STROUHAL NUMBER DETERMINATION OF THE TRANSIENT FLOW ON A SINGLE CYLINDER BY MEANS OF WAVELETS

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ABSTRACT

This paper presents experimental results of the accelerating and decelerating flow in the wake of a cylinder obtained by means of hot wire anemometry measurements in a wind tunnel with high blockage ratio. The analysis was done in Fourier and wavelet spaces. The Strouhal number for Reynolds numbers up to 3×10^4 *was studied at transient flow and compared with the results obtained steady flows at several velocities uniformly distributed from* $Re = 0$ *to* 3×10^4*. Results show that the wavelet analysis is a valuable tool to deal with both transient and stationary phenomena and that is able to capture the transient characteristics acquired at once, as the Fourier analysis can do with the steady state acquisitions set.*

1. INTRODUCTION

The study of flow on cylinders and the wake formed behind them is of great interest and object of many research studies. A single cylinder as well as cylinder arrangements simulate a wide range of practical situations, e. g. transmission lines and offshore structures, as well as of more complex arrangements and equipments, like tube banks of shell and tube heat exchangers. The concern about equipment integrity is due to the close relationship between fluid flow around a solid surface or a structural element and the vibrations induced by the flow in the structure.

In general, fluid flow loads on a structure submitted to a flow can be classified in static and dynamic loads. The former, due to the mean pressure variation on the flow along the structure, the latter, associated to pressure and velocity fluctuations due to vortex shedding and to the turbulent flow.

The first article relating frequency (of aeolian tones) and velocity of the flow over a bluff body was written by V. Strouhal in 1878. Since 1908, with the works performed by H. Bénard (1908 a, 1908 b), studies of vortex shedding are found in the literature, with focus on the behavior of the wake of a single cylinder as well as two or more cylinders, as in Brika et al., 1997 Xu et al., 2003, Ozono, 2003, Lee et al., 2004, where only the steady state is considered.

Experimental results in turbulence are usually characterized by their mean values and through Fourier analysis, which provide information about the behavior of steady state phenomena in the frequency domain. In transient flows, for instance, beside their mean values not being constant, additional phenomena may appear, as the flow velocity changes with time

Wavelets are valuable tools to analyze non-stationary time series and their possibly singularities (Farge et al., 1999). Wavelet transforms were used in applications as Mouri et al., 1999, to investigate the turbulence homogeneity at several scales, or to obtain power and cross spectrum, as in Perrier et al., 1995 and Hajj et al., 2000 or to detect coherent structures (Gilliam et al., 2000). Alam et al., 2003, used wavelet analysis with Fourier analysis for the interpretation of switching flows, while Indrusiak et al., 2005 studied transient phenomena in tube banks.

Most articles about flow on bluff-bodies consider an infinite domain, but in many cases it is important to take into account the effect of the blockage ratio. West and Appelt, 1982, studied the blockage effect on Strouhal number for Reynolds numbers between 10^4 and 10^5. They show that, for blockage ratios higher than 6% there is a distinct distortion of the flow field, with complex effects that made unsuitable a correction method. Davis et al., 1983, studied the confined flow around rectangular cylinders at various Reynolds numbers and blockage ratios and found that the Strouhal number and the drag coefficient increase with the blockage ratio. The effect is more pronounced at lower Reynods numbers.

The purpose of this paper is to investigate the behavior of a transient wake and the influence of the wind tunnel blockage ratio, using wavelet analysis applied to hot wire anemometry signals on accelerating and decelerating wakes behind a single cylinder. The wavelet results were compared to Fourier results obtained from series of steady state measurements up to a Reynolds number of 3×10^4.

2. BACKGROUND

Wavelet analysis is based on the idea of stretching and compressing the window of the windowed Fourier transform, according to the frequencies to be localized, thus allowing the definition of the scales of interest in time and frequency domains. The bases of wavelet transforms are generated through dilations and translations of a single function named wavelet, $\psi(t)$ with finite energy and a zero average.

The discrete wavelet transform (DWT) deals with dyadic scales, and is given by:

$$\tilde{X}(j,k) = \sum_t x(t)\psi_{j,k}(t) \qquad j,k \in I \tag{1}$$

where (j, k) are the dyadic scale and position coefficients.

