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UNTERSUCHUNG EINER HINTERKANNTE BEI EINEM EINZELSCHAUFEL MIT HILFE DES WAVELET CONDITIONINGS

INVESTIGATION OF A SINGLE AIRFOIL TRAILING-EDGE FLOW USING WAVELET CONDITIONING

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Trailing-edge, wavelet, unsteady wall pressure

Abstract

The present study deals with the application of wavelet theory as a tool for the analysis of unsteady experimental data. Normalized wavelet coefficients are used as an energy detector in the time-frequency domain. Conditional average is performed on detected energy bursts, which allows highlighting the coherent structures within the suction side boundary layer of a single high-loaded airfoil.

Introduction

If turbulence has been investigated for centuries, the analysis of turbulent data still remains complex. Indeed, turbulent flows are characterized by the convection and burst of small scales, which are very difficult to detect as these phenomena are taking place in a very noisy environment. The rise of computing power and simulation techniques as well as the development of Laser based measuring systems such as PIV drove the development of sophisticated vortex detection methods in velocity fields.

Conversely, little progress was made until the last two decades in order to enhance the post-processing of time signals. Usually, time signals are considered as ergodic and their analysis is carried out in the frequency domain by means of Fourier transforms. Though, turbulent structures are localized in time and space, and their energetic contribution to any time signal is thus localized in time and frequency. As a result, signals from turbulent data are highly intermittent, which prevents from using the ergodicity hypothesis and limits the spectral analysis.

During the early eighties, a new class of mathematical functions called wavelets was developed to deal with time-frequency analysis. Their application to turbulence was first performed by Farge 1992. Among others, Farge proposed a wavelet based quantity in order to measure the intermittency of a turbulent time signal. Based on this work, Camussi and Guj 1997 developed a conditioning average method in order to investigate turbulent flows. This method is applied in the present study on simultaneous wall pressure-velocity measurement in the vicinity of a high loaded airfoil trailing-edge.

This work is organized as follows. The wavelet theory and conditional average are presented in a first part. The measurements are then described, and their analysis is carried out in a third part. Conclusions are drawn in a final part.

Wavelet conditioning

Wavelets are functions with compact support which allow a decomposition of a time signal in time *t* and a so-called resolution scale *r*, whose inverse is related to the frequency. A wavelet family is derived from an original wavelet, called the Mother wavelet $\Psi(t)$, by translation in time and dilatation of the mother wavelet. Practically, the Mother wavelet can be considered as a bandpass filter of center frequency f_c. Any wavelet of resolution scale *r* is then a bandpass filter of frequency f_c/r. The most widespread wavelet is the so-called Gaussian wavelet, whose expression and thus center frequency can be obtained analytically. An example is given in the Abb. 1. During the last two decades, dozens of wavelet families have been developed.

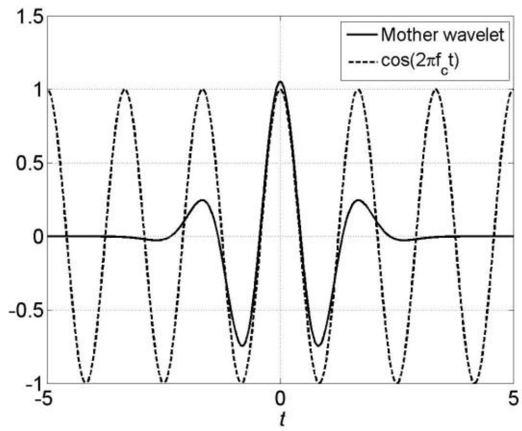

Abb. 1: Illustration of the Gaussian Mother wavelet. Comparison with a cosine.

Formally, the projection of a time signal *s(t)* in the (*t*,*r*) space is carried out according to the formula:

$$\omega(t,r) = \frac{1}{\sqrt{C_\Psi}} \int_{-\infty}^{\infty} \Psi^* \left(\frac{t-\tau}{r}\right) s(\tau) d\tau$$

where * denotes the complex conjugate and C_Ψ is a normalizing coefficient depending on the mean value of $\Psi(t)$.

Depending on the way the wavelet family is built, the decomposition can be reversible or not. When the wavelet supports are disjoints, wavelet transform is called discrete and the wavelet decomposition is bijective. Discrete wavelet transform is often used when dealing with a huge among of data, for there exist fast computation algorithms based on a dyadic decomposition of the (*t*,*r*) space, similarly to the fast Fourier transform. This method presents though a major drawback: the dyadic (*t*,*r*) space decomposition leads to a lack of resolution in time at low frequencies and in frequency at high frequencies. This is why wavelets with overlapping support can be used when precision is sought. In this case, the decomposition is called continuous wavelet transform.

