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Wavelet Time-Frequency Analysis of Accelerating and Decelerating Flows in a Tube Bank

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ABSTRACT

In the present work, the steady approximation for accelerating and decelerating flows through tube banks is discussed. With this purpose, the experimental study of velocity and pressure fluctuations of transient turbulent cross flow in a tube bank with square arrangement and pitch-to diameter ratio of 1.26 is performed. The Reynolds number at steady state flow, computed with the tube diameter and the flow velocity in the narrow gap between tubes, is 8×10^4. Air is the working fluid. The accelerating and decelerating transients are obtained by means of start and stop of the centrifugal blower. Wavelet and wavelet packet multiresolution analysis were applied to decompose the signal in frequency bands, using Daubechies 20 wavelet and scale functions, thus allowing the analysis of phenomena in a time-frequency domain. The resulting decomposed signals in both transients and in the steady state were analyzed with usual statistic tools and the results were compared with the steady state assumption., demonstrating the ability of wavelets as a tool for analyzing time varying signals.

KEY WORDS: tube banks, turbulence, transient flows, wavelets, multiresolution analysis

INTRODUCTION

Banks of tubes or rods are found in the nuclear and process industries, being the most common geometry used in heat exchangers. Attempts to increase heat exchange ratios in heat transfer equipments do not consider, as a priority of project criteria, structural effects caused by the turbulent fluid flow, unless failures occur [1]. By attempting to improve the heat transfer process, dynamic loads are increased and may produce vibration of the structures, leading, generally, to fatigue cracks and fretting-wear damage of the components, which are one of the failure sources affecting nuclear power plant performance [2].

Pressure fluctuations result from velocity fluctuations at several points of the flow field [3]. They are produced by the interaction of velocity gradients with velocity fluctuations and Reynolds stresses [4]. The amplitude of the pressure fluctuations may be influenced by velocity fluctuations at a distance comparable to the wavelength of these fluctuations [5]. The search of form and magnitude of pressure and velocity fluctuations and the interdependence between these quantities is necessary for the comprehension of the complex phenomena in tube banks, since the resulting forces applied to the tubes by the turbulent flow will be given by the integral of the pressure field around each tube in the bank. From the fluctuating pressure field, a fluctuating excitation force will result, which may induce vibration of the tube if its natural frequency is present in the excitation force. [6].

The concern about heat transfer equipment integrity is, therefore, due to the close relationship between fluid flow around a solid surface and the vibrations induced by the flow in the structure by wall pressure fluctuations.

The classic approach to these studies is the Fourier analysis, which can give information about the frequencies involved and the interdependence of simultaneous phenomena (e. g. velocity and pressure fluctuations at different locations). An ergodic hypothesis of the time series is necessary in this case, being mean values independent of the sampling process. This hypothesis fails in time varying series, which means that Fourier analysis cannot deal with a signal that is changing over time and, therefore, its mean values are not constant. Furthermore, many processes of interest in fluid dynamics are not stationary. In accelerating flows, for instance, beside their mean values not being constant, additional phenomena may appear, as the flow velocity changes with time.

Unsteady flows occur frequently in nuclear and process installations, due to reciprocating pumps, water hammer phenomenon and process control. Analysis of such flows is often based on a quasi-steady approximation, with the transient phenomena being considered as having the same characteristics to those of steady flow at the same instantaneous Reynolds number. Many earlier studies have shown that this approximation is not always feasible. Therefore, dynamic loads like those produced by vortex shedding and other hydrodynamic processes, like fluidelastic instabilities, turbulent buffeting and acoustic resonance should be investigated under transient conditions.

The modern literature presents the wavelets as a tool to analyze such class of problems, including time varying series and discontinuities in this series. The purpose of this paper is to explore the use of wavelets in the study of accelerating and decelerating turbulent flows through tube banks.

BACKGROUND

Spectral Analysis

Spectral analysis is essentially a modification of the Fourier analysis, more suitable for random time functions than for deterministic functions. It consists basically in the approximation of time series through a summation of sine and cosine functions called Fourier series [7].

