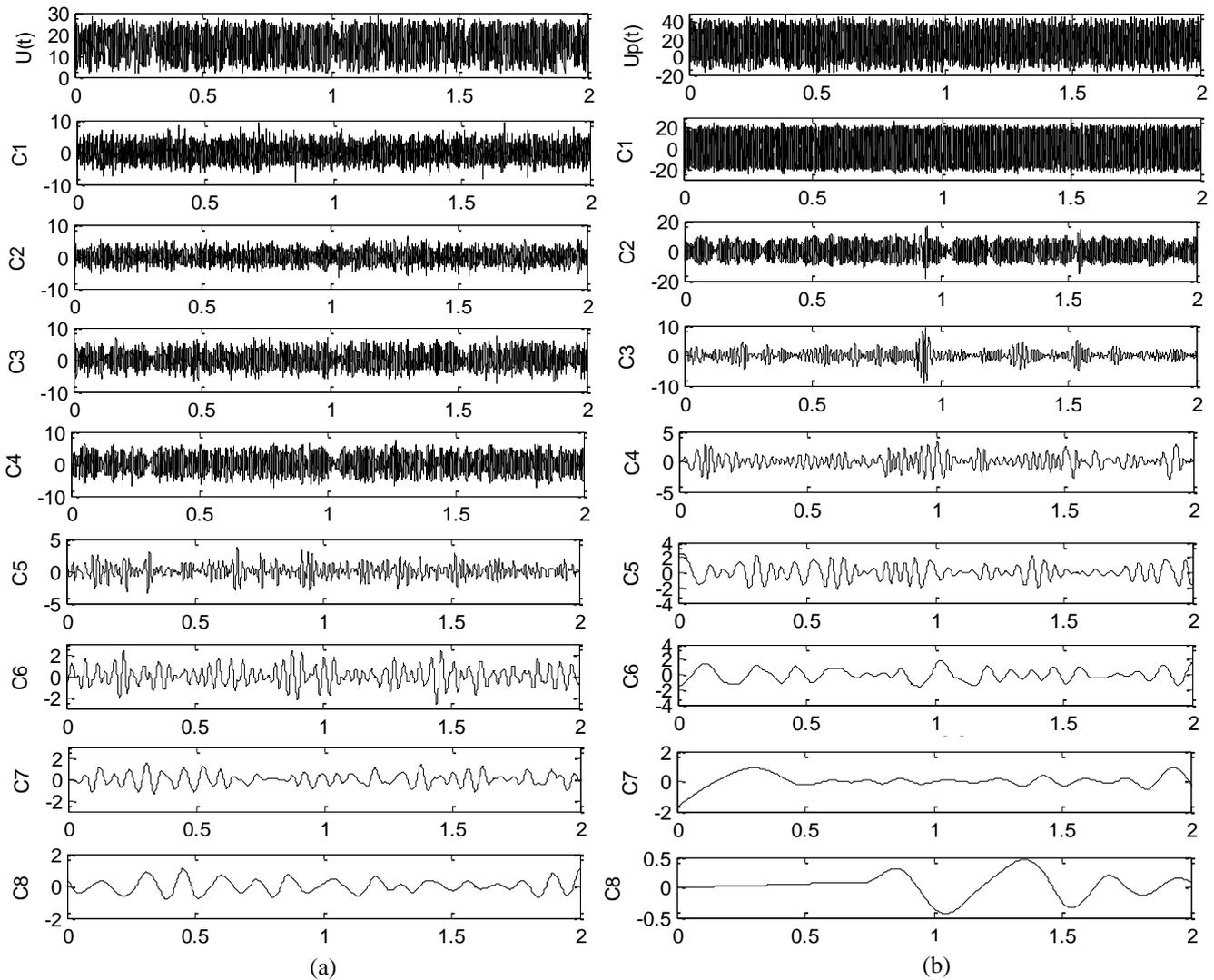


Figure 2. The 8 first IMF components for a) smooth cylinder with traditional EEMD method and b) smooth cylinder with a perturbation of 350 Hz and 20 m/s of amplitude.

