

Part III

Effects induced by accelerating flows on rigid slender structures

Chapter 5

Estimation of thunderstorm-induced mean wind speeds and accelerations through continuous wavelet-based procedures

As anticipated in Chapter 3, the definition of the slowly-varying mean wind speed for thunderstorm outflows is not a straightforward task as it is for synoptic winds. It is customary to derive the time-varying mean from a moving average over a suitable time interval, i.e. (Choi and Hidayat, 2002; Chen and Letchford, 2004b), which is chosen on the basis of its capacity to provide a satisfactory description of the main, generally low-frequency, fluctuations present in a typical time history of the velocity recorded during a thunderstorm. The rationale of this decomposition is that the residual fluctuation deriving from the subtraction of the slowly-varying mean, after appropriate manipulations, should be treated with suitable techniques to obtain a reduced fluctuation, which may be represented with sufficient accuracy through a zero mean fluctuation schematised as a stationary process.

Several averaging time intervals were tested, for instance, by (Lombardo et al., 2014). On the basis of the analysis of a high number of thunderstorm records, (Solari, Burlando, et al., 2015) suggested that a moving average period of 30 [s] might be a reasonable choice to obtain a satisfactory separation between the low and high frequency components present in the velocity signals. The effect of applying different filters to the average procedure carried out within the window width was also recently discussed by (Tubino and Solari, 2020).

Several more advanced processing procedures were also proposed, such as proper orthogonal decomposition, variable averaging interval, empirical mode decomposition and discrete wavelet transform, e.g. (Chen and Letchford, 2005; McCullough et al., 2014; Su, Huang, and Xu, 2015).

However, it should be pointed out that the choice of the procedure to derive a suitable time-varying mean should be driven by its application. In particular, if the prediction of the response of a structure to the effects induced by a thunderstorm is the main purpose, it is reasonable to require that the time-varying mean should not only adequately follow the trend of the original wind signal, but also that it should not cause a dynamic amplification effect, but only a quasi-static contribution to the structural response. This implies that the maximum frequency present in the moving mean be sufficiently smaller than the first natural frequency of the structure in consideration (Su, Huang, and Xu, 2015; Kareem et al., 2019), and that it has to be inherently associated with turbulence components which slowly vary with time, so that they may be considered as highly coherent for the spatial scales associated with the structure. As a matter of fact, the mechanical admittance function for a SDOF system, for frequencies which are sufficiently lower than the fundamental one n_1 (i.e. $0.5-0.6 n_1$) is close to $\frac{1}{k}$, being k the structural stiffness. Consequently, the magnification function is almost

unitary, indicating a quasi-steady behaviour of the structure to the excitation. This remark permits to justify the adoption, in the first part of the Thesis, of the slowly-varying mobile mean wind speed evaluated through a moving average period of 30 [s].

The extraction of a sensible mean wind speed from signals is only one of many peculiar aspects associated with thunderstorm outflows. While that subject has been greatly investigated and deepened in the literature in the last twenty years, the same great effort has not been devoted to other challenging aspects associated with these phenomena, for instance the estimation of thunderstorm-induced accelerations, which are caused by the rapid and dramatic variations of wind speed and direction (Wakimoto, 2001). These can have great impact on the dynamic response of a structure, in particular generating accelerations that exceed those caused by stationary synoptic events at comparable wind speeds (Bentz and Kijewski-Correa, 2009). (Kijewski-Correa and Bentz, 2011) related this aspect to the broad-band character of the energy associated with thunderstorm outflows, able to excite multiple modes of the structure. Moreover, the rapidness with which wind speed varies might subvert the applicability of the strip and quasi-steady theory (Kawai, 1983) because of two possible effects. First, acceleration-induced forces arise on a body subjected to an unsteady flow, and these may be related to two different components (inertial forces), namely the added mass force and the Froude-Krylov force (Buresti, 2012). On the other hand, the vorticity field around the body might be affected by the velocity variation, inducing a change of the aerodynamic loads not related to the inertial forces. Therefore, the definition of thunderstorm-induced accelerations would be instrumental also for the definition of similitude parameters to be employed in the reproduction of unsteady flows in suitable wind tunnels, aiming at characterising the effects associated with non-stationary winds on structures, e.g., (Jesson et al., 2015; Elawady et al., 2017; Ting Yang and Matthew S. Mason, 2019).

There is no reason why the separation of components seen for the wind speed should not apply for the acceleration as well. This would permit to define a slowly-varying acceleration, associated with components of the energy cascade which are strongly coherent for the examined structure. This component may be used to estimate the effects underlined before.

In this chapter, the continuous wavelet transform is used to extract suitable slowly-varying means and, consequently, fluctuating residuals, from thunderstorm-induced wind velocity signals. Secondly, the velocity such obtained is derived to estimate the slowly-varying mean acceleration associated with the signal. This quantity is then subtracted from the original signal of acceleration to define its fluctuating component. The continuous wavelet transform permits to follow in time the variation of the frequencies contributing to the energy or to other features of a given signal. The choice of the continuous wavelet transform, rather than the more commonly used discrete one, is connected with the greater flexibility that it may provide. Indeed, the extraction of a slowly-varying mean is practically equivalent to a low-pass filtering with a cut-off frequency that should be suitably chosen according to the characteristics of the velocity signal characterising the class of thunderstorm events in consideration. If the discrete wavelet transform is used, this choice cannot be arbitrary because the discretisation of the scales (connected to the inverse of the frequencies) must be carried following powers of two, whereas with the continuous transform it may be freely selected according to the required application. More in general, when the wavelet transform is applied to obtain a time-frequency description of a time-varying signal, the choice of the continuous or discrete version depends on the particular application. Thus, thanks to a suitable choice of particular wavelet shapes and of well-defined time and frequency shifts, the discrete transform provides an orthogonal representation, capable of describing the given signal with a minimum number of coefficients at different levels of detail. Therefore, that type of transform is particularly suited for signal compression, denoising or transmission. Conversely, when the primary goal is a detailed time-frequency analysis, with a precise localisation of signal transients, the continuous transform is definitely preferable, and is thus a perfect candidate to obtain a flexible procedure to analyse

the wind time histories obtained during thunderstorm events. As a counterpart, the continuous transform is not an orthogonal representation, which implies that it is redundant, i.e. that the output time-frequency maps contain information regarding not only the analysed function but also the wavelet functions. However, this is not a great drawback, e.g. (Kijewski-Correa and Kareem, 2006), for an experienced user and it actually provides a stable representation and the possibility of choosing the wavelets freely, so that they have desirable properties as regards the interpretation of the results and the application of dynamical filters.

Following this introduction, a brief description of the continuous wavelet transform is provided in Section 5.1. Section 5.2 firstly illustrates traditional techniques to extract the slowly-varying mean wind speed of a thunderstorm outflow signal, then describes the novel continuous wavelet transform-based technique to pursue the same scope, reporting also an example. In Section 5.3, the slowly-varying wind speed is derived, obtaining the slowly-varying mean acceleration and, consequently, its fluctuating component, which are characterised in statistical terms. Section 5.4 extends the application of the technique to a set of 15 wind events associated with thunderstorm outflows, reporting ensemble analyses in terms of statistical characterisation of the residual, permitting to express remarks about the importance of acceleration-induced forces on structures. Section 5.5 reports the conclusions.

5.1 Outline of continuous wavelet transform procedures

A wavelet can be any real or complex-valued function $\psi(t) \in L^2$ that satisfies the following admissibility condition:

$$C_\psi = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} |F_\psi|^2 |\omega|^{-1} d\omega < \infty \quad (5.1)$$

where $|F_\psi(\omega)|$ is the Fourier transform of $\psi(t)$; this condition implies, in practice, that $\psi(t)$ has zero mean value.

The function $\psi(t)$ is called the mother wavelet and can be used to generate a wavelet family $\psi_{a\tau}(t)$ by continuous translation and dilatation

$$\psi_{a\tau}(t) = a^{-\frac{1}{p}} \psi\left(\frac{t-\tau}{a}\right) \quad (5.2)$$

where the scale a and the parameter τ characterise the dilation and the translation of the wavelet function, respectively. The value of p defines which is the norm of the wavelet that is constant upon dilation. In particular, it may readily be seen that when $p = 1$ or $p = 2$ the $L1$ or the $L2$ norms, respectively, of the dilated and translated wavelets $\psi_{a\tau}(t)$ are constant and equal to the corresponding values of the mother wavelet.

The continuous wavelet transform of a function $x(t)$ is defined as the L^2 inner product between $x(t)$ and the wavelet family $\psi_{a\tau}(t)$:

$$W_x(a, \tau) = \int_{-\infty}^{+\infty} x(t) \psi_{a\tau}^*(t) dt \quad (5.3)$$

where $*$ indicates complex conjugation.

The formula for the inverse transform is the following, e.g. (Kaiser, 1994).

$$x(t) = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} \int_0^{+\infty} a^{\left(\frac{2}{p}-3\right)} W_x(a, \tau) \psi_{a\tau} da d\tau \quad (5.4)$$

The energy of the signal may also be recovered from the wavelet transform:

$$||x(t)||^2 = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} \int_0^{+\infty} a^{\left(\frac{2}{p}-3\right)} |W_x(a, \tau)|^2 da d\tau \quad (5.5)$$

In the following, both values 1 and 2 are used for the parameter p , and the corresponding transforms are denoted as the $L1$ and $L2$ transforms. Indeed, even if the $L2$ transform is the most commonly used, it may be noted that in certain circumstances the $L1$ transform may be preferable for the characterisation of the higher frequencies which can be present in a signal. In the present Thesis, the complex Morlet wavelet is used:

$$\psi(t) = \exp(\omega_0 t) \exp\left(-\frac{t^2}{2}\right) \quad (5.6)$$

whose Fourier transform is

$$F_\psi(\omega) = \exp\left(\frac{-(\omega - \omega_0)^2}{2}\right) \quad (5.7)$$

Although this wavelet does not exactly satisfy the admissibility condition, it becomes admissible when $\omega_0 \geq 6$ within typical computer round-off accuracy. The Morlet wavelet is chosen because of its many favorable features, the first of which is that a simple relation holds between the scale parameter a and the usual Fourier frequency n , viz. $n = \frac{\omega_0}{2\pi a}$. Furthermore, it is a progressive wavelet, i.e. an analytic signal with $F_\psi = 0$ for $\omega < 0$, which is an advantageous feature for the characterisation of modulated signals, e.g. (Carmona, Hwang, and Torrésani, 1998; Buresti, Lombardi, and Bellazzini, 2004; Mallat, 2009). The Morlet wavelet has also an optimal joint time-frequency concentration and provides an excellent compromise between time and frequency resolution. In fact, the dilation procedure expressed by Eq. 5.2 allows the definition of analysing wavelet functions which are all characterised by the same number of oscillations, obtaining Heisenberg boxes whose areas are a function of the resolution in time and frequency (Addison, 2002). The wavelet functions are then stretched in such a way that they provide a good frequency resolution at low frequencies and a good time resolution at high frequencies. The output of the wavelet transform at a particular couple of time and frequency represents the contribution, in a certain time interval around the chosen instant, of frequencies contained in a certain interval around the selected one. The dimensions of those intervals define the frequency and time resolutions of the transform and depend on the chosen wavelet. According to the requirements of the procedure in which the wavelet transform is used, one may choose to improve the frequency or the time resolution. For instance, it is seen in the following that, in certain circumstances, it may be useful to improve the frequency resolution even if this decreases the time resolution. With the Morlet wavelet this can be done easily by increasing the value of the central frequency parameter ω_0 .