The Fourier transform of a finite series gives only a finite number of coefficients, depending on the length of the time series, and therefore neglects the coefficients related to the higher frequencies. Nevertheless, these frequencies must be filtered at the acquisition process, to prevent aliasing. In the wavelet transform of a finite series, the length of the series also restricts the number of computable coefficients but, unlike the Fourier transform, the remaining coefficients are related to the lower frequencies, including the mean value of the signal, and cannot be disregarded. In practice, the DWT of a series with more than 2^J elements is computed for $1 \le j \le J$, being J a convenient arbitrary choice. The remaining part of the signal, containing the mean values for a scale J, is given by:

$$\tilde{X}(J,k) = \sum_t x(t)\phi_{J,k}(t) \tag{2}$$

where $\phi(t)$ is the scaling function associated to the wavelet function. Then, any discrete time series with a sampling frequency Fs can be represented by:

$$x(t) = \sum_k \tilde{X}(J,k)\phi_{J,k}(t) + \sum_{j \le J}\sum_k \tilde{X}(j,k)\psi_{j,k}(t) \tag{3}$$

where the first term is the approximation of the signal at the scale J, which corresponds to the frequency interval $[0, Fs/2^{J+1}]$ and the inner summation of the second term are details of the signal at the scales j ($1 \le j \le J$), which corresponds to frequency intervals $[Fs/2^{j+1}, Fs/2^j]$

The DWT is computed via the pyramid algorithm (Mallat, 1999). A modification of this algorithm yields the so called discrete wavelet packet transform (DWPT), where each detail series is wavelet transformed in two series, with respectively lower and upper half bandwidth frequency interval. For each level j one can obtain 2^j successive intervals of equal bandwidth. This recursive transformation of detail series is represented in a binary tree. Any admissible binary tree can be chosen for the representation of the signal in the wavelet space, with frequency intervals of variable bandwidths, according to the analysis to be done. An admissible tree is any binary tree where each node has either 0 or 2 branches.

The discrete wavelet packet transform is done by

$$\tilde{X}(j,m,k) = \int_{-\infty}^{\infty} x(t)\,\psi_{j,m,k}(t)\,dt \tag{4}$$

where m is the modulation parameter.

3. EXPERIMENTAL TECHNIQUE

The test section, is a 1370 mm long rectangular channel, with 146 mm height and a width of 193 mm. Air, at room temperature, is the working fluid, driven by a centrifugal blower, passed by a diffuser and a set of honeycombs and screens, before reaching the measurement location with about 1% turbulence. The cylinder has a diameter of 32 mm and is rigidly mounted in the channel. The incidence angle of the flow on the cylinder is 90°. Upstream the measurement location, a Pitot tube is placed at a fixed position to measure the steady reference velocity of the experiments. The geometric blockage ratio is 16.5%.

Velocity and velocity fluctuations where measured by means of a DANTEC *StreamLine* constant temperature hot wire anemometer, with a single straight (reference) probe mounted close to the Pitot tube and a double (X) probe positioned at the wake, 100 mm downstream the cylinder. To ensure the repeatability of the accelerating and decelerating processes, a frequency inverter was coupled to the blower supply.

Simultaneous data acquisition of wake and reference velocities were performed with a 12 bit Keithley DAS-58 A/D-converter board with a sampling frequency of 800 Hz and low pass filtered at 300 Hz.

Computations of the wavelet transforms were performed using the Matlab 5.3 software.

Analysis of uncertainties of the results shows a contribution of 1.4 % from the measurement equipments (including hot wire and A/D converter). The mean error of the determination of the flow velocity with a hot wire was about 3.4%. Velocity fluctuations in the main flow direction were obtained with a mean error of 15%, while the transverse component had an error of about 30%. The error of the determination of the Strouhal number varies from 13% at lowest Reynolds numbers investigated to about 2% at highest Reynolds numbers investigated.

4. RESULTS

To study the behavior of the wake frequencies at the transient part of the signal, two experiments were performed. For the first one, the frequency inverter coupled to the blower set acceleration and deceleration ramp time interval of 10 seconds each, in order to capture both transients at the same acquisition. For the second experiment, the frequency inverter was set at several frequencies between 6 and 60 Hz, in order to obtain regularly spaced velocity values for performing acquisitions at steady states.