For better relate each IMF component to its corresponding flow scales, the Fourier power spectra of IMF for both, reference and disturbed velocity signals are represented in Fig. 3. The results for smooth cylinder in traditional EEMD and with the added perturbation are shown in Figs. 3.a) and 3.b) respectively. The Fourier power spectra of IMF for cylinder with tripwire in traditional EEMD and with the added perturbation are represented in Figs. 3.c) and 3.d) respectively. For the traditional EEMD situation, with and without tripwire, it is possible to see that the first five IMF components present peaks corresponding to the vortex shedding frequency located at 137 Hz, and its harmonic at 274 Hz for smooth cylinder, and 100Hz and 200 Hz for tripwire. In both cases is noticeable that C1 does not fit perfectly in the velocity spectra, presenting higher energy levels which are a consequence of mode mixing. Higher order IMF components present the large scales in the flow, and the energy contributing for the fluid motion.

For the perturbed signals, with and without tripwire, the first component C1, presents the peak corresponding to the periodic function added on the reference signal and the mode mixing is reduced, visible in the perfect fit of C1 with the velocity spectra. The vortex shedding frequencies concentrate in more specific IMFs, C1 and C2 for smooth cylinder and C2 and C3 for cylinder with tripwire. An increase in the energy level appears close to the vortex shedding frequency peak and is visible in the spectra of components C3 for the perturbed smooth cylinder, and C3 and C4 for the perturbed cylinder with tripwire. This distortion is probably caused by the addition of the periodic perturbation and may not influence in the reconstructed signal. IMF components higher than C8 are not physically significant and present no

energetic contributions to the flow motion being considered pseudo frequencies generated by the decomposition method and are therefore omitted of this analysis.