If a complex wavelet is used, the output of the transform is complex and may be represented in maps where, for each value of time and frequency, various quantities may be reported. The most common one is the square modulus of the transform, which is directly connected with the energy of the signal and may also be advantageously used to develop dynamical filters. This may be done, for instance, by choosing a threshold value and applying it to the map: the values above the threshold are kept and those below it are put to zero. The inverse transform is then applied and the extracted signal is equivalent to the application of a particular band-pass filter with continuously varying multiple bands. In other words, only the frequencies giving a chosen level of contribution to the energy of the signal fluctuations are thus retained in different intervals of time, e.g. (Torrence and Compo, 1998). On the other hand, the information contained in the square modulus of the transform may be used to identify the fundamental harmonic components which are present in the signal, especially if this is irregular and intermittent, such as, for instance, the flow near the tip of a finite body

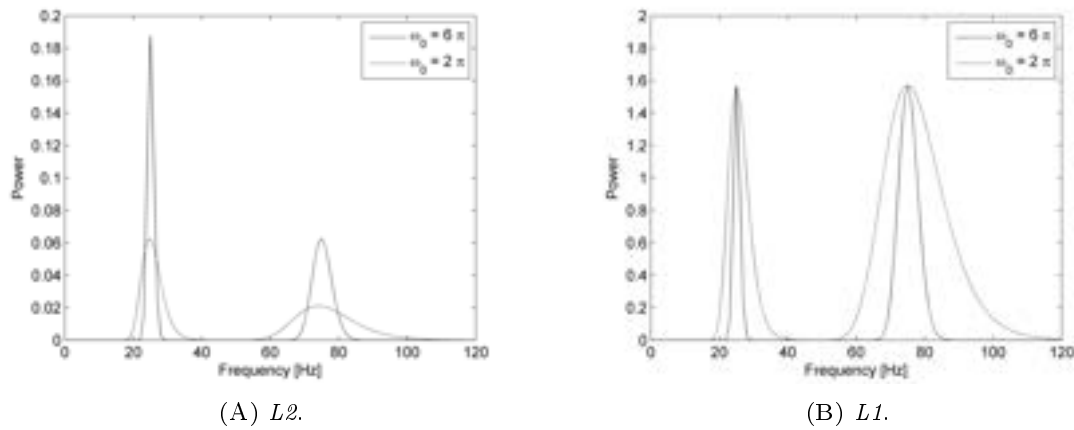


FIGURE 5.1: Morlet wavelet power spectra with different values of ω_0 ; courtesy of Prof. Guido Buresti.

(Buresti, 1998) or thunderstorm-induced effects on structures (Figure 1.5B).

If the values of the square modulus of the wavelet transform are integrated in time, a wavelet spectrum is obtained, which may be shown to be connected with the Fourier power spectrum averaged by the power spectrum of the wavelet. Particularly for highly non-stationary and modulated signals, the wavelet spectra are smoother than the Fourier spectra and the dominating frequencies may better be highlighted without the necessity of any averaging procedure. The wavelet power spectrum can thus be evaluated as:

$$P_{x,W}(a) = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} |W_x(a, \tau)|^2 d\tau \quad (5.8)$$

On the other hand, cross-sections of the square modulus maps at fixed times provide the time variation of the frequencies contributing to the energy of the signal, and may thus be connected with a sort of time-varying power spectrum. However, in this case the wavelet finite time resolution must be considered, which implies that even sudden changes of the dominating frequencies produce effects on the map cross-sections for intervals of time that encompass the instants when the variations take place.

To show the potential of the continuous wavelet transform, in Figure 5.1 examples are shown of the $L2$ and $L1$ spectra of a signal representing the addition of two sinusoidal functions of equal amplitude at 25 [Hz] and 75 [Hz]; the spectra are obtained with the Morlet wavelet and two values of the parameter ω_0 . As can be seen, in the $L2$ spectra the areas below the curves are equal for the two frequencies and the shape of the curves represent the Fourier transforms of the Morlet wavelet; conversely, in the $L1$ spectra the maximum values are equal. Thus in wavelet spectra the information on the presence of sinusoidal contributions is given by the frequencies of the peaks, and these are enhanced for the higher frequencies when the $L1$ transform is used, irrespective of their contribution to the energy of the signal. Furthermore, Figure 5.1 also suggests that when the objective is the extraction of narrow-band components rather than the analysis of their time variation, using a high value of the parameter ω_0 may be advantageous to avoid possible spectral interferences.

The wavelet transform may also be used to characterise the correlation between two signals, providing not only the time variation of the frequencies simultaneously present in the two signals that contribute to their correlation, but also the phase between the fluctuations at those frequencies. Indeed, if $W_x(a, \tau)$ and $W_y(a, \tau)$ are, respectively, the wavelet transforms of two signal $x(t)$ and $y(t)$, it is possible to define the wavelet cross-scalogram (Onorato et al.,

1997) as follows

$$W_{xy}(a, \tau) = W_x^*(a, \tau)W_y(a, \tau) \quad (5.9)$$

If a complex wavelet is used, it may be shown (Daubechies, 1992; Onorato et al., 1997) that the real part of the cross-scalogram (ReW_{xy}) gives the time-local contribution of each scale (frequency) to the correlation between the two signals. For instance, if the $L2$ transform is used, it is possible to write:

$$\int_{-\infty}^{+\infty} x(t)y(t)dt = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} \int_0^{+\infty} \frac{1}{a^2} ReW_{xy}(a, \tau) da d\tau \quad (5.10)$$

The real part of the cross-scalogram is hereinafter named as the co-scalogram CoW_{xy} . It is then possible to define a wavelet local correlation coefficient (Buresti and Lombardi, 1999):

$$WLCC(a, \tau) = \frac{CoW_{xy}(a, \tau)}{|W_x(a, \tau)||W_y(a, \tau)|} \quad (5.11)$$

which provides the time-local contribution of each frequency present in $x(t)$ and $y(t)$ to their correlation coefficient.

In the following, the term *CWT* shortens the name continuous wavelet transform. Moreover, the explicit dependence of all the quantities on the time t is implicitly considered in the sections concerning applications.

5.2 Velocity analysis

This section is articulated in order to firstly provide a background concerning one family of procedures to extract the mobile mean from records associated with thunderstorm outflows, the moving average technique adopting suitable weighting functions (Section 5.2.1). Then, with the same scope, a novel continuous wavelet transform-based technique is proposed and illustrated (Section 5.2.2), describing the parameters to be assigned. The procedure has been applied on a selected 10-minute wind event record, which is present in the databases of the “*Wind and Ports*” (WP) (Solari, Repetto, et al., 2012) and “*Wind, Ports and Sea*” (WPS) (Repetto et al., 2018) European projects, exploring the sensitivity of the filtering to the parameters. Finally, the obtained time-varying mean wind speed is compared with the outcomes of the two different strategies described in Section 5.2.1: the statistical characteristics of the residual and the correlation between the mean speed and the residuals are analysed and commented for the different methods.

5.2.1 Moving average techniques adopting suitable weighting functions

Summarising what has been reported by (Tubino and Solari, 2020), the moving average technique represents the most common way to extract the time-varying mean of non-stationary winds, because of its simplicity. Often, this procedure is accomplished by defining a time window of size T_W . As mentioned in the introduction and Chapter 3, that quantity is often put equal to 30 [s] for thunderstorm outflows. The classical weighting function is constant and has been extensively applied by many authors, e.g. (Choi and Hidayat, 2002; Chen and Letchford, 2004a; Solari, Burlando, et al., 2015).

Its representation in the time domain is:

$$w_C(t) = \begin{cases} \frac{1}{T_W} & |t| < \frac{T_W}{2} \\ 0 & |t| > \frac{T_W}{2} \end{cases} \quad (5.12)$$

As pointed out by (Su, Huang, and Xu, 2015), it is possible to adopt different and more suitable weighting functions, rather than the constant one. While they proposed a kernel regression technique, (Tubino and Solari, 2020) focused their attention on a Gaussian weighting function, which is defined in the time domain as:

$$w_G(t) = \begin{cases} \frac{\exp\left(-\frac{\phi t^2}{T_W^2}\right)}{\int_{-\frac{T_W}{2}}^{+\frac{T_W}{2}} \exp\left(-\frac{\phi t^2}{T_W^2}, dt\right)} & |t| < \frac{T_W}{2} \\ 0 & |t| > \frac{T_W}{2} \end{cases} \quad (5.13)$$

While for the constant weighting function T_W is the only parameter to be assigned, the Gaussian one also requires a second parameter, ϕ , which is responsible of the truncation outside the interval $\left[-\frac{T_W}{2}; \frac{T_W}{2}\right]$; in fact, if ϕ is greater or equal to 12, that effect can be neglected and the Fourier transform of w_G is:

$$F_{w_G}(n) \approx \exp\left(-\frac{\pi^2 n^2 T_W^2}{\phi}\right) \quad (5.14)$$

A value of ϕ greater but close to 12 allows the separation between the harmonic content of the mean and fluctuating components to be clarified, whilst that does not occur for the constant weighting function.

A remarkable result of the paper by (Tubino and Solari, 2020) is that the traditional adoption of a constant weighting function is the responsible of the unphysical oscillation behaviour which are potentially found in the low frequency range of the power spectral density function (PSDf) associated with the longitudinal reduced fluctuation, $\tilde{U}'$ (Solari, Burlando, et al., 2015; Zhang et al., 2018). This drawback can produce errors when estimating the dynamic response of structures whose mechanical admittance harmonic content is in the range where the oscillations are more evident. When a Gaussian weighting is instead adopted, the associated reduced turbulence is characterised by a smoother PSDf, preventing thus the unphysical oscillations which have been mentioned before. On the other hand, the adoption of a Gaussian weighting function leads to a higher correlation coefficient between the mean velocity and its fluctuating component. They finally advised the adoption of advanced procedures to extract the mobile mean, such as wavelet transforms.

5.2.2 A continuous wavelet transform-based novel technique

The concepts introduced in Section 5.1 regarding the *CWT* are now applied on a 10-min wind event associated with a real thunderstorm outflow. The signal has been acquired in Genoa in the night between the 2nd and 3rd of November, 2012 (WE3 in Chapters 3 and 4). The change of the flow direction is neglected in this analysis. The sampling frequency at which the anemometer network handled by the University of Genoa samples the registration is 10 [Hz], therefore the wind event of interest is composed of 6000 samples. The continuous wavelet transform, Eq. 5.3, is applied on the central 4096 ($=2^{12}$) samples (identified by the black dashed vertical lines in Figure 5.2A) on a frequency range which varies from 0.001 [Hz] to 10 [Hz]. Consequently, four different frequency decades are identified ($10^{-3} - 10^{-2}$, $10^{-2} - 10^{-1}$, $10^{-1} - 1$, $1 - 10$ [Hz]). In order to have a better resolution at low frequencies, the frequency scales to study the energetic contribution of the signal have been assigned in the same number (501) to each decade. The results concerning frequencies higher than the Nqvist frequency (5 [Hz], in this case) have been disregarded. Before carrying out the transforms, a zero-padding before and after the signals was carried out in order to obtain 8192 (2^{13}) samples. However, in the following all the reported analyses refer to the central 4096 samples.