The signals in the wake were acquired simultaneously with the reference velocity. The axial velocity, parallel to the tunnel axis, and the transversal velocity, perpendicular to both tunnel and cylinder axes were computed from the signals of the X probe. The wavelet analyses of the wake fluctuations were performed mainly using the transversal velocity, where the features of the wake are more visible. The Strouhal number, computed for the higher velocity of the wind tunnel, is 0.222. This is an acceptable result taking into account the high value of blockage ratio of the present work. The study of the transient part was performed taking this value as reference.

The DWT decomposes the signal at successive approximation and detail sets of coefficients, each of them with a scale of double length and a frequency interval of half width than that of the preceding one. The dyadic frequency bandwidths are too large to give any quantitative detailed information about the evolution of the wake frequencies along time. Therefore, the DWPT was applied. The first 7th level reconstructed series, up to 103.1 Hz, are shown in Figure 1. The series show the velocity fluctuations at successive frequency intervals, each with the same bandwidth of 3.1 Hz.

For each frequency interval, departing from 9.4 Hz and following the series until 93.8 Hz, two localized increases of amplitude are observed, showing the presence of the vortex street at the corresponding frequency and times related to acceleration and deceleration. At the next frequency interval, from 93.8 to 96.9 Hz, the increase of amplitude, which begins near the onset of steady state velocity, holds until the beginning of the deceleration, denoting the steady state wake. Indeed, the Fourier spectrum of the steady part of the signal gives 94 Hz as the vortex shedding frequency. At frequencies above 96.9 Hz, the sequence of increased amplitudes disappears and only small amplitudes remain at the part of the signal that corresponds to the steady state. For frequencies lower than 9.4 Hz, the presence of the amplitudes corresponding to the vortex shedding is not visible, due to the low energy level of the wake. The frequency in problems involving steady fluid flow impinging on a structure is represented usually in non-dimensional form as Strouhal number, defined for a cylinder with the diameter and the approaching velocity. A transient Strouhal number can be similarly defined with the instantaneous mean approaching velocity and the mean frequency of the interval, $\bar{f}(t)$. The instantaneous mean approaching velocity was obtained from the reconstructed 7th level approximation set of the DWT of the reference velocity, which corresponds to a low pass filter of 3.1 Hz.

For each reconstructed series, corresponding to a given frequency interval, the two localized increases of amplitude denote the temporal position of the wake at acceleration and deceleration process and can be associated to the respective mean approaching velocity to compute the transient Strouhal number. Figure 2 shows an example of the scheme used for the determination of the mean frequency and the corresponding mean approaching velocity. Uncertainty is due to the vortex shedding process, which does not occur at a single distinct frequency, but rather it wanders over a narrow interval of frequencies with a range of amplitudes (Schlichting, 1979). Heisenberg's uncertainty principle (Mallat, 1999) limits the use of a higher-level DWPT with a narrower frequency bandwidth, because the time localization of the wake features becomes less accurate.

Figure 3-a shows the values of the transient Strouhal numbers S(t) computed for each detail

series of Figure 1, as a function of instantaneous Reynolds number. They are plotted along with the results obtained from a succession of steady state acquisitions using Fourier. The results show good agreement with those of the transient wake, suggesting that the transient wake behaves as a succession of steady states. They also allow concluding that: a) the performed wavelet analysis is effective for the identification of transient features of the signal and b) the accuracy of the time-frequency localization of the wavelet transform is sufficient to perform such analysis, considering the limitations imposed by the uncertainty principle.

Taking into account the results of error analysis for Strouhal numbers obtained from both methods, the values became closer to 0.21, although with still a strong increase at lower Reynolds numbers. This is not in agreement with the traditional results shown in Schlichting, 1979, and Blevins, 1990.

The high blockage ratio of the test section is the cause of the unexpected high values of the Strouhal number at lower Reynolds number. According to Žukauskas, 1972, the deviation of the flow for a blockage of 16% can increase the velocity to about 80%, depending on the position around the cylinder diameter.

The plot of velocity as a frequency function, Figure 3-b, shows the linear behavior that corresponds to the definition of the Strouhal number, with a non-zero linear coefficient, due to the blockage. The works of West and Apelt, 1982 and Davis et al., 1983, show a tendency similar to that of the results of the present study.