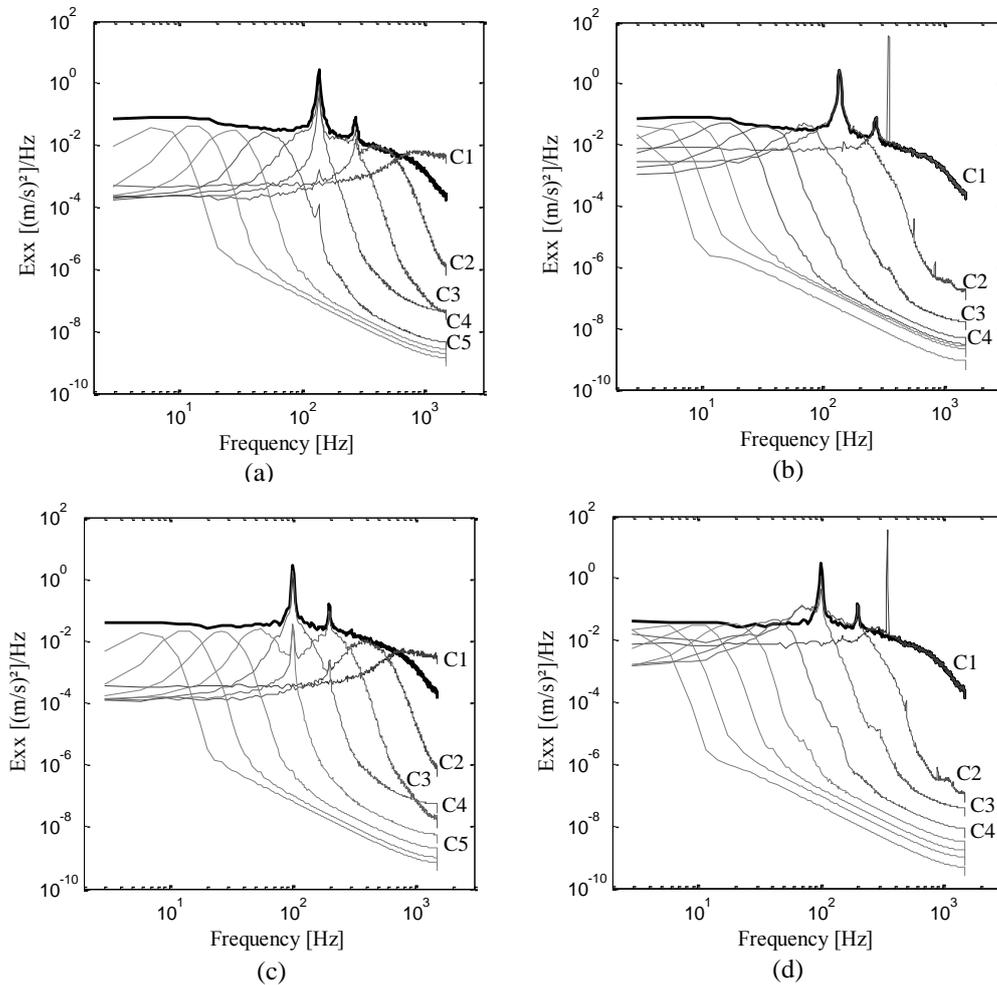


Figure 3. Power spectral density of velocity signal and IMF components for a) smooth cylinder with traditional EEMD method and b) smooth cylinder with a perturbation of 350 Hz and 20 m/s of amplitude, c) cylinder with tripwire traditional EEMD and d) cylinder with tripwire with a perturbation of 350 Hz and 20 m/s of amplitude.

Once having all the IMF components for the reference signals and perturbed signals the Hilbert transform is performed on each one. The Hilbert spectral analysis shows the instantaneous frequency at each corresponding time and energy amplitude, it can be interpreted as a joint amplitude-frequency-time distribution, showing the exact occurrence time of each flow oscillation. The Normalized Hilbert Spectra (NHS) for the eight first IMFs are showed in Fig. 4.a) and 4.c) for reference signals of smooth cylinder and cylinder with tripwire respectively. The vortex shedding frequency is evident by the concentration of amplitudes around the frequency values of 137 Hz for smooth cylinder and 100 Hz for tripwire cylinder. It is possible to notice dispersion of amplitudes in a wide range in the higher frequencies, and the first harmonic is not identifiable. In the results with trip wire, Figure 4c) and d), the frequency shedding ranges around 100Hz, due the presence of the obstacle. In the Figure 4 d), where the signal receive a perturbation of 350Hz, a dispersed range around 200Hz is observed and is associated with the first harmonic of the vortex shedding frequency. In Figure 4 c), the harmonic frequency is not visible. Figure 4.b) and 4.c) show the NHS for perturbed signals of smooth cylinder and cylinder with tripwire respectively, and in both cases the NHS present frequency ranges clear to identify. The IMF corresponding to the periodic perturbation (C1) was omitted for the purpose of comparison. It is possible to see that the addition of a periodic perturbation of constant amplitude and a high frequency promoted a better filtering on the IMF components eliminating the dispersion in the higher frequencies and enhancing their oscillatory behavior in the vortex shedding range. The addition of the perturbation for the cylinder with tripwire allowed the identification of the first harmonic of the vortex shedding which was not clearly identified in the traditional EEMD.