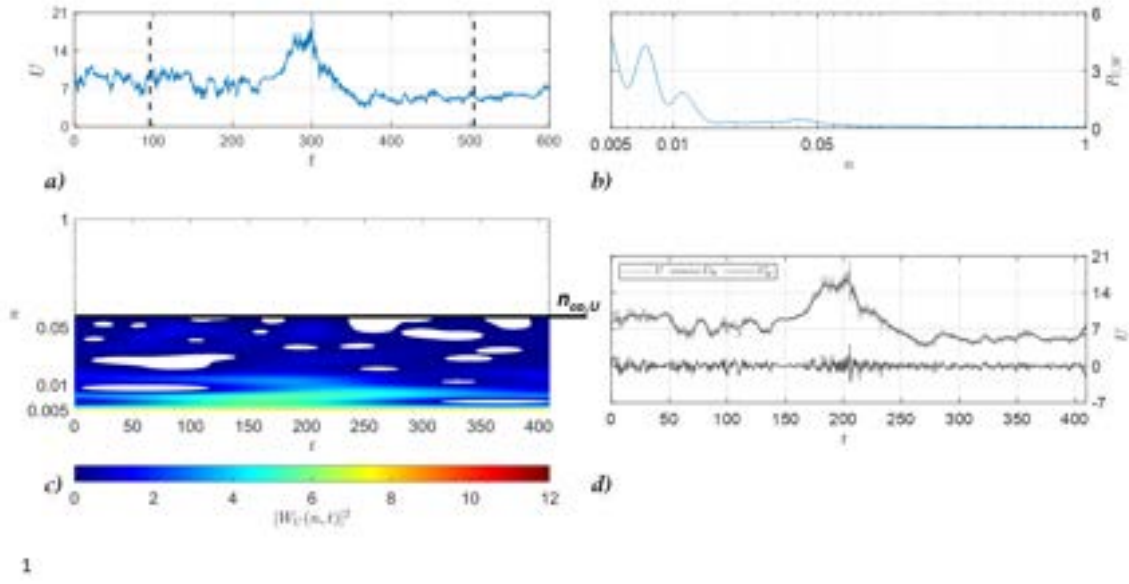


FIGURE 5.2: Description of the continuous wavelet transform-based technique on a wind signal associated with thunderstorm outflows to estimate a time-varying mean wind speed. A) time-history of the wind speed and identification of the 4096 ($=2^{12}$) samples; B) Wavelet power spectrum; C) filtering of the energy map with the adoption of adequate thresholding parameters and cut-off frequency; D) extraction of the mobile mean wind speed $U_W(t)$ and definition of the residual $U'_W(t)$.

This procedure allows the use of the efficient FFT routine to evaluate the wavelet transform and avoids undesired end effects.

After the definition of the mother wavelet, adopting a Morlet with a central frequency $\omega_0 = 2\pi$, it is firstly possible to display the $L1$ wavelet power spectrum $P_{U,W}$, Eq. 5.8, as in Figure 5.2B. This allows the dominating frequencies present in the signal to be detected. The $L1$ Energy wavelet map, defined as the square value of the modulus of the transform, is physiologically addicted by the presence of high contribution at $\frac{1}{2^{12}} [Hz]$, which constitutes the fundamental wave for the slowly-varying mobile mean. The thresholding procedure described in Section 5.1 is now applied. The energy map evaluated with the $L1$ CWT is analysed from an energetic point of view, to define the dynamic filtering. In particular, the thresholding procedure is not carried out on the entire map, but singularly on portions of it, relevant to the different decades indicated before. This choice has been adopted to overcome the possible problem that the excessive contribution associated with the fundamental wave could hide other energetic contributions that might turn out to be important in the reconstruction of the slowly-varying mobile mean. The threshold value has been defined through the parameter λ (thresholding parameter) which multiplies the mean value of the energy relevant to a certain portion of the map. Several values of λ have been investigated, defining a range which starts from low (0.2) to high (1.4) values. Obviously, the choice of a higher threshold constitutes a higher barrier, and consequently the procedure filters out higher contributions than in the case of low threshold.

A second parameter that has to be defined as input in the analysis is the cut-off frequency $n_{co,U}$, which is the frequency over which the procedure filters out all the contributions of the map, regardless of the relevant energy. To be consistent with the paper by (Tubino and Solari,

2020), this value is assumed as $n_{co,U} = \frac{2}{T_W} = \frac{2}{30[s]} = 0.067 [Hz]$. In fact, the action of both constant and Gaussian weighting functions convert almost the entire contribution over $\frac{2}{T_W}$ into fluctuating components.

Applying the inverse transform, Eq. 5.4, allows the definition of the slowly-varying mobile mean of the signal U_W .

Figure 5.2C displays the energy map evaluated through a *L1 CWT* which is filtered by applying the parameter $\lambda = 0.2$ and the cut-off frequency $n_{co,U} = 0.067 [Hz]$. Figure 5.2D presents the variation with time of the original signal U in blue and the relevant slowly-varying mobile mean U_W in red. The difference between these two quantities represents the residual fluctuating turbulence U'_W (black in the figure). As mentioned before, numerous analyses have been carried out to quantify the effects associated with the thresholding parameter λ . Figure 5.3 shows the quantity U'_W evaluated from the cases $\lambda = 0.2$ (black line) and $\lambda = 1.4$ (red line), considering the same cut-off frequency. When the thresholding parameter increases, the residual becomes richer in terms of frequency content and, in fact, the red line locally presents a mean value that is different from zero. The corresponding PDFs may be found in Figure 5.4. Moreover, Figure 5.5 compares the slowly-varying mobile means such as defined by reporting their harmonic content (studying the Fourier transforms). The blue line concerns the original signal.

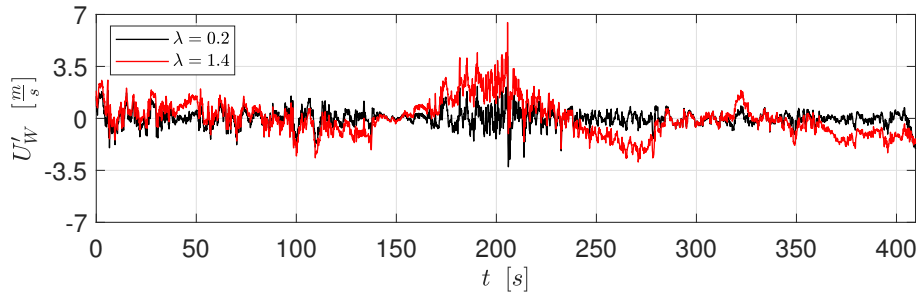


FIGURE 5.3: Time-variation of the quantity $U'_W(t)$ evaluated with two different thresholding parameter λ .

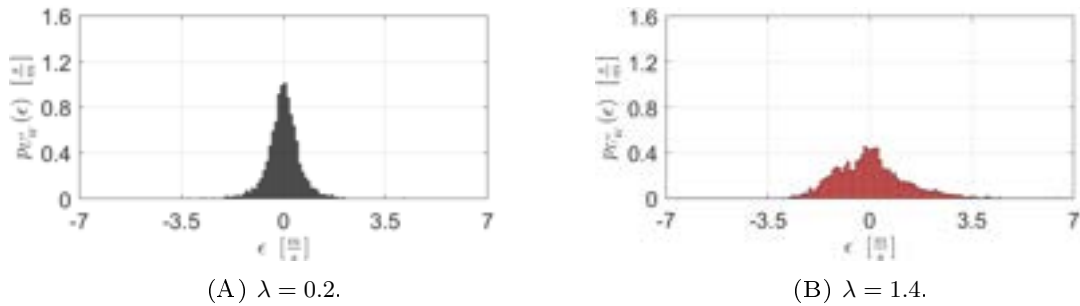


FIGURE 5.4: Pdfs of $U'_W(t)$:

λ	0.2	0.6	1.0	1.4
$std(U'_W) \left[\frac{m}{s}\right]$	0.53	0.58	0.80	1.15
$skew(U'_W) [-]$	-0.13	0.35	0.56	0.55
$kurt(U'_W) [-]$	6.21	5.55	4.23	3.63

TABLE 5.1: Statistical characterisation of the residual for different values of λ .

λ	0.2	0.6	1.0	1.4
$c_{corr}(U_W - U'_W) [-]$	0.071	0.33	0.56	0.60

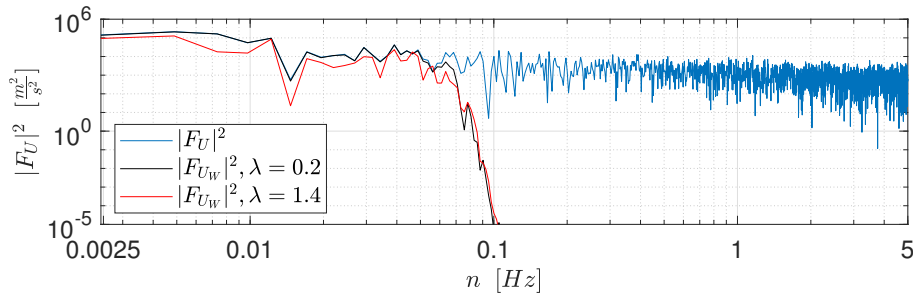
TABLE 5.2: Correlation coefficients for different values of λ .FIGURE 5.5: Sensitivity of the spectral content of the rebuilt signal to λ .

Table 5.1 summarises the statistical characterisation of the residual U'_W for different values of the thresholding parameter λ (0.2, 0.6, 1, 1.4). While the first row reports the values of the standard deviation of the residual, the second and the third rows investigate the variation of its skewness and kurtosis. It is noted that, while the standard deviation increases with λ , the kurtosis decreases. Analogously, Table 5.2 shows the variation of the correlation coefficient c_{corr} between the extracted mobile mean and the residual. Increasing the value of the thresholding parameter has the effect of including contributions at low frequencies into the residual, so that the correlation between this and the corresponding mean increases. In the light of the results expressed by this second table, and observing the time-histories in Figure 5.3, a choice of a low value of the thresholding parameter (0.2) seems to represent the optimal choice to filter signals associated with thunderstorm outflows.

5.3 Acceleration analysis

After a brief opening (Section 5.3.1) concerning the estimation of wind-induced forces, already introduced in the opening of the chapter, Section 5.3.2 numerically derives the slowly-varying mean part of the acceleration, starting from the slowly-varying mean wind speed obtained in Section 5.2.2. In this way, an evaluation of the dynamic part of the acceleration is also possible. Section 5.3.3 describes the sensitivity of the procedure to the cut-off parameter $n_{co,U}$, whose choice, as stressed in the introduction of the chapter, should be a function of the application the user intends for the analysis.

5.3.1 Acceleration-induced forces

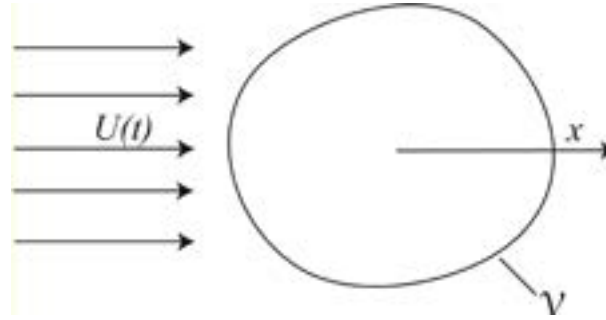


FIGURE 5.6: Fixed body immersed in a unidirectional unsteady flow; courtesy of Prof. Guido Buresti.

This section aims at the derivation of the aerodynamic forces linked to the velocity and to the acceleration of a given free-stream. For the sake of simplicity, the forces are expressed as acting on a fixed body immersed in a unidirectional unsteady wind $U(t)$ (Figure 5.6) by means of the Morison equation (Morison, Johnson, and O'Brien, 1953), in a form in which the sign of the velocity is assumed not to vary, as may be considered reasonable for winds.

$$F_x(t) = \frac{1}{2}\rho AU^2 c_D + \rho V c_a \frac{\partial U}{\partial t} + \rho V \frac{\partial U}{\partial t} \quad (5.15)$$

The terms which had not been introduced before in this Thesis are the reference surface A , the added mass coefficient c_a and the body volume V . The two terms proportional to the acceleration $\frac{\partial U}{\partial t}$ are, respectively, the added mass and the Froude-Krylov forces. The first one arises because of the variation of the energy of the fluid. The second acts on any volume of fluid inside a flow whose velocity is uniform in space but varies in time (Buresti, 2012). Introducing the so-called inertia coefficient $c_m = 1 + c_a$, it is possible to reformulate Eq. 5.15 in a more traditional way:

$$F_x(t) = \frac{1}{2}\rho AU^2 c_D + \rho V c_m \frac{\partial U}{\partial t} \quad (5.16)$$

The coefficients c_D , c_a and c_m are generally obtained in such a way that the actual variation of a measured force best fits (in the mean square sense) the one given by the equation.