The present results are complementary to those of West and Apelt showing that, for blockage ratio of 16.5% and $Re < 2.5 \times 10^4$, the Strouhal numbers are strongly affected by the deviation of the flow around the cylinder and experience an increment of as large as 57% at lower Reynolds numbers.

5. CONCLUDING REMARKS

In this work, a discrete wavelet analysis was used to study the transient behavior of the known phenomenon of a wake behind a circular cylinder perpendicular to a turbulent flow.

The transient flows were obtained during the time interval from rest to the steady state of the wind tunnel blower and also the interval from steady state to the rest, by turning the blower on or off. A frequency inverter was also applied to control the duration of these processes.

Comparison of the results of the transient Strouhal number with a succession of steady states demonstrates that, the wavelet analysis of the transient signal, obtained at once, from only one acquisition, has a close agreement with the results of the set of acquisitions at steady flows, with the velocity of the blower adjusted at regularly spaced values.

Despite of the higher uncertainties at lower Reynolds numbers for both Fourier and wavelet analysis, this is a time saving technique which can assure the stability of the environmental conditions during the experiment.

The results of the present work complement those of West and Apelt, showing that, also for high blockage ratios, the Strouhal number is not independent from but rather increases at low Reynolds numbers

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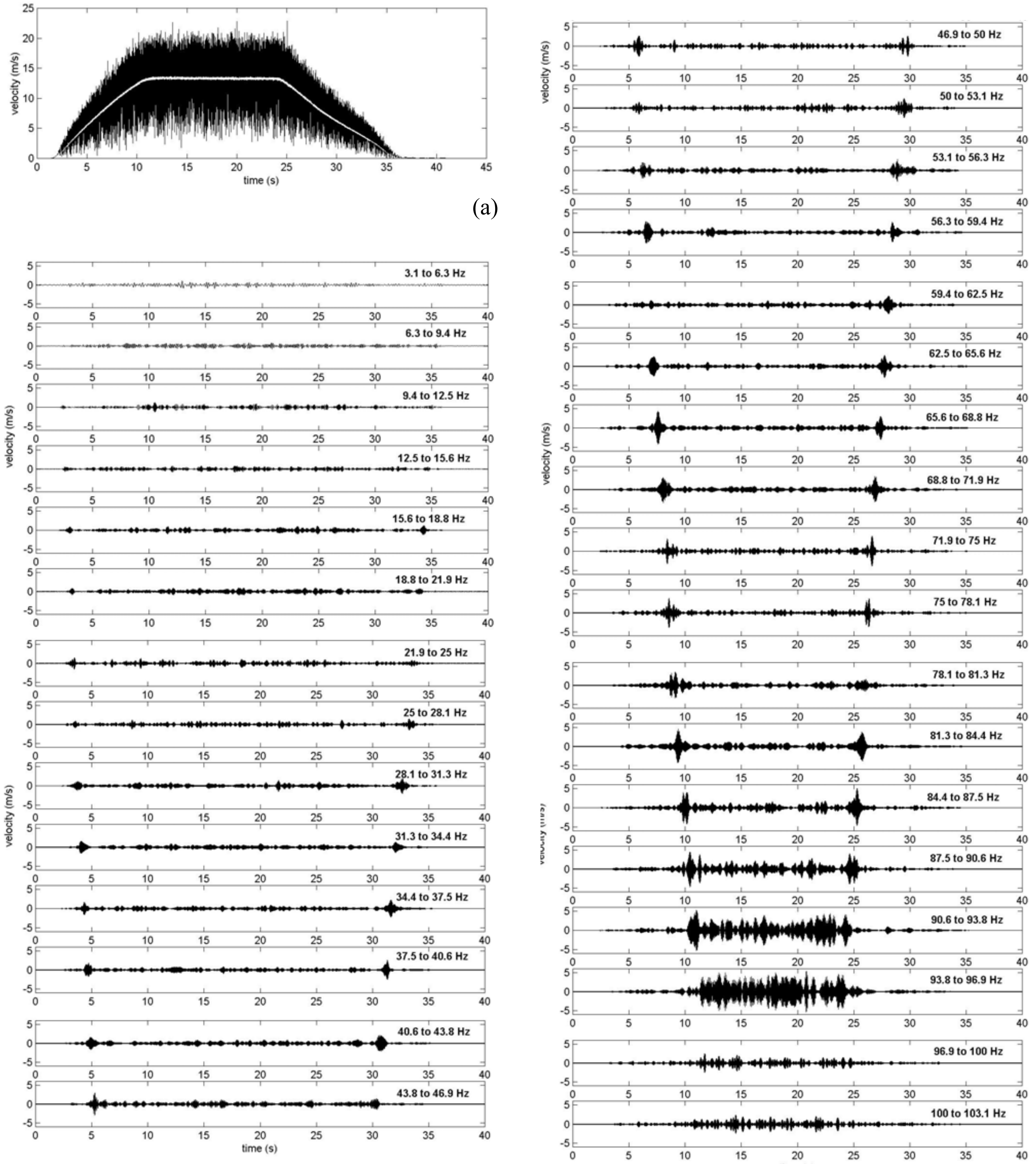