The quantity $\omega^2(t,r)$ can be related to the energy contained the time signal *s(t)* at the time *t* and scale *r*. As a consequence, the Fourier autospectrum $S_{ss}(f)$ can be recovered by integrating all the coefficients at a given scale with respect to the time. In order to highlight the relative contributions of the wavelet coefficients to the autospectrum, Farge defined the LIM (for *Local Intermittency Measure*) as:

$$LIM(t,r) = \frac{\omega^2(t,r)}{\langle \omega^2(t,r) \rangle_t}$$

where $<.>_t$ stands for the average in time.

The conditional average method developed by Camussi and Guj (1997) relies on the hypothesis that the fluctuations generated by the turbulent structures are masked by random fluctuations, which have thus a zero average. This has been taken into advantage in a three steps method as follows:

Step 1: The wavelet transform of the signal is carried out. A working frequency and therefore a resolution scale are chosen in order to compute the LIM. In practice, a discrete rather than continuous wavelet transform is carried out and the LIM is computed at a high frequency, so that the precision on time is kept high. Using discrete wavelet transform, the greatest achievable precision is half the sampling rate.

Step 2: LIM coefficients are thresholded. Each time a LIM coefficient is greater than the threshold, an event is considered to happen and a sample of the original time signal centered on the detection time is extracted.

Step 3: An average of the extracted time samples is carried out. As the random fluctuations cancelled each other, the time signature of the most probable coherent event is revealed.

Step 1:
LIM distribution
Detection of events

Step 2:
Sample extraction from the original time signal

Step 3:
Averaged of the extracted samples

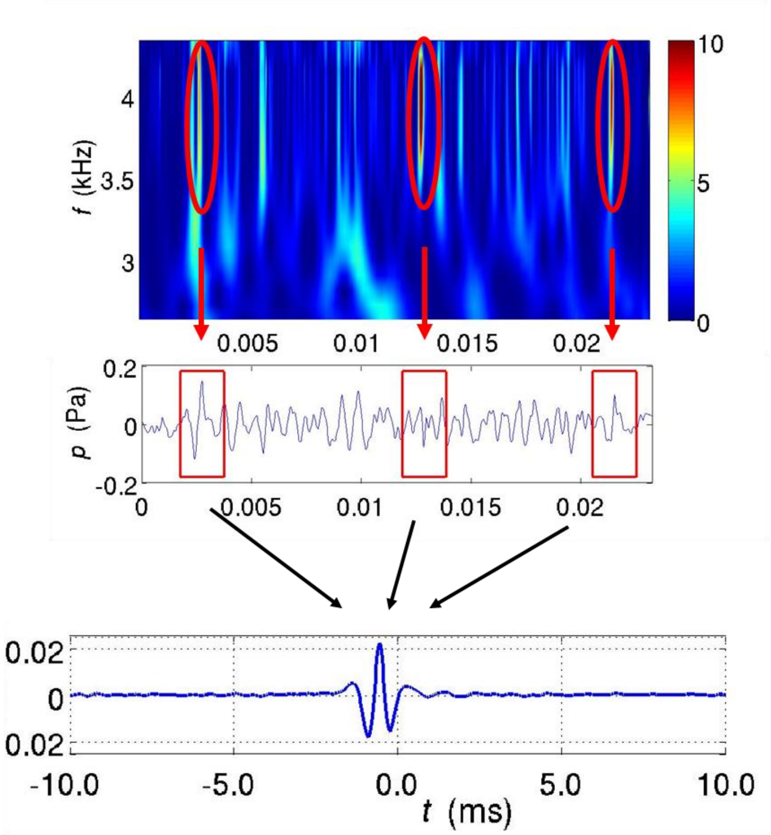

Abb. 2: Sketch of the auto-conditioning method.

A sketch of the method is presented on the Abb. 2. Practice shows that the trigger level has little effect on the results (Camussi & al. 2010), provided that enough samples are detected (statistic convergence must be achieved). On the contrary, the choice of the Mother wavelet may have an impact on the detection time of the events (Grilliat 2009). The present method is called auto-conditioning.

The last two steps of the conditioning method are not necessarily to be performed on the original time signal. This latter can be replaced with any other signal that has been recorded simultaneously. In that case, the method is called cross-conditioning. Velocity fields can be used as well: 2D-PIV fields in a blade tip leakage conditioned with wall pressure (Camussi & al 2010) showed that far-field pressure events detected in the high-frequency ranged were statistically related to large scale velocity fluctuations occurring in the tip leakage region of a single airfoil.

In the present study, velocity fluctuations occurring in the vicinity of the trailing edge are conditioned with wall pressure fluctuations measured on the suction side.