As a note of caution, it should be reminded that the Morison equation is an approximation and that the various coefficients are, in principle, a function of time and of the flow parameters. Furthermore, the prediction of the added mass is highly uncertain for a bluff body in a generic time-varying upstream flow due to the lack of available experimental data, most of which refer only to purely sinusoidal oscillatory flows with application to wave-induced forces.

As an example, assuming the body to be a slender finite cylinder with span-wise length L , cross-flow dimension H and cross-section S . As a reference surface for the drag force it is then reasonable to take the frontal area $A = LH$, while the body volume is equal to $V = LS$. It is then possible to write the expression for the force as follows:

$$F_x(t) = \frac{1}{2}\rho L H U^2 c_D \left(1 + 2 \frac{c_m}{c_D} \frac{S}{H} \frac{\frac{\partial U}{\partial t}}{U^2} \right) \quad (5.17)$$

The second term inside the parenthesis provides the relative importance of the acceleration-induced force compared to the drag force acting on the body in a steady flow having the same velocity.

It should be noted that the term is directly proportional to the double of the ratio between

acceleration and the square value of the velocity, to the ratio $\frac{cm}{c_D}$ (which may be of the order of 2) and to a reference length d equal to $\frac{S}{H}$.

It is immediate to observe that, for usual wind velocities and accelerations, the force directly connected with the acceleration may be significant only if the body is elongated in the flow direction, i.e. if $\frac{S}{H}$ is large. Nonetheless, in certain cases one might analyse the opportunity of considering the existence of a force proportional to the flow acceleration. This refers also to the possibility of deriving the relevant inertia coefficients during wind tunnel tests, through suitable (albeit non-trivial) procedures for the analysis of the obtained force signals.

Eq. 5.17 also offers the opportunity to introduce the acceleration parameter K_a :

$$K_a = \frac{\partial U}{\partial t} \frac{d}{U^2} \quad (5.18)$$

This quantity represents a non-dimensional parameter which allows the characterisation of an unsteady flow. It is recalled in Chapters 6 and 7.

5.3.2 Numerical estimation of the slowly-varying mean acceleration

Concerning the signal U presented in Figure 5.2A, the numerical estimate of the thunderstorm-induced acceleration a may be performed through a 2^{nd} order central finite differentiation, as shown in Figure 5.7.

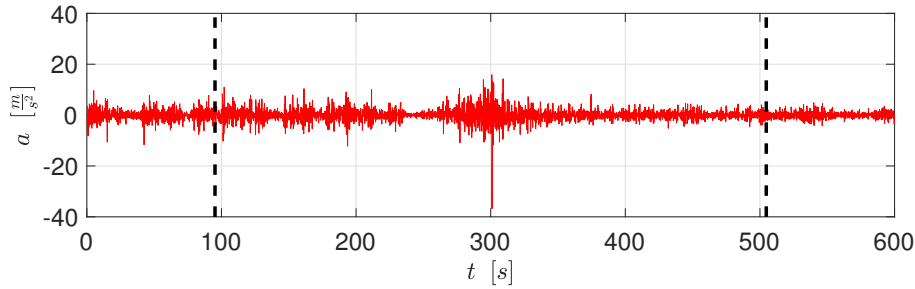


FIGURE 5.7: Numerical derivation of the signal U presented in Figure 5.2A, with the indication of the interval which encloses the central 2^{12} samples.

Figure 5.8 displays the $L1$ wavelet power spectrum of the acceleration a . Non unexpectedly, the harmonic content of the acceleration is greater at higher frequencies compared to the spectrum of the velocity from which it is derived (Figure 5.2B), also because of the noise introduced in the derivation process.

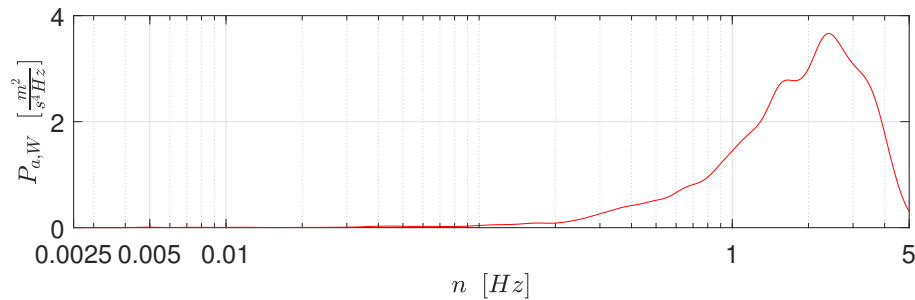


FIGURE 5.8: Wavelet power spectrum of the signal presented in Figure 5.7.

Deriving with the same numerical technique the signal U_W , associated with turbulence components which have a spatial dimension of the same order as the structure, it is possible to obtain the slowly-varying mean acceleration, hereinafter called a_W . By subtracting the latter from a , it is possible to estimate the fluctuating part of the acceleration, a'_W . The evaluation of a_W (in magenta) and a'_W (in black) for WE3 are reported in Figure 5.9. They are both normalised to their corresponding standard deviations.

Following up the analyses carried out for U'_W , a_W and a'_W are now studied by characterising their PDFs. Concerning a_W , the mean value of its absolute value is $0.13 \left[\frac{m}{s^2} \right]$, its standard deviation is $0.17 \left[\frac{m}{s^2} \right]$ and the maximum of its absolute value is $0.64 \left[\frac{m}{s^2} \right]$. The corresponding kurtosis is 4.2.

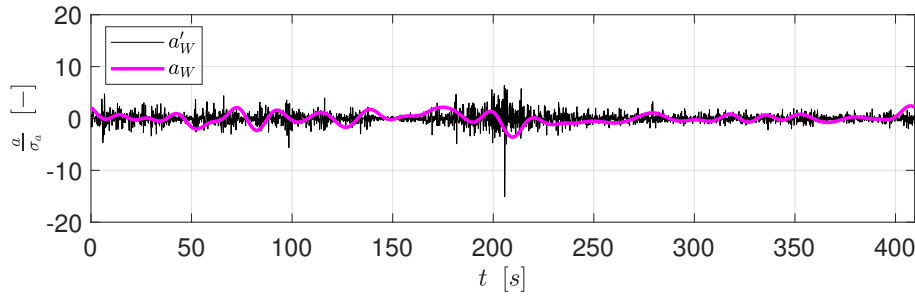


FIGURE 5.9: Thunderstorm-induced acceleration time history a_W and a'_W for the wind event of interest (normalised to their corresponding standard deviations).

The residual component, a'_W , exhibits a standard deviation equal to $1.92 \left[\frac{m}{s^2} \right]$. The relevant kurtosis is much higher than its counterpart of a_W , being equal to 22. This is inherently driven by the spikiest components of the original signal, which dominate the fluctuating part of the signal.

Acceleration-induced forces are not investigated on this single wind event, since a deeper discussion on this matter is carried out in Section 5.4, by analysing 15 different signals.

5.3.3 Effect of the cut-off frequency

As highlighted previously, the extraction of the slowly-varying mean wind speed from a wind signal has to be correlated with the structural application. If the aim is the evaluation of the dynamic response of a structure to a thunderstorm outflow, one has to consider both the spectral content of the phenomenon and the natural frequencies of the system. As an example, if the structure of interest is rigid, the user can define a time-varying mean wind speed still applying the procedure which is illustrated in Section 5.2.2, adopting suitable values for the wavelet procedure, in particular concerning the cut-off frequency $n_{co,U}$. An application in this context is now briefly reported, concerning the definition of the slowly-varying mean acceleration for a structure whose first natural frequency is $\approx 2 \text{ [Hz]}$. The same signal studied before undergoes again the procedure, now applying a cut-off frequency equal to $n_{co,U} = 1 \text{ [Hz]} (=0.5n_1)$. The high spectral content in the decade between 0.1 and 1 [Hz] is the cause of a noisy rebuilt signal, characterised by a continuous succession of peaks, which is not adequate to collect statistical information about acceleration. In order to limit that, it is possible to assign to that range of frequency a higher thresholding parameter λ , capable of limiting the spiky features of the signal.

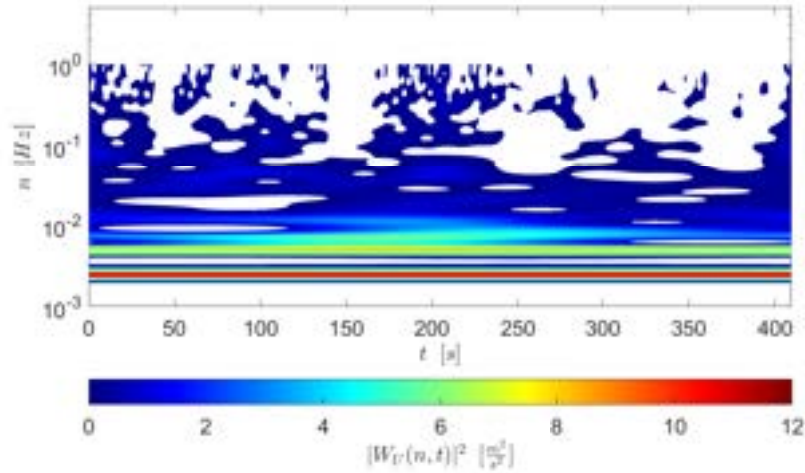


FIGURE 5.10: Filtering of the $L1$ energy wavelet map with the new set of parameters.

Nevertheless, the chosen value has still to be able to preserve an adequate spectral content of the signal, in accordance with the one associated with the original signal of acceleration. In this example, the parameter λ concerning the third decade has been put equal to 1, whereas in the first two decades it was chosen equal to 0.2.

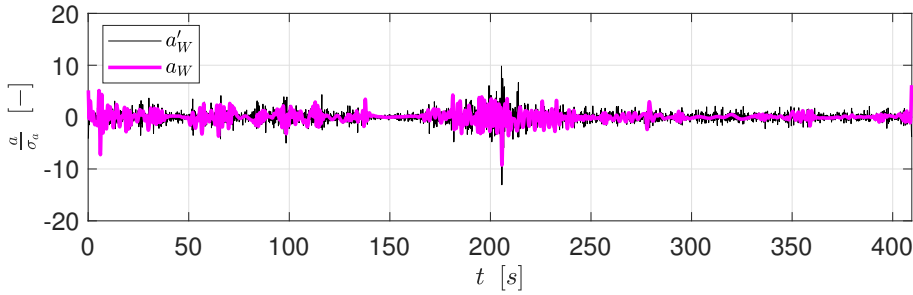
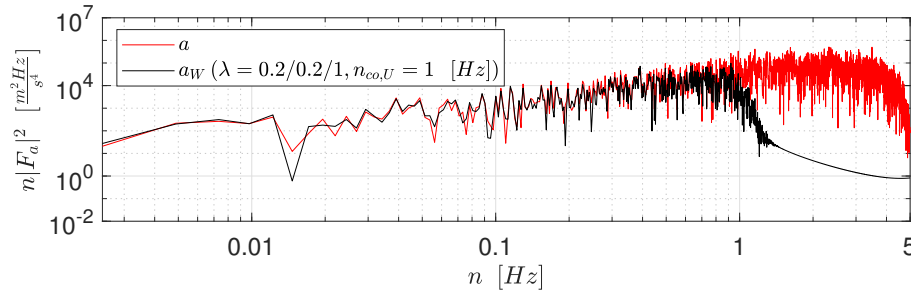


FIGURE 5.11: Comparison between the time histories of a_W and a'_W evaluated with the new set of parameters (normalised to their corresponding standard deviations).