Let f (t) be a generic function, defined in the interval [-π, π], which satisfies the Dirichlet conditions. Thus, f (t) can be approximated by a Fourier series, where the Fourier coefficients are the inner products of f (t) with the Fourier Basis function.

A usual method [8] to obtain the auto spectral density function of a random time series is the approximation of blocks of smaller length of this series by a Fourier series, where a spectral window multiplies each block, so that a block begins and ends with zero

Wavelet Analysis

Wavelet analysis is similar to Fourier analysis in that the original function is expanded over an orthogonal basis. The Fourier basis is a set of sinusoidal functions and the wavelet basis is a set formed by dilations and translations of a single wavelet function, the so-called mother wavelet.

A wavelet can be described as a wavy function carefully constructed so as to have certain mathematical properties [9]. An entire set of wavelets is constructed from a single "mother wavelet" so to represent a large class of functions, being considered a refinement of Fourier analysis.

As the name suggests, a wavelet is a "small wave" and grows and decays essentially in a limited time period [10]. A wavelet function tends to zero as time goes to infinity (compact support) and integrates to zero while its square integrates to unity.

There are many different wavelets such as that developed by Yves Meyer and Ingrid Daubechies [11] and the oldest one developed by A. Haar in 1910, considered the most suitable function to the introduction and of the understanding of wavelet analysis.

The simple function which defines a wavelet is called a "mother wavelet" since many others are generated through simple operations of dilations and translations. Denoting the scale as a and the position as b, the continuous wavelet basis is given by:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{1}$$

To have a discrete wavelet basis, a and b are replaced respectively by 2^j and $k2^j$, where j and k are the so called dyadic dilation and translation indexes, thus

$$\psi_{j,k}(t) = 2^{-j/2}\psi\left(2^{-j}t - k\right) \tag{2}$$

A 2^N long time series is expressed in a discrete wavelet basis as:

$$f(t) = \sum_{j=0}^{N}\sum_{k=1}^{2^{N-j}} d_{j,k}\psi_{j,k}(t) \tag{3}$$

Where, as in Fourier analysis, the wavelet or detail coefficients $d_{j,k}$ are simply the inner products of f(t) with the corresponding basis functions.

Associated to each "mother wavelet" there is a "father wavelet" or scaling function, which also gives birth to an orthogonal basis by means of dilations and translations:

$$\phi_{j,k}(t) = 2^{-j/2}\phi\left(2^{-j}t - k\right) \tag{4}$$

A j^{th} degree smoothed time series can be obtained combining the set $\{\phi_{j,k}, k = 1,\ldots,2^{N-j}\}$ with the scaling or approximation coefficients $a_{j,k}$ given by the inner products of f(t) with the corresponding basis scaling functions:

$$f(t)_{j^{th}smooth} = \sum_{k=1}^{2^{N-j}} a_{j,k}\phi_{j,k}(t) \tag{5}$$

The decomposition of the signal with a scaling function performs an averaging of the original data over the scale interval, while wavelet transform coefficients are related to differences of averages of successive scales.

In practice, the Haar wavelet is seldom applied because it is poorly frequency defined. Other types of wavelet and scaling functions are preferred. The choice of the best wavelet for a given problem is not straightforward. In some situations, the results are similar for most wavelets, but for some problems, the result of the analysis depends hardly upon the wavelet type used. Daubechies (db20) wavelet functions were selected in the wide wavelet world following a best filtering criterion.

All the sets $\left\{\psi_{j,k}\right\}$ and $\left\{\phi_{j,k}\right\}$ are mutually orthogonal, therefore the function can be expressed as:

$$f(t)=\sum_{k} a_{J,k}\phi_{J,k}(t)+\sum_{j\leq J}\sum_{k} d_{j,k}\psi_{j,k}(t) \tag{6}$$

where J is the index of the last decomposition level of interest, where the decomposition sequence, which can run until the level N, is truncated.

For a 2^N point sample, the indexes vary as follows: $1 \leq j \leq J \leq N$ and $1 \leq k \leq 2^{N-j}$. In other words, a time series f(t) can be write as a sum of a coarse scaling series and J increasingly fine detail series.