(a)

(b)

(c)

Fig. 1: (a) The transient wake velocity and the corresponding reference velocity (in white); (b) and (c) Reconstruction of the transient wake velocity for successive frequency intervals with 3.1 Hz bandwidth.

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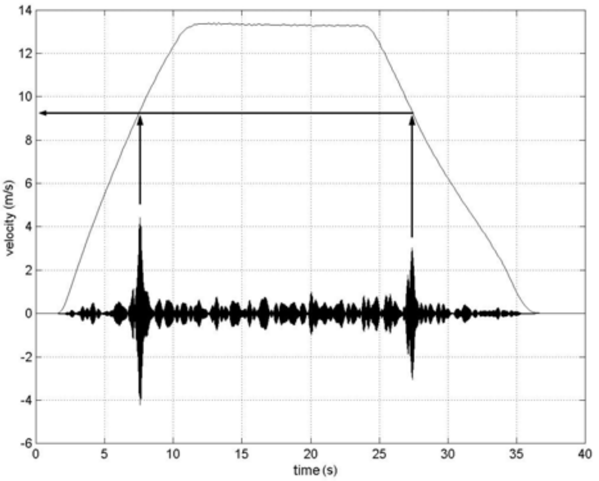

Fig. 2. Time localization, for a chosen frequency interval, of the transient vortex shedding and respective transient incident velocity.

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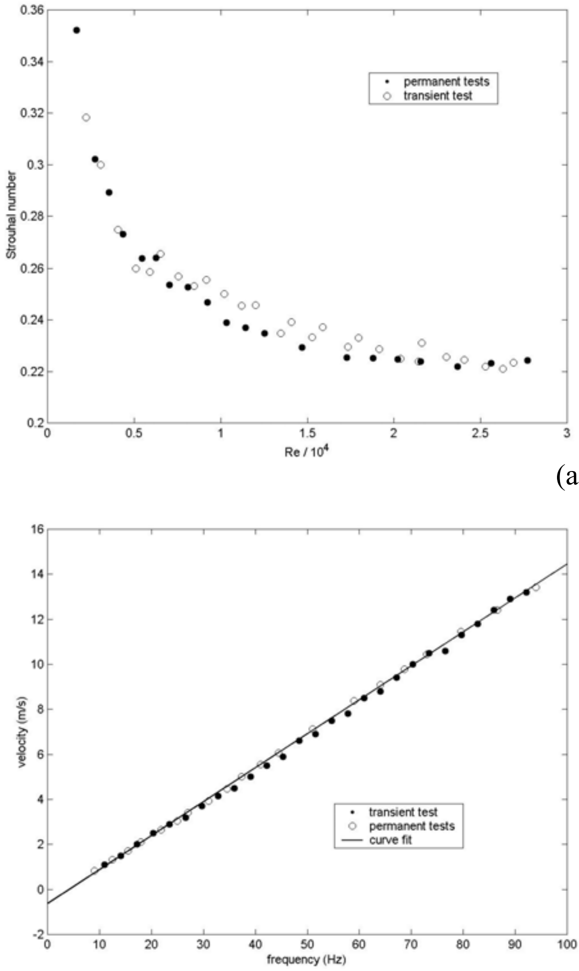

Fig. 3: (a) Strouhal numbers S(t) as a function of Reynolds number. (b) Transient frequency and approaching velocity corresponding to Strouhal and Reynolds numbers of (a).