Figure 5.10 shows the filtering procedure carried out on the $L1$ wavelet energy map. The effect of a higher thresholding parameter on the higher decade is evident, pointed out by the many areas on the graph which are put to zero. The reconstruction of the time-varying mean velocity and its derivative lead to the definition of a new separation between the slowly-varying part of the acceleration and its residual part. Following the scheme introduced in Figure 5.9, Figure 5.11 reflects the same quantities obtained with the new setting of parameters. The quantity a_W now obtained is evidently affected by higher frequency content, as highlighted by its maximum (in absolute value), $7.35 \left[\frac{m}{s^2} \right]$, and its standard deviation, $0.79 \left[\frac{m}{s^2} \right]$.

FIGURE 5.12: Sensitivity of the spectral content of the rebuilt signal to λ .

It is remarkable to appreciate that there are parts of the new signal a_W which have not been affected by the new cut-off frequency, as in the time interval around 150 [s], or in correspondence of 300 [s]. That is linked with the choice of a high value of λ , which in these time intervals constitutes a severe barrier in terms of dynamic filters (as also shown in Figure 5.10), preventing the presence of high frequency contents. On the other hand, the central part of the signal is evidently affected by the presence of the new contributions. In spite of the choice of a high thresholding parameter λ for the third decade, Figure 5.12 - which shows the comparison between the spectral content of the original signal of acceleration (Figure 5.7) and a_W evaluated with the new setting of parameters - depicts how the procedure was effective enough to maintain an adequate level of energy in the whole frequency range in which the dynamic filter has acted.

5.4 Ensemble analysis of 15 thunderstorm outflows

Event name	Port of	Anem n°	Date
WE1	La Spezia	2	Jan., the 30 th , 2015
WE2	Genoa	1	Oct., the 28 th , 2012
WE3	Genoa	1	Nov., the 3 rd , 2012
WE4	Livorno	1	Dec., the 16 th , 2011
WE5	Livorno	4	Jan., the 18 th , 2014
WE6	Livorno	5	Nov., the 16 th , 2010
WE7	Livorno	5	Oct., the 15 th , 2012
WE8	La Spezia	3	Oct., the 25 th , 2011
WE9	La Spezia	3	Oct., the 15 th , 2012
WE10	La Spezia	3	Feb., the 9 th , 2014
WE11	La Spezia	2	Oct., the 25 th , 2011
WE12	Genoa	1	Nov., the 28 th , 2012
WE13	La Spezia	3	Apr., the 11 th , 2012
WE14	La Spezia	3	Oct., the 13 th , 2014
WE15	La Spezia	3	Aug., the 24 th , 2015

TABLE 5.3: Generalities about the fifteen thunderstorm outflow records selected from the WP and WPS databases.

While Sections 5.2 and 5.3 aim at the description of the defined techniques and their applications on a selected wind event, in this section the procedures are applied on a set of 15 different wind events (hereinafter called WE1 – WE15) selected from the database of the projects “*Wind and Ports*” and “*Wind, Ports and Sea*” (Appendix F). Generalities about these events

are given in Table 5.3. As already mentioned, WE3 is the signal which has been extensively studied in Sections 5.2 and 5.3. Seeking to statistically characterise the residual fluctuation - now called U'_α in generic terms, with $\alpha = C, G, W$, since the three different methodologies (Constant weighting function, Gaussian weighting function, and *CWT*) introduced in Section 5.2 are investigated - Table 5.4 shows the comparison between the mean values (evaluated as the mean of the quantities obtained for the 15 wind events) of the standard deviation, the skewness and the kurtosis of U'_α .

Residual	U'_C	U'_G	U'_W
$std(U'_\alpha) \left[\frac{m}{s}\right]$	1.43	1.20	1.04
$skew(U'_\alpha) [-]$	-0.13	0.061	-0.036
$kurt(U'_\alpha) [-]$	5.32	5.79	6.18

TABLE 5.4: Statistical characterisation of the generic residual U'_α .

The novel technique here proposed leads to a slightly reduced standard deviation with respect to the other two methods, and to a kurtosis equal to 6.18, slightly higher than the other two.

Analogously, Table 5.5 shows the mean value of the correlation coefficient, $\bar{c}_{corr}$, between the mobile mean wind speed and the corresponding residual fluctuation. As it was already possible to appreciate from Figure 5.13, the adoption of the novel procedure, with an assignment of a cut-off frequency, allows a better separation between the harmonic content of the two quantities to take place, reducing the value of the correlation coefficient.

Residual	U'_C	U'_G	U'_W
$\bar{c}_{corr} [-]$	0.096	0.11	0.055

TABLE 5.5: Statistical characterisation of the generic residual U'_α .

Inspired by the remarks by (Tubino and Solari, 2020), Figure 5.13 displays the comparison between the 15 averaged *L1* wavelet power spectra of different non-stationary quantities: while the black line reports the averaged power spectrum evaluated analysing the original signals, the blue line indicates the result for the turbulent component obtained through the constant weighting function, which reflects what was highlighted by (Tubino and Solari, 2020), albeit now referred to the fluctuating component, rather than the reduced fluctuating one. There is a frequency range in which the spectral content of the fluctuating component oscillates around the line of the original signal. Then, again, Figure 5.13 shows the green line, which is associated with the turbulent component evaluated through a Gaussian weighting function, which seems to well capture the harmonic content of the original signals, leading to a smoother transition from the mean part to the turbulent one. Moreover, the red line is relevant to the turbulent component U'_W evaluated with the method proposed in this chapter. The averaged power spectrum correctly follows the original signal at low frequencies, without amplifying any energetic contribution, at variance with the constant weighting function.

Location	Genoa (3)	Livorno (4)	La Spezia (8)
$std(a_W) \left[\frac{m}{s^2}\right]$	0.22	0.24	0.27
$skew(a_W) [-]$	0.10	0.08	0.03
$kurt(a_W) [-]$	3.75	4.09	4.33
$mean(a_W) \left[\frac{m}{s^2}\right]$	0.17	0.18	0.20
$max(a_W) \left[\frac{m}{s^2}\right]$	0.74	0.82	0.94
$std(a'_W) \left[\frac{m}{s^2}\right]$	3.01	3.21	4.45

TABLE 5.6: Mean on 15 thunderstorm outflows of the statistical properties of a_W and a'_W for three locations.

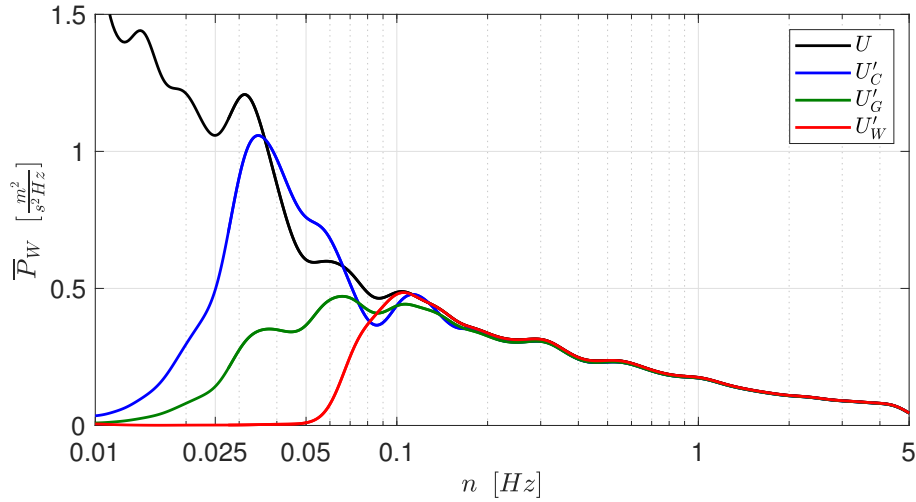


FIGURE 5.13: Averaged (on 15 wind events) $L1$ wavelet power spectrum of different quantities.

Furthermore, its ramp-up seems quite steep, preventing a wide range where residual and mean wind speed can exhibit correlation. As a matter of fact, this positive results was anticipated by Table 5.5, and seems to constitute a further improvement to the adoption of a Gaussian window function, since its most important drawback was the presence of a higher correlation coefficient if compared with the constant weighting function. Moving to accelerations, the analyses hereinafter carried out allow precious knowledge about this quantity (often overlooked in literature) to be gained. After the separation of the data coming from different locations (namely, Genoa, Livorno and La Spezia, see Table 5.3), statistical information has been gathered and organised in Table 5.6. The data which are reported are the standard deviation, the skewness and the kurtosis of a_W , which is further investigated applying the absolute value and furnishing the mean and the maximum of $|a_W|$. Moreover, its counterpart, a'_W , is analysed as well, providing information about its standard deviation. To avoid possible end effects induced by the wavelet procedure, data belonging to the first and last 10 seconds have been excluded from the analysis. Each of the three columns is dedicated to a different location (from left to right: Genoa, Livorno, La Spezia). The number in brackets next to the name of the location indicates the number of events which have been considered for the analysis.

Observing the data presented in Table 5.6, it transpires that La Spezia is apparently a location characterised by higher accelerations, which is reflected in both values linked to a_W and to a'_W . In particular, concerning a_W , the values of the standard deviation, the mean and the maximum of its absolute value confirm this remark.

This seems in agreement with the paper by (Zhang et al., 2018), who – working on a much wider thunderstorm database (29 wind events in Livorno and 25 wind events in La Spezia) – stated that the area of La Spezia is more likely to be subjected to intense thunderstorms, rather than the area around Livorno.

The values here reported are also in agreement with one of the few references which provide a quantification of thunderstorm-induced accelerations, written by (M. S. Mason and T. Yang, 2016). They estimated in $1 \left[\frac{m}{s^2} \right]$ the acceleration associated with the signal reported by (Fujita, 1985), regarding the Andrews Air Force Base microburst (Figure 1.5B).

Lastly, a discussion concerning the acceleration-induced aerodynamic forces is here proposed, supported by pictures specifically concerning the outcomes of WE10. As Section 5.3.1 points out, these forces are strictly related to the quantity $2 \frac{\partial U}{U^2}$. Its quasi-steady part, because of the considerations made in Section 5.2, might well be represented by $2 \frac{a_W}{U_W^2}$. After naming this latter quantity as R_a , Eq. 5.17 proves that it plays a fundamental role into the assessment of the acceleration-induced aerodynamic loading, coinciding with the load per unit length of the body (to be multiplied with $\frac{c_m}{c_D}$, commonly greater than 1).

To investigate the parameters which affect this term, Figure 5.14 displays the temporal variation of R_a (in black, with ordinate readable on the right axes of the pictures) against the quantities U , U_W (Figure 5.14A) and a_W (Figure 5.14B). It is recalled that, as mentioned before, the first and last 10 seconds of the signal have been disregarded from the analysis to avoid end effects. Because of this, the quantities U_W , a_W and R_a are characterised by slightly shorter time-histories, if compared with U .