Wavelet analysis can be understood as a refinement of Fourier analysis. The Fourier transform describes an original function in terms of its frequency components, over the whole domain. But for describing a signal that is changing over time, one needs to know the time-frequency localization of the related amplitudes. In equation (5) the coefficients $d_{j,k}$ are related to the amplitudes at a given position k, corresponding to instant $t = 2^j k\Delta t$ and a period $2^j\Delta t$, where Δt is the acquisition interval. Then, there is a vector $\{d_{j,k}\}$ associated to each frequency interval $[1/(2^{j+1}\Delta t), 1/(2^j\Delta t)]$.

When used for signal processing, wavelet analysis has, as a first result, the detection of singularities, because wavelet coefficients are very sensible to discontinuities and abrupt behavior changes of the signal. The features of the signal are more visible at continuous wavelet analysis, but the discrete analysis is more feasible, because it is much more computing time and space saving than the continuous one.

Each set of detail coefficients retains the information concerning to a definite frequency interval and the signal can be reconstructed separately for each one of these intervals. These sets $f_j(t)$, which are part of the original signal, point out the localized time behavior of the signal at the corresponding frequency interval. However, the width of the frequency interval depends on the decomposition level, being larger for higher frequencies.

To obtain narrower frequency intervals another wavelet decomposition procedure must be applied. Regarding each detail coefficient vector as a series by itself and decomposing that series using the same wavelet and scaling functions, two series with respectively lower and upper half width frequency interval are obtained. This scheme, applied recursively at all levels, generates a "wavelet tree", and is called wavelet packet transform. Each wavelet packet transform is associated with a level j, and the j^{th} level decomposes the frequency interval of the original signal [0,f/2] into 2^{j} equal and individual intervals [10].

The first advantage of this band pass filter action of wavelet packet decomposition is that, by reconstructing separately each frequency interval, the signal can be seen and its behaviour analysed in a time frequency domain.

EXPERIMENTAL TECHNIQUE

The test section is a 1370 mm long rectangular channel, with 146 mm height and a maximal (adjustable) width of 193 mm, Fig. (1-a). 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 measurement location with about 1 % turbulence intensity.

For measurements of velocity and velocity fluctuations, DANTEC constant temperature hot wire anemometers were applied. Two single and a double hot wire probes were applied. The double wire probe; has one wire perpendicular to the main flow and a second wire inclined 45^o to the main flow, so that two components of the velocity vector and their fluctuations could be measured simultaneously.

Wall pressure fluctuations were measured by ENDEVCO piezo-resistive pressure transducers, mounted inside the tubes and connected to a pressure tap drilled in a nylon support adjusted to the tube inner wall.

Figure (1-b) shows schematic location of the probes in the tube bank. The support of hot wire "1" was fixed on the upper wall, while hot wire "2" was inserted from the outlet. The pressure transducer was installed in the central tube of the third row of the bank. All probes were placed at the same distance from upper and lower walls.

Data acquisition of velocity and pressure were performed with a Keithley DAS-58 A/D-converter board with a sampling frequency of 25 kHz, and a low pass filter set at 10 kHz for velocity and 1.6 kHz for pressure.

Time series were acquired in a transient flow, starting from rest and running to the stationary state, or from stationary state to rest, respectively, by turning the blower "on" or "off".