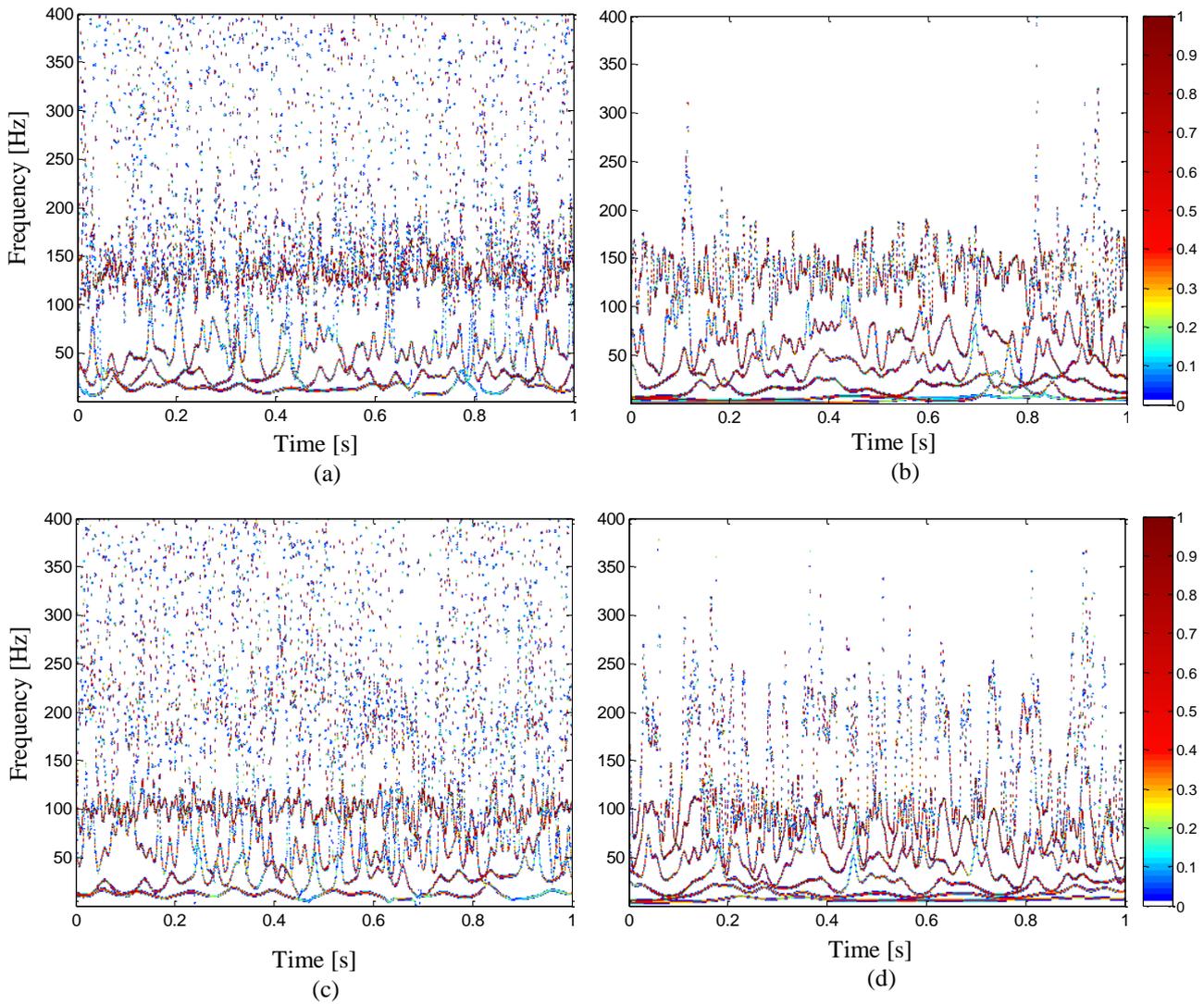


Figure 4. Normalized Hilbert Spectra for 1 second, a) smooth cylinder with traditional EEMD and b) smooth cylinder with deterministic perturbation of 350 Hz and 20 m/s amplitude, c) with tripwire traditional EEMD and d) cylinder with tripwire and perturbation of 350 Hz and 20 m/s amplitude.

A comparison between the reference signal and the reconstructed signals for traditional EEMD and the perturbed-added signals is performed in order to evaluate the effectiveness of HHT in properly separating perturbations and the influence of the perturbation addition it in the IMF components.

The velocity signals were reconstructed using the IMF components originated in the EEMD with and without the perturbation, and compared to the reference velocity signal that was acquired experimentally. The IMF corresponding to the perturbation (C2), is not included in the reconstructed signal for the perturbed added cases. The comparison between reference and reconstructed velocity signal is shown in Fig. 5, the reference signal is represented in black dotted lines, and the reconstructed IMF based signal in blue solid lines. The mean error between the reference signals and the reconstructed ones are: 0.021% for smooth cylinder, 0,140% for cylinder with tripwire, 5.567% for smooth cylinder with the added perturbation and 7.70% for the tripwire cylinder with the added perturbation. The addition of the perturbation smoothed out the reconstructed signal, increasing the mean error between the reference signal and the reconstructed signal.

The recovered perturbation is compared with the numerically generated perturbation, in order to evaluate if the HHT is capable to accurately separate it from the signal. Figure 6.a) and 6.b) shows the numerically generated periodic perturbation in black dotted lines and the IMF recovered perturbation (component C2) in blue solid line for the smooth cylinder and for the cylinder with tripwire respectively. The mean error between the numerical perturbation and the perturbation recovered by HHT are 3.65% for the smooth cylinder and 9.08% for the tripwire case.