Experimental set-up

The experimental set-up is described in details in Camussi & al 2010. Only the major features are recalled hereafter. Sketches of the experimental set-up are given on the Abb. 3.

A thick and high-cambered airfoil, a NACA 5510 with 200 mm chord and 200 mm span, was placed in the potential core of a jet exiting the anechoic wind tunnel at the Centre Acoutique, Ecole Centrale de Lyon, France. The jet was limited on top and bottom by two walls. The wind tunnel section was 200*450 mm^2.

The angle of attack α was set to 15°. Though, the jet exiting the wind tunnel is deviated by the airfoil, which modifies the effective angle of attack. According to Brooks & al 1989, the effective angle of attack lied by 8°. This is close to the value used during the RANS simulation from Boudet & al. 2009. Based on a free air flow configuration, the authors obtained the same pressure distribution on the airfoil by setting the angle of attack to 7.5°. Measurements were performed at U_o = 70 m/s, which corresponds to a chord based Reynolds number Re = 930000.

A hot-wire probe, a *Dantec 55P11*, was mounted 3 mm downstream from the trailing edge (7.5 mm downstream the pressure probe), 2 mm away from the mean line in the suction side. Acquisitions were carried out using the *Labview* software with a sampling rate of 44.1 kHz.

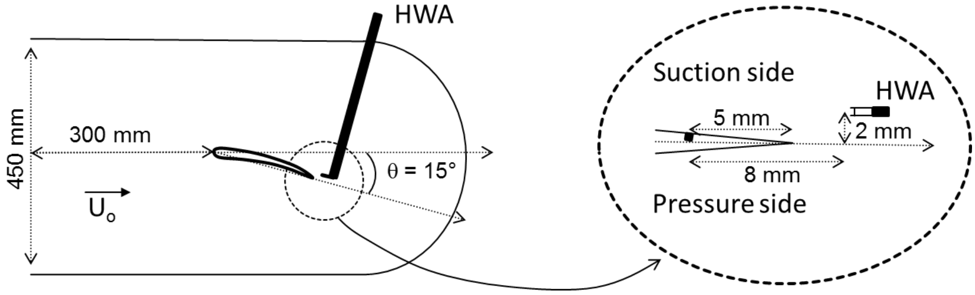

Abb. 3: Sketch of the experimental set-up: side-view (left) and close-up on the tailing-edge area (right).

Wall pressure measurements were carried out using the remote microphone technique described by Perennes & Roger 1998. This method consists in designing small pinholes at the airfoil surface and connecting them to flush mounted microphones at the top of the airfoil by means of capillary tubes. This way, unsteady wall pressure measurements can be carried out with a great spatial resolution. The microphone was a B&K ICP 4935, and the acquisition were carried out at a 44.1kHz sampling rate with help of a National Instruments PXI and the software IDDEAS. The pinhole (eg the pressure probe) was located on the suction side, 5 mm upstream from the trailing edge.

The transfer function from the pinhole to the microphone was measured using the method developed by Perennes and Roger (1998). Its phase was post-processed in order to measure the convection time within the capillary tube. This time is of the order of 0.5 ms.

Results

The wall pressure and velocity PSD are given on the Abb. 4. Even if the wall pressure fluctuations exhibit strong fluctuations at low frequencies, which is attributed to the impinging jet (eg Grilliat 2009), both PSD are representative of a trailing edge flow. In particular, the high frequency decreasing rate (respectively f^{-2} for wall pressure and $f^{-4/3}$) are typical of a suction side boundary layer and a turbulent wake.

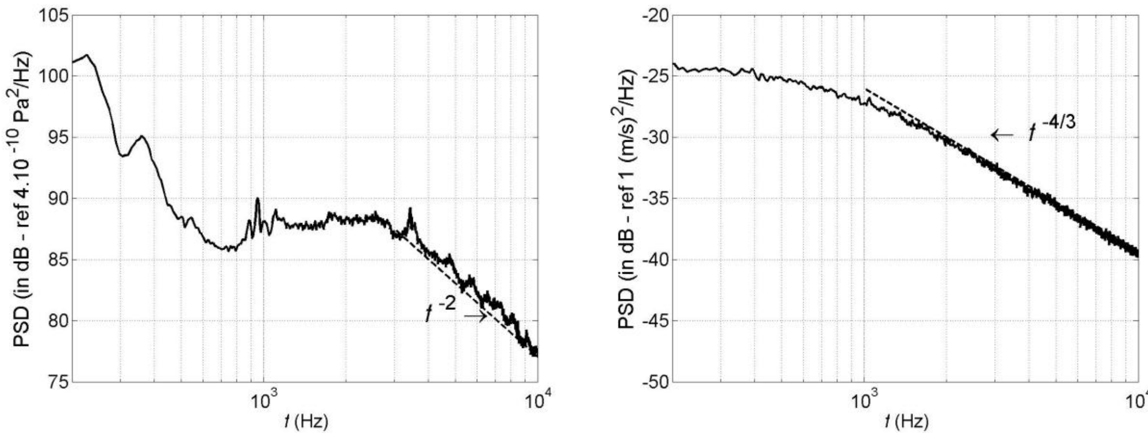

Abb. 4: Sketch of the experimental set-up: side-view (left) and close-up on the tailing-edge area (right).