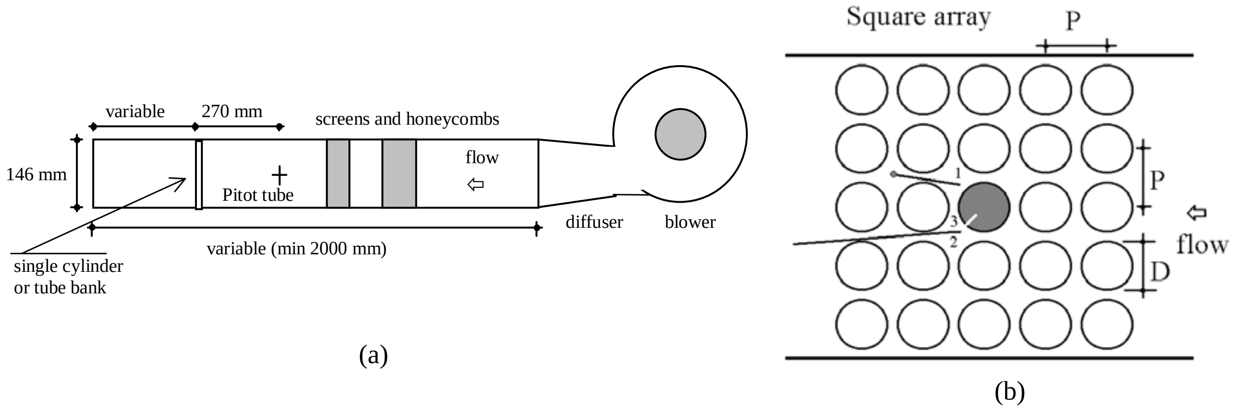


Fig. 1: Schematic view of the test section: (a) wind tunnel configuration; (b) tube bank with location of probes: 1, 2- hot wires, 3- pressure tap for pressure transducer.

At the first experiment two velocity components were acquired with a single tube assembled perpendicular to the flow, in order to produce a vortex street and, for comparison, a reference velocity was acquired in the wind tunnel free flow, which was considered homogeneous at the measurement location.

The second experiment was performed in a tube bank, with pitch to diameter ratio of 1.26, with tubes square arranged perpendicular to the main flow of the wind tunnel. The wall pressure of central tube of the 3rd row was acquired simultaneously with the velocities at both sides of the cylinder, in the region where separation occur.

Wavelet analysis was performed using the Matlab 5.3 software.

Analysis of uncertainties in the results has 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 is about 3.4%. Velocity fluctuations in the main flow direction are obtained with a mean error of 15%, while transverse velocity has an error of about 30%.

RESULTS

Fig. (2a) shows the transient signal acquired in the wake of a cylinder and the reference velocity. The Reynolds number defined with the tube diameter and the reference velocity was 3.1×10^4.

The power spectrum of the last half part of the vortex street series, Fig. (2b), where steady state is reached, shows nearly 104 Hz as the predominant frequency of vortex shedding in the wake. This is in agreement with the frequency of 98.5 Hz obtained by using the Strouhal number of 0.21.

In order to analyze the vortex street development, the transversal velocity fluctuations perpendicular to both tube and tunnel axis was computed from the signals obtained by the double wire probe. An 11th level wavelet packet decomposition was applied to the time series, performing the so-called multiresolution analysis, and then the 11th level nodes were reconstructed. The results for some nodes were displayed in Fig. (3).

Each signal of Fig. (3) shows clearly a transient increase of amplitudes, which occurs later for higher frequencies, showing the presence of the transient vortex shedding at the corresponding frequency and time. At last frequency interval, 103.7 to 109.8 Hz, the amplitude increase, which begins nearly the onset of stationary velocity, holds until the end of the time series, showing the presence of the stationary vortex shedding.

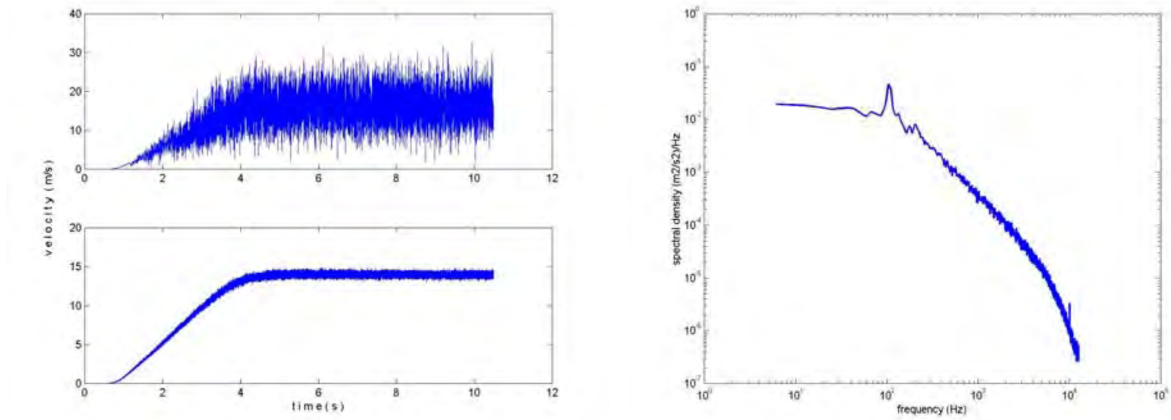
In order to relate the transient vortex shedding frequency and the free stream transient velocities approaching the cylinder, for each 6.1 Hz frequency band, from 30.5 to 103.7 Hz, the mean point of transient increase of amplitudes, which denotes the time frequency location of transient wake, was used to find the corresponding transient approaching velocity, according to the scheme shown at Fig. (4a). Some uncertainty in the determination of such points is due to, according to [6], the vortex shedding itself, which does not occur at a single distinct frequency, but rather it wanders over a narrow band of frequencies with a range of amplitudes.