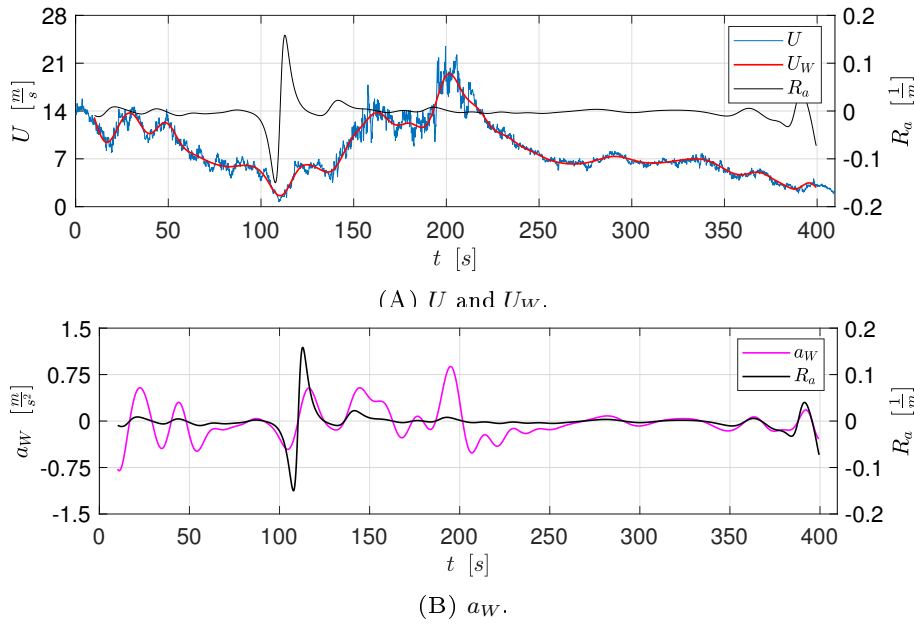


FIGURE 5.14: WE10, variation of R_a with other quantities.

Figures 5.14A and 5.14B clearly show that R_a is featured by a double peak in correspondence of $t \approx 110$ [s], reaching values down to -0.15 and then up to +0.16 $\left[\frac{1}{m} \right]$. Such magnitude might translate into an increase of the aerodynamic loading (per unit length of the body), of 20-30 % (see Eq. 5.17), which is not negligible. On the other hand, Figures 5.14A and 5.14B clearly highlight that these peaks occur in correspondence of a drop of wind speed, while the dependence appears less marked with respect to the acceleration. The latter, instead, dictates the final sign. Extending the analysis to the whole set of 15 signals, Figure 5.15 reports the variation of the absolute value of R_a against the square value of the wind speed, U_W^2 (in abscissa), and the absolute value of the acceleration, $|a_W|$, which rules the

colours associated with the dots. To reduce the number of points in the graph, only the data associated with a value of $|a_W|$ greater than $0.4 \left[\frac{m}{s^2}\right]$ have been displayed. From this picture, it immediately stands out that the magnitudes of R_a are much more sensitive to the values assumed by the wind speed, rather than the corresponding accelerations. In fact, high values of R_a are reached for low velocities only, regardless of the relevant accelerations. Conversely, when U_W^2 is high, the influence of the acceleration is strongly limited, as clarified by the plot, which shows that all the different curves relative to different levels of acceleration collapse in one, exhibiting almost null values of $|R_a|$. Therefore, Figure 5.15 reveals that acceleration-induced loading may be important for low wind speeds only, and their influence disappears for higher velocities (which are normally the design wind speeds of a structure). On the other hand, they may still constitute a meaningful contribution to the total aerodynamic loading for bodies that are elongated in the flow direction.

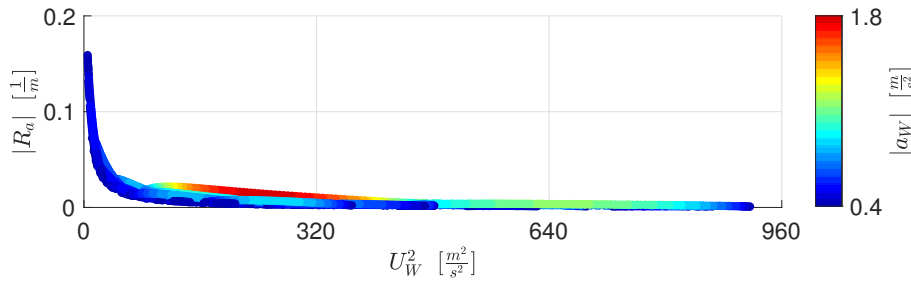


FIGURE 5.15: Variation of $|R_a|$ with U_W^2 (in abscissa) and $|a_W|$ (colour bar).

This result seems in agreement with the outcomes expressed by (M. S. Mason and T. Yang, 2016). Their results were related to the choice of a reference body, for which they defined a characteristic length. Moreover, they covered a large range of accelerations, comprising much higher values than the realistic magnitudes normally found in thunderstorm outflows (Table 5.6).

5.5 Conclusions

This chapter employs the continuous wavelet transform for multiple purposes. Firstly, it is applied to separate the slowly-varying mobile mean wind speed of a thunderstorm outflow signal from its fluctuating part (a popular topic in Wind Engineering), followed by the definition of the corresponding acceleration (a not so popular subject in the community) and the estimation of acceleration-induced aerodynamic forces. It has been remarked that the separation cannot be performed without taking into account the structural application which the procedure is intended for. For instance, if the scope is the evaluation of the dynamic response of a structure, the slowly-varying mobile mean wind speed has to be characterised by an harmonic content which is low enough compared to the content of the mechanical admittance of the structure.

The continuous wavelet transform is an extremely suitable method, which permits to perform a dynamic filter on the signal, not affected by an a-priori choice concerning the width of the time window, as it occurs for more traditional weighting functions. The main drawback of the continuous wavelet transform is the generation of redundancies in the process, which are associated with the non-orthogonality of the bases; this aspect does not constitute a significant problem for users thanks to the thresholding procedure, which permits to tackle the problem using an energetic approach.

An important parameter to be assigned is the cut-off frequency $n_{co,U}$, which indicates the

frequency over which all the signal is converted into turbulence. It can be assumed according to the spectral properties and the correlation lengths of the thunderstorms, as well as the natural frequencies of the structure. The thresholding parameter λ , instead, governs the action of the dynamic filter, constituting the energetic threshold below which the contributions of the energy map are disregarded from the definition of the slowly-varying mobile mean and are converted into turbulence. These contributions are associated with different frequencies for different time instants. The choice of λ has always to be supported through cross-checks concerning the spectral content and its comparison with the original signal, which should be well followed in the range of frequency of interest. The direct link between the parameters $n_{co,U}$ and λ and the spectral content of the phenomena and of the structure highlight the versatility of the novel technique for a particular scope.

The numerical derivative of the slowly-varying mean wind speed U_W leads to the definition of the slowly-varying mean acceleration a_W , which, as well as U_W , is associated with wind fluctuating components which are highly coherent for the spatial scales concerning the structure of interest. Its estimation allows the evaluation of the acceleration-induced aerodynamic forces, which are proportional to the term named R_a . Both values of a_W and R_a are of great interest for the wind tunnel simulation of unsteady flows able to reproduce thunderstorm outflows. In particular, the term R_a may be instrumental to define the non-dimensional acceleration parameter K_a . Concerning this aspect, the data gathered in this chapter may constitute a contribution to an advancement in knowledge.

The flexibility of the proposed technique is particularly evident in the assessment of a_W . The thresholding parameter may be adjusted for the different decades into which the signal can be framed, in order to improve the estimation of the acceleration.

The technique has been applied on a set of 15 wind signals, belonging to the database of the “*Wind and Ports*” and “*Wind, Ports and Sea*” European Projects, and presents multiple advantages compared to more consolidated techniques (i.e., constant and Gaussian weighting functions applied on fixed time windows): it avoids the typical unphysical oscillations in the spectral content of the turbulence, which are typical of the constant weighting function (Tubino and Solari, 2020), and prevents the wide spectral range of transition between the mean and the turbulent parts, which is the cause of high correlation coefficients between the two components in the application of the Gaussian weighting function.

Concerning the accelerations, both values associated with a_W and a'_W may provide information concerning which locations are likely to be subjected to more intense thunderstorms. In the research here presented, it appears that the thunderstorms which have been selected in La Spezia are characterised by higher accelerations if compared to the ones in Livorno, as already investigated by (Zhang et al., 2018), or Genoa.

Focusing on the acceleration-induced aerodynamic forces, the estimation of the related quantity R_a reveals that they have a limited influence on the total load of a structure subjected to thunderstorm outflows. Indeed, its influence may be significant only for low wind speeds, while for the higher ones (i.e. design wind speed) its importance almost disappears, except for bodies which are elongated in the alongwind direction.

A possible future investigation might involve the adoption of a wider database, in order to enrich the information concerning a_W and R_a for different locations.

Chapter 6

Wind tunnel tests

This chapter serves as an introduction for the parts of the Thesis concerning the wind tunnel tests, carried out at the multiple-fan wind tunnel of the Tamkang University, in Taipei. The wind tunnel model is a rigid sectional model of a square cylinder. This choice is discussed in Section 6.1, which also provides a literature review concerning the relevant effects of steady and unsteady flows. Section 6.2 gives a general background about the multiple-fan wind tunnels, prototypes developed in the Nineties able to reproduce unsteady flows. Section 6.3 is specifically devoted to describe the facility where the tests have been carried out. Section 6.4 illustrates the wind tunnel model and Section 6.5 describes the available equipment to conduct the experimental campaign. Section 6.6 gives a general overview of the wind tunnel tests and Section 6.7 proposes the methodology which is adopted to study the quantities of interest, specifically in the unsteady conditions.

6.1 The case study

This section describes the object of the wind tunnel test campaign, namely a sectional model of a square cylinder. Firstly, it is described why this shape is a fundamental reference for Structural Engineering (Section 6.1.1) and, secondly, a relevant literature survey is proposed, focusing on the aerodynamic behaviour of this body both in steady and unsteady conditions (Section 6.1.2).

6.1.1 The importance of the square cylinder in Structural Engineering



FIGURE 6.1: Constantin Brâncuși's Endless Column at Târgu Jiu (Romania).

In Chapter 3 and Chapter 4, one of the reference structures is Brâncuși's Endless Column, at Târgu Jiu, in Romania (Figure 6.1). The variation of its cross-section has been an innovative feature in its design, probably never replicated until the beginning of the new millenium. Its conceiving is based on the axis mundi, linking Earth to the sky. Its incredible slenderness ratio (66) clearly reflects the aerodynamic performance of the column, which is achieved with a superimposition of modules whose section continuously varies, mitigating the vortex-shedding phenomenon and, consequently, the wind loading. The variation of the cross-section with the height is only one of the methods to aerodynamically control the structure. (Solari, 2009a; Solari, 2009b), in 2009, summarised in *Costruzioni Metalliche* the possible precautions that a designer can take into account to achieve that scope, such as the definition of an appropriate level of the sharpness of the corners (already discussed in Chapter 4), a sensible shape of the tip of the structure, the possible presence of porous parts and openings, the installation of helical strakes or shrouds, the flanking of buildings and the active control of the wind-induced vibrations. Examples of structures which take advantage of these considerations are shown in Figure 6.2 and briefly commented upon hereinafter.



(A) Taipei 101, Taipei.



(B) World Financial Center, Shanghai.



(C) Burj Khalifa, Dubai.



(D) Freedom Tower, New York.



(E) Infinity Tower, Dubai.



(F) Shanghai Tower, Shanghai.

FIGURE 6.2: Examples of aerodynamically controlled skyscrapers.