The results from the conditioning procedure are presented on the Abb. 5. In order to account for the propagation time within the capillary tube, the velocity signal has been shifted of 0.5 ms. The auto-conditioned pressure signal exhibits a small positive hump, followed by successive negative and positive peaks. Conversely, the cross-conditioned velocity signal presents a small negative hump, followed by a high positive peak and a secondary negative hump. In a nutshell, the signals present out of phase fluctuations, which is typical for velocity and pressure. These fluctuations can thus be interpreted as the signature of a coherent structure successively convected past the pressure and HWA probes.

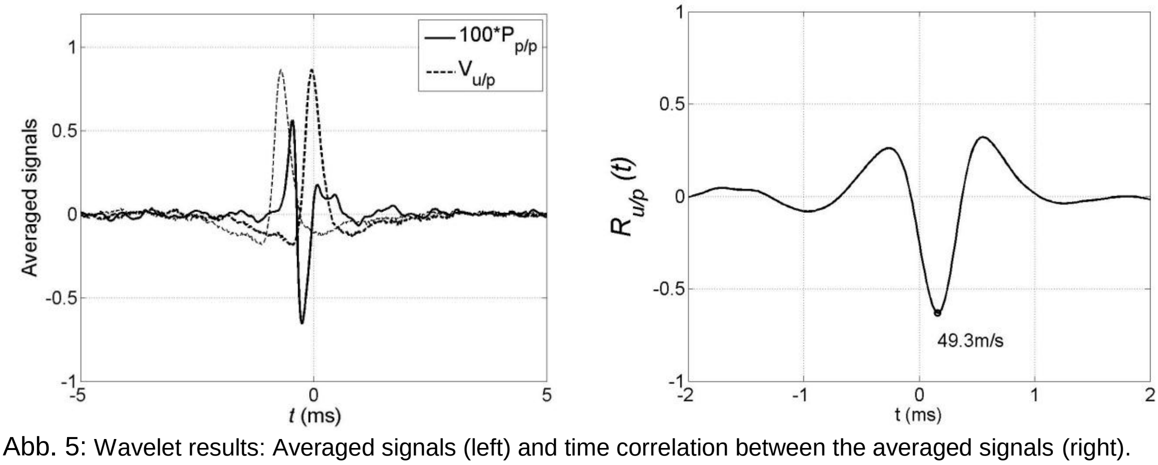

Abb. 5: Wavelet results: Averaged signals (left) and time correlation between the averaged signals (right).

In order to measure the convection velocity, a time correlation between the averaged signals was carried out. According to the out of phase fluctuations, the minimum was sought, leading to the time delay. Knowing the distance between the two probes, the convection velocity U_c = 49.3 m/s could be calculated. This velocity is 70% of the inflow velocity U_0, which is of the order of convection velocities within a turbulent boundary layer. This further supports the interpretation of the averaged signals.

A parametric study on the influence of the velocity U_0 was carried out by Grilliat 2009. Pressure and velocity peaks were successfully reduced respectively with $U_0^{1.5}$ and U_0. A stunning overlap of the time signals was achieved by using an exotic time scale: $t.U_0^{0.5}$. This nonphysical result was explained with help of the potential theory. A model of the flow was built, consisting in an elementary vortex convected at the velocity U_c along a wall. It was found that the pressure a velocity time signals generated by the vortex scaled with $t.U_c/b_0$ (b_0 being the distance of the vortex to the wall). The convection velocity being proportional to the inflow velocity U_0, the parameter b_0 scales with $U_0^{0.5}$, which is typical of a laminar boundary layer. It is thus supposed that the observed structures are generated very close to the laminar sublayer on the airfoil suction side.

Conclusions and Outlook:

Wavelet conditioning has been described. When dealing with turbulent time signals, this tool can extend a spectral analysis. In the present study, pressure and velocity fluctuations in the vicinity of a single airfoil trailing-edge were conditioned with the pressure fluctuations, highlighting the convection of turbulent structures past the two probes.

This technique can be used with other measurement systems, such as LDA of PIV devices. This way, noisy velocity fields can be cleaned and statistically related to energetical fluctuations of any signal recorded simultaneously. Work is currently performed in order to improve the technique.

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