The transient Strouhal number can be evaluated as:

$$\mathrm{Str}(t) = \frac{\overline{w}_s(t)\,D}{\overline{U}_{app}(t)} \tag{7}$$

where D is the tube diameter, $\overline{U}_{app}$ is the instantaneous mean approaching velocity and $\overline{w}_s$ is the mean frequency of the band.

Fig. (4b) shows, against Reynolds number, the transient Strouhal number, which is approximately constant along time, the slight variations around 0.21 (in red) are due to the experimental inherent uncertainties.



(a) (b)

Fig.2: (a) Transient velocity in the wake of a cylinder and free stream reference velocity. (b) Power spectrum of the stationary part of the vortex street series.

Fig. (6) shows the power spectral density of the stationary part of velocities and pressure signals of the second experiment, performed in a tube bank. More detailed results of pressure and velocity fluctuations for this geometry can be found in Ref. [12]. According to [13], the pressure measurements provide no information about fluid periodicities in banks with in line tubes. The spectrum of velocity fluctuations can provide some information, if taken behind the first row, because the flow within the rest of the array becomes fully turbulent. The measurements shown in this paper, however, were made behind the third row and consequently, one can see only a fully turbulence spectrum, with no evidence of vorticity shedding. In general, the behavior of spectra agree with former results obtained in Ref. [12] for this geometry. In the spectrum of pressure fluctuation the effect of the low pass filter at 1.6 kHz is clearly observed. This procedure allowed to avoid resonance peaks due to the connection from pressure transducer to the pressure tap.