The Taipei 101 (Figure 6.2A), which is 509 [m] high, is realised by repeating the same module along the height and the action of the wind is counterbalanced by the presence of a tuned mass damper placed between the 88th and the 92nd floor, which, in collaboration with two additional dampers, mitigates the vibrations of the upper floors. Figure 6.2B is a picture of the World Financial Center in Shanghai, which is 492 [m] high and is characterised by a trapezoidal hole close to the tip. Also in this case, two tuned mass dampers

are employed to reduce possible vibrations. Figure 6.2C shows the Burj Khalifa, which is a fascinating skyscraper that was inaugurated in 2010; with its 829 [m], it overcame the Taipei 101, becoming the highest building in the world. Its cross-section has three lobes (resembling a white flower which grows in the desert) and rotates along the height, continuously changing its orientation and, consequently, its incidence against the incoming wind. At the same time, its dimensions are reduced with the height. As in the case of the Endless Column, these features destroy the regularity of the wake, so that the use of dampers becomes ineffective and pointless. For the 541 [m] of the Freedom Tower (2013) (Figure 6.2D), designed in the area of the World Trade Center in New York, the designers drastically removed the traditional sharp edges with an innovative solution: the 4 corners symmetrically split, furnishing to the facades 8 isosceles triangles, alternatively presenting their vertices at the top or at the bottom. Other interesting examples are the Infinity Tower (2013) (Figure 6.2E), a 330 [m] high building in Dubai, which completely twists its base of 90 degrees when reaching the top to aerodynamically control the structure. Still on the same line, the Shanghai Tower (2014, Figure 6.2F) reaches its 632 [m] with a tapering and twisting of its cross-section; furthermore, its edges are adequately rounded. If, on one hand, all the skyscrapers that have been recently built are characterised by one or more of the criteria listed before to reduce wind-actions, many other buildings, built during the previous century, were realised neglecting any concept of aerodynamics. One of the most important designers of that era was Mies van der Rohe, whose concept of architecture finds its environment in Chicago and New York, where elegant and rational boxes of glass were realised. They are square or rectangular prisms, featured by extreme regularity in cross-section and in height and by sharp edges (i.e. the Seagram Building in New York, 1958, Figure 6.3A), which encourages the formation of a well-defined wake and the alternate shedding of vortices. This entails the necessity of conceiving robust structures to withstand the high wind loading, developing new techniques to design the resistant part of the building. It is in this context that one of the most important engineers of the last century, Fazlur Rahman Khan, entered the scene of Structural Engineering: thanks to the first prototypes of computer, he designed, in 1969, the John Hancock Center (Figure 6.3B), which is 410 [m] high. This structure withstands the horizontal wind action thanks to stiff diagonal members, which also have an architectural function. Furthermore, the cross-section uniformly varies with the height. Another remarkable project in which Khan was involved in is the World Trade Center, (1973, Figure 6.3C), which reaches the height of 430 [m] and is characterised by rounded angles at 45 degrees, which replace the classical sharp edges. Also the doubling of a single skyscraper highlights this design, which for the first time included the studying of the building in a wind tunnel. A last example of the architecture in this period reported herein is the Citicorp Building (1977, Figure 6.3D), which, for the first time in the history, hosts a tuned mass damper of 400 [tons]. The comparison between the pictures shown in Figure 6.2 and Figure 6.3 clearly indicate that only in the last years the action of wind has been mitigated working on the aerodynamics and the shape of the constructions. Most of the buildings present in the world still respect the canons of extreme regularity of the cross-section with height, preferably working with square or rectangular bases. This is the reason why, in the framework of this Thesis, a wind tunnel campaign has been carried out on the sectional model of a square cylinder.



(A) Seagram Building, New York.



(B) John Hancock Center, Chicago.



(C) World Trade Center, New York.



(D) Citicorp Building, New York.

FIGURE 6.3: Examples of skyscrapers from last century.

6.1.2 Square cylinder in steady and unsteady conditions

Because of the importance of square cylinders in Civil Engineering (but not only), many scientists have been carrying out wind tunnel investigations concerning their aerodynamic behaviour, studying the effects associated with the sharpness of the edges, the presence of free-stream turbulence (already cited in Chapter 4) and the occurring of Reynolds effects. Therefore, nowadays, the square cylinder constitutes one of the most important benchmarks replicated by many laboratories and research centers to validate their measurements. One of the pioneers has been Vickery, who in 1966 published a paper (Vickery, 1966) in which the results of measurements of fluctuating lift and drag on a long square cylinder are reported. The most remarkable result consists in the reduction in base suction at small angles of attack (incidences lower than 10 degrees) due to the presence of large-scale turbulence. At zero degrees, in smooth flow and with a Reynolds number $Re = 10^5$, the mean base-pressure coefficient was found to be equal to $\bar{c}_{p,b} = -1.31$ (where the pressure averages the registration from the tappings at the mid and quarter points of the downstream face). Further investigations have been carried out by three Japanese researchers (Nakaguchi, Hashimoto,

Author(s)	$\frac{\sqrt{U'^2}}{U} [\%]$	Re	$\bar{c}_{P,b}$	$\bar{c}_D$
Vickery, 1966	smooth	10^5	-1.31	—
—	10	—	0.71	—
Nakaguchi, Hashimoto, and Muto, 1968	smooth	$2 - 6 \cdot 10^4$	-1.50	2.10
Bearman and Trueman, 1972	< 0.3	$4.7 \cdot 10^4$	-1.40	2.19
Lee, 1975	< 0.5	$1.76 \cdot 10^4$	-1.30	2.05
—	6.5	—	-1.18	1.93
Ootsuki et al., 1980	< 0.2	$6.5 - 7 \cdot 10^4$	-1.35	2.08
Bearman and Obasaju, 1982	< 0.3	$4.7 \cdot 10^4$	-1.65	—
Mizota and Okajima, 1982	smooth	$7.14 \cdot 10^4$	-1.64	—
Okajima, 1982	< 0.5	$4.2 \cdot 10^4$	-1.47	—
Norberg, 1993	< 0.06	$400 - 3 \cdot 10^4$	-1.38	2.16
Tamura and T. Miyagi, 1998	0.4	$3 \cdot 10^4$	—	2.09
—	6.5	—	—	1.79
—	14.0	—	—	1.49
Yang and Matthew S. Mason, 2019	< 0.5	$0.93 - 12.3 \cdot 10^4$	—	2.14
Noda and Nakayama, 2003	0.2	$6.89 \cdot 10^4$	-1.48	2.16
Sohankar, 2006 (CFD)	smooth	$10^3 - 5 \cdot 10^6$	-1.50	2.2

TABLE 6.1: Aerodynamic properties related to drag coefficient from previous studies (steady flow). Most of the data have been gathered after (Noda and Nakayama, 2003) and (Yang and Matthew S. Mason, 2019).

and Muto, 1968), under smooth flow conditions, who defined a $\bar{c}_{P,b} = -1.50$, for a Reynolds number range $Re = 2 - 6 \cdot 10^4$. Moreover, they furnished a mean drag coefficient $\bar{c}_D = 2.10$. A slightly higher drag coefficient, $\bar{c}_D = 2.19$, was proposed by Bearman and Trueman in 1972 (Bearman and Trueman, 1972), for a similar Reynolds number ($Re = 4.7 \cdot 10^4$). Another extensive wind tunnel campaign was carried out by Robertson et al. (Robertson et al., 1972) and, afterwards, by Lee (Lee, 1975); the latter confirmed the findings of Vickery concerning turbulence and obtained a $\bar{c}_D = 2.05$ and a mean base-pressure coefficient equal to Vickery for a $Re = 2.9 \cdot 10^4$. Petty, in 1979 (Petty, 1979), focused his attention on the scale of turbulence, which would have been the object of other investigations (Ootsuki et al., 1980; Nakamura and Ohya, 1984; Durao, Heitor, and Pereira, 1988; Lyn and Rodi, 1994). Additional remarkable publications concerning the aerodynamic behaviour of a square cylinder in smooth flow were published in 1982 (Bearman and Obasaju, 1982; Mizota and Okajima, 1982; Okajima, 1982), still reporting mean-base pressure coefficients between -1.65 and -1.47 . In 1993, Norberg (Norberg, 1993), for a Reynolds number range $Re = 400 - 3 \cdot 10^4$, conducted a wind tunnel test campaign, investigating several incidences of square and rectangular cylinders in a wind tunnel with a turbulence intensity lower than 0.06 %. For the square case, at zero incidence, the drag coefficient turned out to be 2.16. The same value was proposed by Noda and Nakayama in 2003 (Noda and Nakayama, 2003). Table 6.1 summarises the main results (in terms of base-pressure coefficient $\bar{c}_{P,b}$ and drag coefficient $\bar{c}_D$) reported by the different authors. The description "smooth" is replaced with indication about turbulence if it is provided by the author(s).

Literature is also rich as regards investigations concerning the vortex-shedding phenomenon, aiming at the definition of the factors that affect the detachment of vortices behind the body and the definition of the Strouhal number. Besides the already cited papers, noteworthy publications have been proposed throughout the last 40 years. Obasaju (Obasaju, 1983) evaluated the spectra of pressure and velocity fluctuations on a square cylinder with the variation of the angle of incidence and estimated the Strouhal number to be 0.124, for $Re = 2.14 \cdot 10^4$.

In 1995, Lyn et al. (Lyn, Einav, et al., 1995), by means of a water tunnel and laser doppler velocimetry, found a Strouhal number close to 0.132 for a Reynolds number $Re = 2.14 \cdot 10^4$. The dependence of the phenomenon on the Reynolds number was the object of the work of (Chen and Liu, 1999), who carried out a wind tunnel campaign for a range of Reynolds numbers between 2000 and 21000. While on the front face the pressure distribution seems not to be dependent on the Reynolds number, the side and the rear faces appear to differ for Reynolds number up to 5300, before falling on the same trend for higher values. Then, again, Noda and Nakayama, in their already cited paper (Noda and Nakayama, 2003), found a Strouhal number close to 0.131. Slightly higher values are found in the paper by (Dutta, Muralidhar, and Panigrahi, 2003), who indicated a Strouhal number between 0.141 and 0.143 for a Reynolds number range between 1340 and 9980. Table 6.2 reports the main results coming from the cited papers, this time concerning vortex-shedding. These are the mean values of the Strouhal number $\bar{S}$ and the RMS lift coefficient σ_{c_L} .

While all the previous papers show results obtained through wind or water tunnels, there are references based on Computational Fluid Mechanics (CFD) as well. This is the case of a paper by (Sohankar, 2006), who still obtained results consistent with literature for a large Reynolds number range, between 10^3 and $5 \cdot 10^6$. In his paper, he claimed that the ratio of the mean drag coefficient and the base suction pressure coefficient is approximately constant and equals to 1.47 ± 0.04 . This result is in agreement with other authors, in particular Vickery, Okajima and Norberg. Concerning this quantity, they proposed 1.54 (Vickery, 1966), 1.45 (Okajima, 1982) and 1.53 (Norberg, 1993). CFD has also been recently employed by (Rocchio, Mariotti, and Salvetti, 2020) to highlight the role played by the corners (albeit on a rectangular cylinder with 5:1 aspect ratio). It was found that, if their level of sharpness is not high enough, the mean drag coefficient drops, as already pointed out by (Tamura and T. Miyagi, 1998; Tamura and T. Miyagi, 1999).

Some last remarks for wind tunnel tests in steady flow concern the use of end-plates: (Obasaju, 1979), answering to a work by Lee (Lee, 1977), clarified their role in increasing the drag coefficient and the base suction, thanks to the containment that is realised on the flow, which is less affected by the three-dimensional effects that occur along the longitudinal axis of a slender sectional model.

While the high number of papers and the similarity of their results let transpire that the behaviour of a square cylinder in steady flow is quite consolidated, many uncertainties are still present for the aerodynamic behaviour in unsteady flows. As already indicated in previous chapters, Sarpkaya has been the pioneer of this topic (Sarpkaya, 1963; Sarpkaya, 1966), conducting water tunnel experiments on circular cylinders, from which he obtained a value of the drag coefficient for impulsively-started flows about 25 % higher than their corresponding steady flow values.