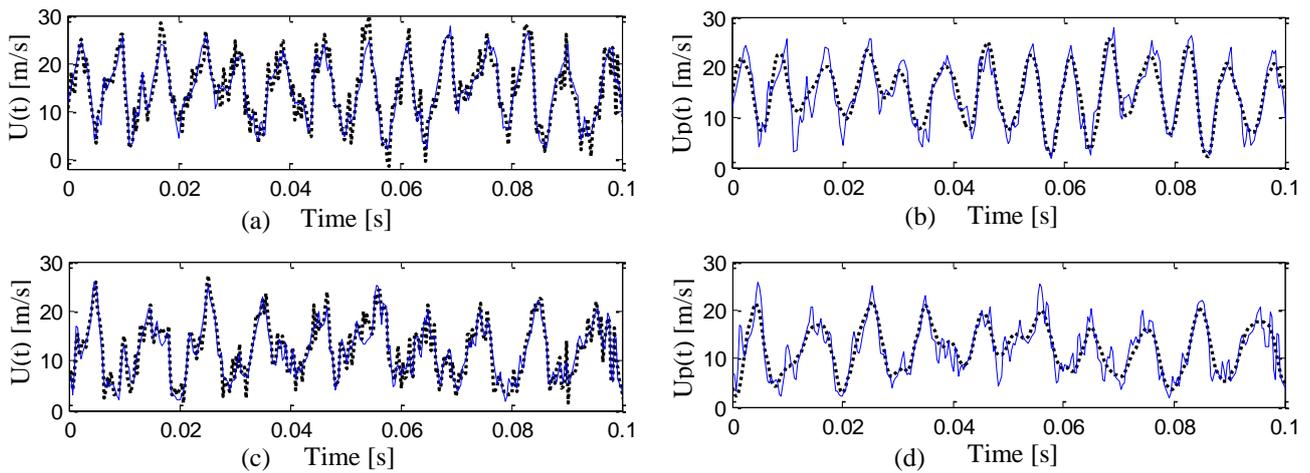


Figure 5. Reference signal (black dotted line) and reconstructed signal from IMFs (blue solid line) for a) smooth cylinder with traditional EEMD and b) smooth cylinder with added perturbation c) cylinder with tripwire in traditional EEMD and d) cylinder with tripwire and added perturbation. Perturbation frequency $f_p = 350$ Hz, amplitude $a_p = 20$ m/s.

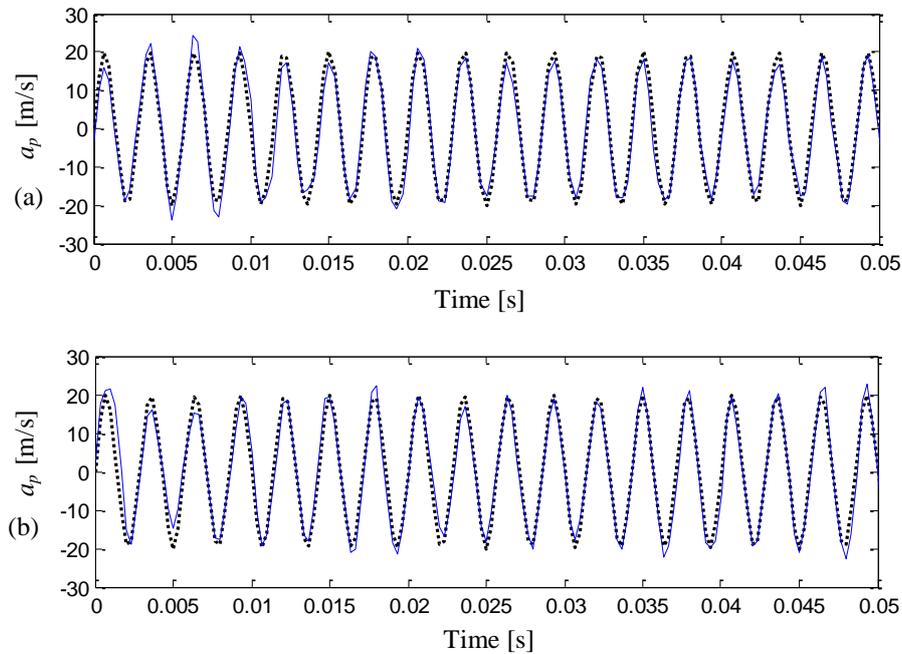


Figure 6. Comparison between the numerical perturbation (black dotted line) and the recovered perturbation form EEMD(blue solid line) for, a) smooth cylinder and b) cylinder with tripwire.