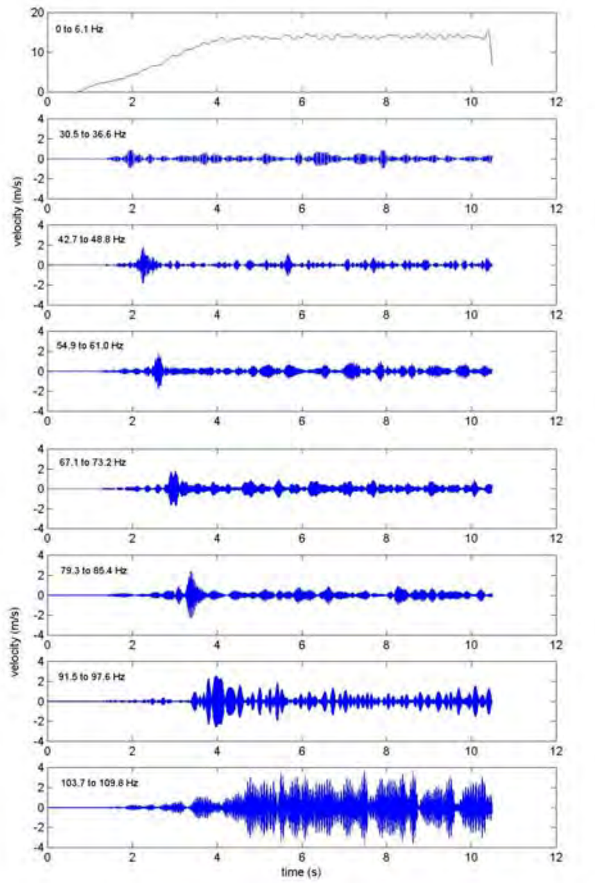
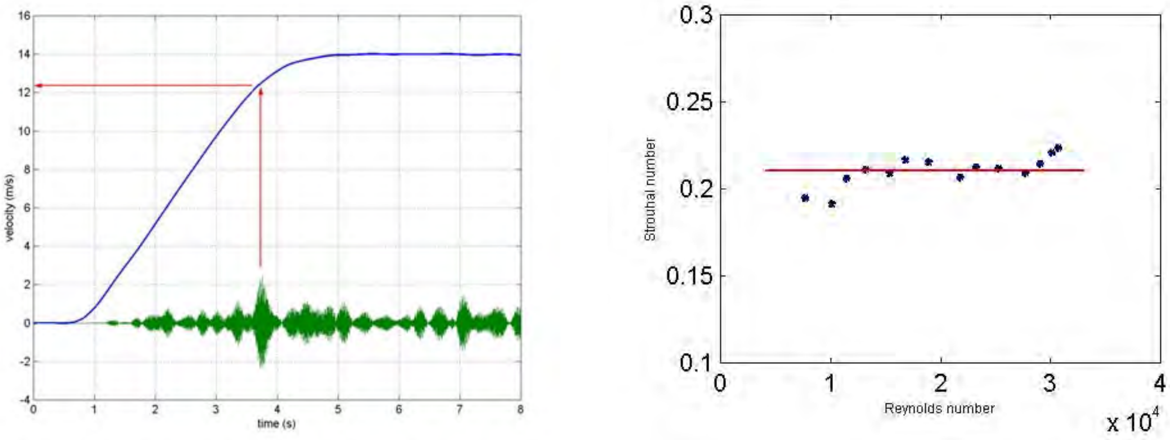


Fig. 3:Some reconstructed nodes for the transient velocity in the wake of a cylinder of Fig (2a), showing the time frequency evolution of the wake.



(a) (b)

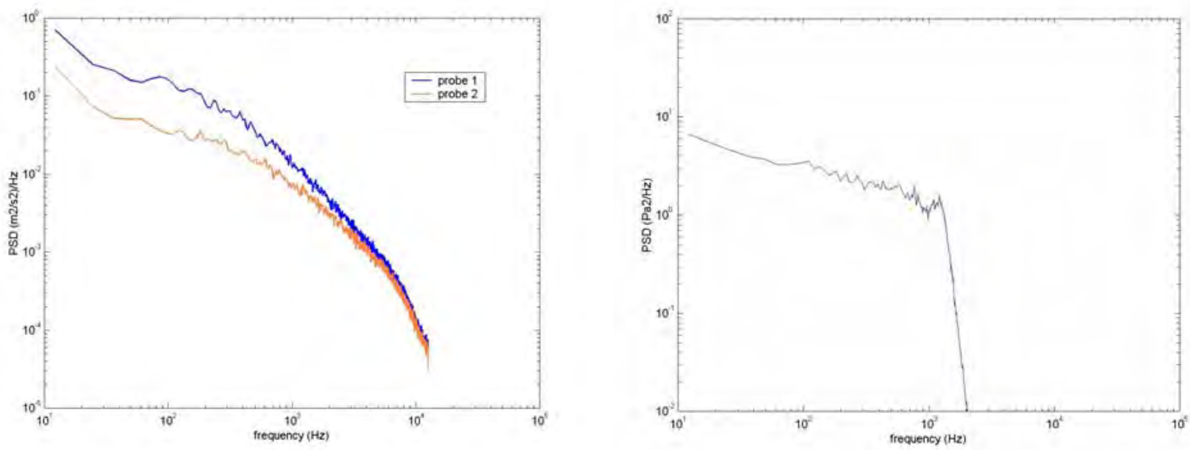
Fig. 4: (a) Time location of the transient vortex shedding and respective instantaneous mean approaching velocity, $\overline{U}_{app}$, for a generic frequency band. (b) Strouhal numbers Str(t) computed from transient frequency and approaching velocity against Reynolds number based on tube diameter

The velocity signals were however analyzed by means of a wavelet packet and some behaviors of the flow were evidenced.

Fig. (7) shows some selected frequency bands of the multiresolution analysis performed over the two simultaneous velocity signals, using the same Db20 filters already used for the wake analysis and the corresponding auto spectral densities. Corresponding colors are blue for Probe “1” and orange for Probe “2”. Location of the probes are given by Fig. (1). In general, the velocity measured by Probe “1”, which was nearer the tube wall than Probe “2” are lower than Probe “2”, but the turbulence intensity, evidenced by the amplitude of the signal and the height of the peaks in spectra are higher for Probe “1”.

The lower frequency band evidenced that the two signals alternate complementarily, at both transient and stationary parts, in order to maintain a regular mean velocity among them. This could be due to the fact that the probes are in the region of separation of the flow behind the tube, although the oscillations appeared to be higher then expected. This, at some extent, unexpected behavior was corroborated by the upper frequency band recomposed nodes, where one can see that the amplitudes of the two signals are almost ever shifted 180^o, with the higher amplitudes of one agreeing with lower amplitudes of the other, in accordance with [13, 14]. However, this phase shift was not observed in the plots of cross spectral densities, not shown here due to reasons of space.

Auto spectral densities (Fig. 7-b) show the dominant frequency of each signal. No contribution from other frequencies are observed, since they were smoothed by the filtering action of the wavelet.



(a) (b)

Fig. 6:Power spectral density of the stationary part of (a) velocity (Probe “2”) and (b) pressure fluctuation signals.

To have a better insight about this behavior, it was made a continuous wavelet analysis of the first quarter part of the signal, Fig. (8). The color scale used shows in lighter green the higher coefficients of the wavelet transform and in darker blue the lower ones. The coefficients are directly related to the energy of the signal and it is noticeable that, at each interval, the signal with the lower mean value have more energy at the fluctuations concerning the carrying energy vortices (lower frequencies).

By decelerating the flow, by turning the blower off, it was expected to make the transient longer than at start of the blower and than to obtain more details about the transient process. This actually happened, but series longer than the A/D capacity were necessary, without giving substantive additional informations.

CONCLUDING REMARKS

In this paper, the accelerating flow through a P/D = 1.26 tube bank is studied using hot wires and wavelet technique. The well known wake from a cylinder perpendicular to a turbulent flow was previously studied for the comprehension of the capabilities of the wavelet tools in a multiresolution analysis context.

The property of band pass filter provided by the concurrent use of wavelet and scaling functions, in a so-called wavelet packet transform, enabled the capture of the behavior of the wake in an accelerating flow. The energy distribution could be observed at each frequency band, which can be done as narrow as desired.

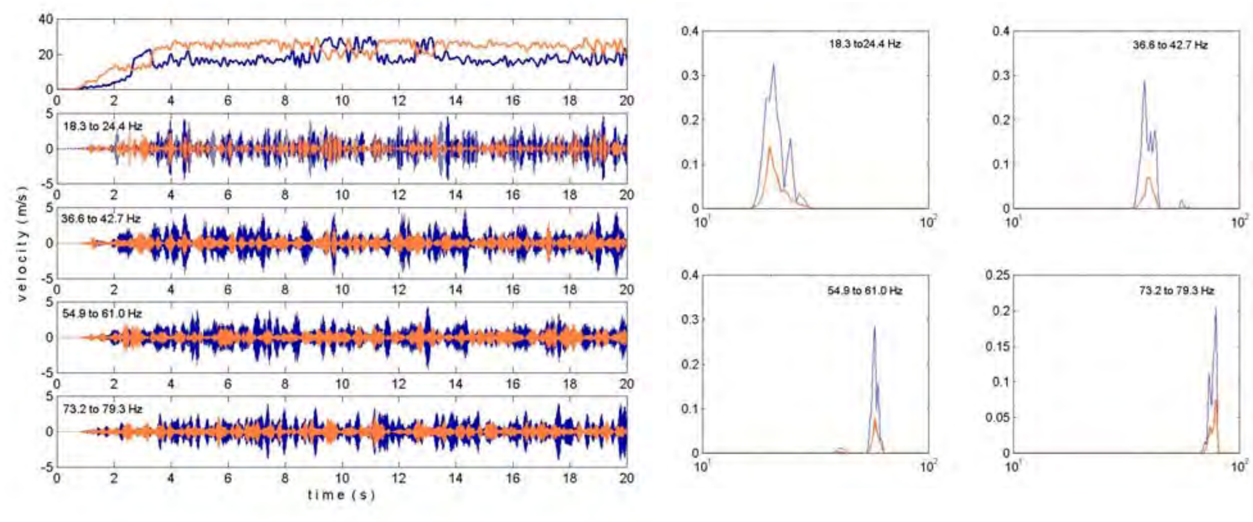
The smoothing property of wavelet decomposition and reconstruction of lower frequencies of the original transient signal is also very useful to obtain an instantaneous mean, as was done in this research work, and in extracting that mean from the signal to obtain the fluctuation.