4. CONCLUSIONS

The application of the Hilbert-Huang Transform to the analysis of circular cylinders in turbulent cross-flow was studied. The Hilbert-Huang Transform is a tool that provides the analysis of data provided by non-linear and non-stationary systems, by means of empirical mode decomposition with an adaptive base, based on the data itself.

A numerical deterministic periodic perturbation whose parameters, amplitude and frequency remain constant in time has been added to the reference velocity signals for the cylinders with and without tripwire. The EEMD algorithm was used in its traditional way, using a finite white noise to filter the flow scales, and in a second moment it was performed using the perturbation in the place of the white noise, with the purpose of eliminating the mode mixing present in the finest scales of the flow and to evaluate the ability of HHT to separate a short period perturbation.

The influences of the added perturbation are seen in the IMF components extracted by de EEMD method. The addition of the perturbation amplifies certain oscillatory behaviors in some IMFs that were not clear in the traditional EEMD procedure. In the power spectral density of the IMF components the elimination of the mode mixing by adding

the high frequency perturbation is made clear by the better fitting of the first IMF component to the original velocity spectra. This result is emphasized by the Hilbert Spectra, where is possible to observe that the addition of the high frequency perturbation cleared the spectra, elimination the dispersion of amplitudes in the highest ranges of frequency. Also the vortex shedding frequency and the first harmonics are more defined.

To evaluate if the HHT was able to properly recover the signals and separate adequately the perturbation, a comparison between the recovered and the reference signals was made. The error between the reference and the recovered signals and perturbations was calculated, and the values were considered in good agreement. The reconstructed signal presented better agreement with the reference one when the EEMD was performed traditionally, the addition of the periodic perturbation smoothed out the reconstructed signal causing increasing the error. Comparing the perturbations, the error between the reference perturbation and the one recovered from EEMD was higher for the cylinder with trip wire, although both signals presented a good agreement.

5. REFERENCES

- Blevins, R. D. 1990. *Flow-Induced Vibration*. Segunda Edição. Nova Iorque: Van Nostrand Reinhold.
- Franzini, G. R., Gonçalves, R. T., Pesce, C. P., Fajarra, A. L. C., Mazzilli, C. E. N., Meneghini, J. R. and Mendes, P. 2014. Vortex-induced vibration experiments with a long semi-immersed flexible cylinder under tension modulation: Fourier transform and Hilbert–Huang spectral analyses. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, v. 37, p. 589–599.
- Huang, N.E., Shen, Z., Long, S.R., Wu, M.C., Shih, H.H., Zheng, Q., Yen, N.-C., Tung, C.C., Liu, H.H., 1998. The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *Proc. R. Soc. Lond. A: Math. Phys. Eng. Sci.* 454, 903–995.
- Huang, N.E., Shen, S.S., 2005. *Hilbert-Huang Transform and Its Applications*. World Scientific, Singapore.
- Igarashi, T. 1986. Effect of Tripping Wires on the Flow around a Circular Cylinder Normal to an Airstream. *Bulletin of JSME*, v. 29, p. 2917-2924.
- Mironov, D.S., Lebiga, V.A., Miao, J.J., Yu., A. Pak. and Zinoviev, V.N. 2017. Application of Hilbert-Huang Transform for Analyzing Non-Stationary Fluctuations of Flow Characteristics - *Proceedings of the XXV Conference on High-Energy Processes in Condensed Matter*.
- Neumeister, R. F., Ost, A. P. and Moller, S. V. 2018. Characteristics of the wake after a cylinder with trip wire on turbulent crossflow. *Anais 11th Spring School on Transition and Turbulence September 17th-21st, 2018, Uberlândia, MG, Brazil*
- Schlichting, 1979. *Boundary layer theory*. McGraw-Hill.
- Wu, Z., Huang, N.E., 2009. Ensemble empirical mode decomposition: a noise-assisted data analysis method. *Adv. Adapt. Data Anal.* 01, 1–41
- Zdravkovich, M. M. *Flow Around Circular Cylinders Vol 1: Fundamentals*. 1o ed. Vol. 1. New York: Oxford University Press, 1997.

6. ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Ensino Superior – Brasil (CAPES) – Finance Code 0001. Ana Paula Ost thanks CAPES, for granting her a fellowship.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.