The good agreement of the transient Strouhal number in the wake of a cylinder computed from parameters obtained in wavelet analysis with the classical stationary Strouhal number of 0.21, corroborates the proper use of wavelet for the transient turbulent wake analysis.

In the analysis of the accelerating flow through a tube bank, the wavelet technique captured the behavior on the wake region of a tube in the bank. The phase shift of the flow in both sides of the tube could be observed in the transient as well as in the steady state flow. The intensity of the velocity fluctuation during the transient part could also be observed in the spectra of the decomposed velocity signals.

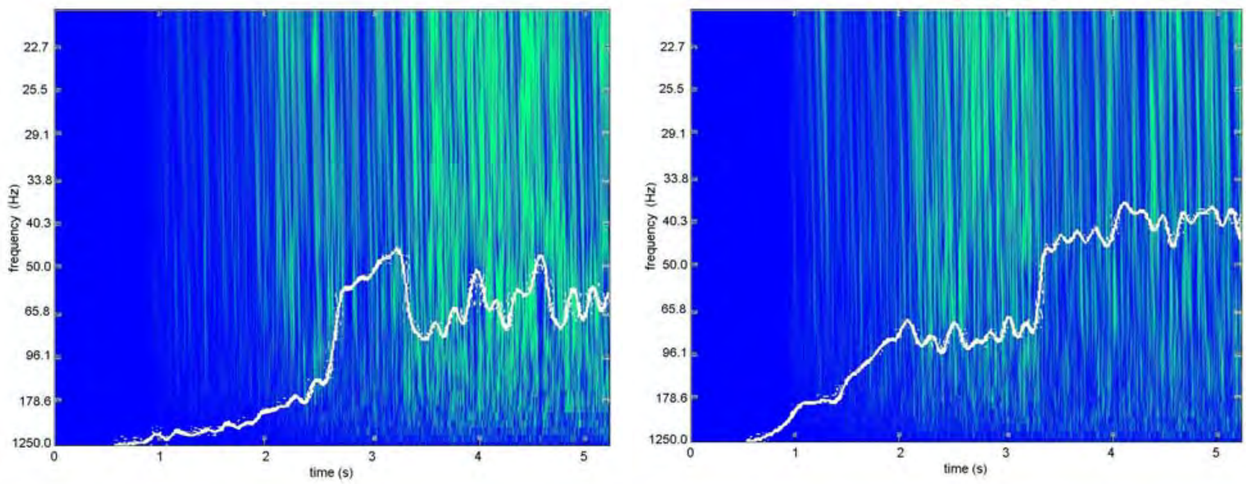
Continuous wavelet transform gave informations about the energy distribution of the signals with time.

The results in this paper show also that wavelet transforms, either discrete or continuous, are very useful tools in the analysis of transient flows through tube banks.



(a) (b)

Fig. 7: (a) Time-frequency analysis of velocity and velocity fluctuation behind the central tube of the third row of the bank. (b) Auto spectral densities of the decompositions. Probe "1" blue, Probe "2" orange.



(a) (b)

Fig. 8: Continuous wavelet transform of the first quarter part of the velocity signals starting from rest. (a) Probe “1”, (b) Probe “2”. Mean velocity signal is superimposed as reference.

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