Author(s)	$\frac{\sqrt{U'^2}}{U} [\%]$	Re	$\bar{S}$	σ_{c_L}
Vickery, 1966	smooth	10^5	0.118	—
—	10	—	0.120	—
Nakaguchi, Hashimoto, and Muto, 1968	smooth	$2 - 6 \cdot 10^4$	0.13	—
Bearman and Trueman, 1972	< 0.3	$4.7 \cdot 10^4$	0.13	—
Lee, 1975	< 0.5	$1.76 \cdot 10^4$	0.122	—
—	6.5	—	0.126	—
Ootsuki et al., 1980	< 0.2	$6.5 - 7 \cdot 10^4$	0.12	0.82
Bearman and Obasaju, 1982	< 0.3	$4.7 \cdot 10^4$	0.125	—
Obasaju, 1983	< 0.04	10^4	0.124	—
Mizota and Okajima, 1982	smooth	$7.14 \cdot 10^4$	0.125	—
Okajima, 1982	< 0.5	$4.2 \cdot 10^4$	0.13	—
Norberg, 1993	< 0.06	$400 - 3 \cdot 10^4$	0.132	—
Lyn, Einav, et al., 1995	2	$2.14 \cdot 10^4$	0.132	—
Tamura and T. Miyagi, 1998	0.4	$3 \cdot 10^4$	—	1.05
—	6.5	—	—	0.74
—	14.0	—	—	0.34
Chen and Liu, 1999	< 0.5	$2000 - 2.1 \cdot 10^4$	0.135	—
Noda and Nakayama, 2003	0.2	$6.89 \cdot 10^4$	0.131	1.18
Dutta, Muralidhar, and Panigrahi, 2003	< 0.05	1340 – 9980	0.141 – 0.143	—
Yang and Matthew S. Mason, 2019	< 0.5	$0.93 - 12.3 \cdot 10^4$	0.13	1.33
Sohankar, 2006 (CFD)	smooth	$10^3 - 5 \cdot 10^6$	0.13	—

TABLE 6.2: Aerodynamic properties related to vortex-shedding from previous studies (steady flow). Most of the data have been gathered after (Noda and Nakayama, 2003) and (Yang and Matthew S. Mason, 2019).

(Taneda and Honji, 1971) published a paper which describes the test of a flat plate normal to the direction of motion subjected to impulsively-started or to uniformly accelerated flow. Then, again, (Sarpkaya and Kline, 1986), carried out a new water tunnel campaign, studying circular and asymmetric (D-shaped, T-shaped, for instance) bodies; the outcome was an overshooting of the instantaneous drag coefficient compared to the steady values. The same impulsive water tunnel set up is employed in 1986 (Sarpkaya and Ihrig, 1986) to test sharp edged rectangular cylinders at small incidence (1 degree). In this case, the overshooting of the drag coefficient happened for elongated bodies only, while for the square cylinder it does not occur. On the other hand, for greater incidences (> 5 degrees), overshooting of drag and lift force coefficients were observed, regardless of the shape of the cylinders. Focusing on the square prism, in the former case the ratio between the drag coefficient in unsteady and in steady conditions is 0.90, whereas in the latter (10 degrees of incidences) it is 1.75, complemented by an overshooting of the mean lift coefficient of 2.1 times.

Subsequently, (Okajima, T. Matsumoto, and Kimura, 1997) studied the aerodynamic coefficients of circular and square cylinders in non-stationary oscillating flows, while Katsura focused his attention on impulsively-started flow (Katsura, 1997). Several researchers of the University of Kyoto put effort in the topic, such as (M. Matsumoto et al., 2007) and (Shirato et al., 2009). If, on one hand, both teams investigated the topic through wind tunnel tests, on the other only the first achieved the sudden increase of wind speed by use of a shutter and tackling the problem with indicial functions; the second studied two-dimensional rectangular cylinders with various aspect ratios.

It is important to point out that in all the above-cited tests the non-dimensional acceleration parameter K_a (Eq. 5.18) is particularly high, being in the range between 0.5 and 2.5,

according to (Yang and Matthew S. Mason, 2019). Also in the light of what investigated in Chapter 5, this number appears to be too high for thunderstorm outflows. For instance, assuming a reference length equal to 5 [m] would lead to the definition of an acceleration parameter that hardly overcomes 0.25, considering the results presented in Figure 5.15 into account. Considering acceleration parameters close to the full-scale ones, Yang and Mason carried out a wind tunnel test campaign at the open-circuit suction wind tunnel of the University of Queensland, which is characterised by a level of turbulence intensity lower than 0.5 %, and showed that for a square cylinder and for 1:3 and 3:1 rectangular cylinders, at zero incidence, it is unlikely to have an increase of the load beyond what is experienced at the same wind speed in steady conditions. They simulated six different accelerating flows: the first two start from an initially quiescent condition, while the third and the fourth begin from a low Re and the last two tests from higher velocities. They also expressed the need to study a broader case of angles of attack and shapes, which, up to now, are still lacking, leaving the subject of fundamentals of transient aerodynamics not yet explored and clarified (Solari, 2020). Also the research concerning three-dimensional bluff bodies is not rich; even though that topic is not covered in the following chapters of this Thesis, some information about it is herein expressed. Thanks to the realisation of an impinging wall jet, remarkable publications concerning experimental tests in wind tunnels have been proposed. In particular, Chay and Letchford, at the beginning of the millennium (Chay and Letchford, 2002; Letchford, Mans, and Chay, 2002), studied the action of the jet exerted on a cube; Zhang et al. (Zhang, Hu, and Sarkar, 2013; Zhang, Sarkar, and Hu, 2013; Zhang, Hu, and Sarkar, 2014; Zhang, Sarkar, and Hu, 2014) analysed its effect on a gable-roof building and (Jesson et al., 2015) investigated a low-rise building model. (Jubayer, Elatar, and Hangan, 2016) observed the action of a downburst on a low-rise building, replicated by the WinEEE Dome at the University of Western Ontario.

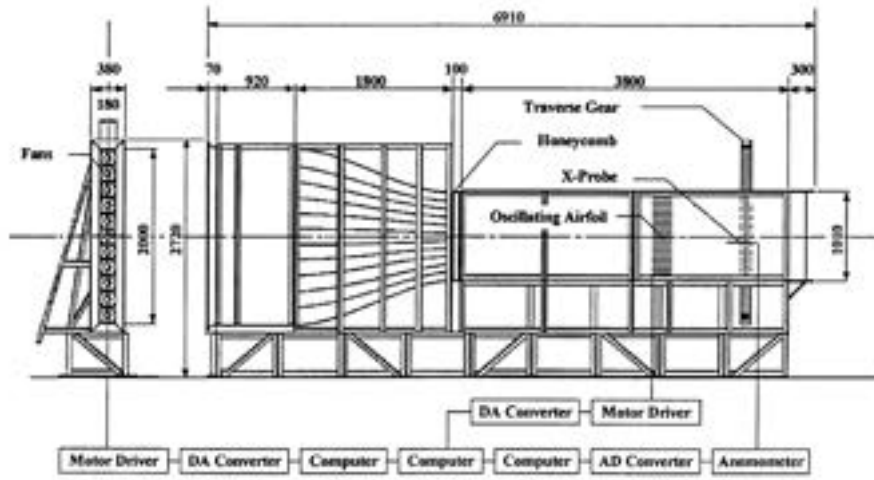
An alternative approach consists in the synergy between CFD and wind tunnel tests, as proposed by (Sengupta et al., 2008), and by Takeuchi et al. (Takeuchi and Maeda, 2012; Takeuchi and Maeda, 2013; Takeuchi, Maeda, and Otsubo, 2013), who carried out an extensive research, inspecting the effects of a short-rise-time gust on a roof shape of a low-rise building. Also (Koliyabandara and M. S. Mason, 2019), studied a roof of a low-rise building model under ramp-up wind events, observing instantaneous pressure coefficients increasing above what expected in steady flow for acceleration parameters greater than $K_a = 0.013$.

While most of the cited tests concern the study of standard structures, Elawady, El Damatty et al. focused their attention on a transmission line to evaluate its response to downburst outflows, firstly through aeroelastic tests at the WinEEE dome (Elawady et al., 2017), and secondly discussing the critical case and the economical suffering associated with the failure of such structure (El Damatty and Elawady, 2018). Amongst the few authors who report downburst effects on full-scale structures, it is possible to cite (Lombardo, M. S. Mason, and Alba, 2018), who analysed the wind loading caused by a downburst striking the full-scale low-rise building laboratory of Texas Tech University.

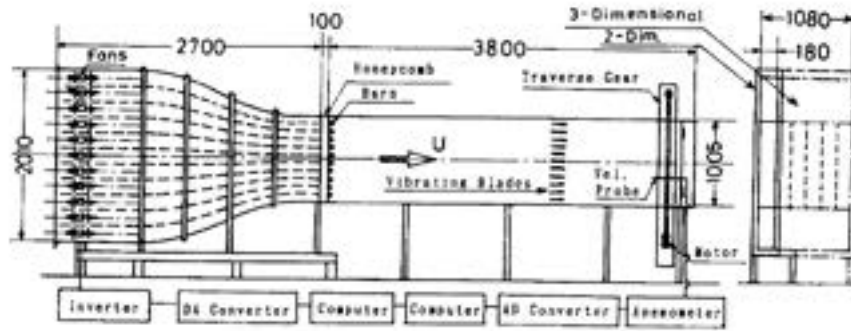
6.2 Simulation of unsteady flows: a new generation of wind tunnel facilities

As highlighted by (Solari, 2014), the modeling and simulation of thunderstorms have been tackled from an experimental viewpoint employing three different families of methods. While the first one is based on the releasing of a liquid mass into a body of less dense liquid, the other two involve the use of wind tunnels, impinging a jet on a flat surface to create a radial outflow (second family), or modifying the traditional axial flow of a wind tunnel (third family). The case of multiple-fan wind tunnel with individually controlled fans belongs to the

third category. In fact, it allows the reproduction of two important features of thunderstorm outflows: the nose-like profile and the rapid change in velocity (Butler et al., 2010).



(A) Two-dimensional multiple-fan wind tunnel, after (Nishi et al., 1997).



(B) Three-dimensional multiple-fan wind tunnels, after (Nishi et al., 1999).

FIGURE 6.4: Scheme of multiple-fan wind tunnel of Miyazaki University.

The first prototype of this kind of wind tunnel was realised in Japan, at the Miyazaki University: at the end of the last century, a first publication was released (Nishi et al., 1997), reporting the description of this novel technique, which consists of the individual control of the fans by computers through a motor-driver, with the aim of reproducing natural wind speeds.

Thanks to the realisation of a two-dimensional multiple-fan wind tunnel (Figure 6.4A) and of a three-dimensional facility (Figure 6.4B), it was possible to demonstrate that this kind of wind tunnels requires a shorter length to reproduce the ABL compared to the conventional BLWTs (which is the main reason why the multiple-fan wind tunnel was conceived) and that the agreement between the spectral components of the longitudinal and vertical velocity components is satisfactory. The two-dimensional facility has a test section length, width, height of 3.8, 0.18, 1.0 [m], and is characterised by a wall of fans which has 11 devices arranged vertically. The test section of the three-dimensional tunnel is featured by a length, width, height of 5.0, 1.0, 1.0 [m], and is characterised by 6 rows of 11 vertical lines of devices, leading to a total of 66 fans. The same authors extended the analyses (Nishi et al., 1999) to carry out a comparison between statistics parameters concerning mean wind velocity, turbulence intensities and scales, obtaining again promising findings. Furthermore, the correlations between

the target and the measured time series fluctuating velocities are high.

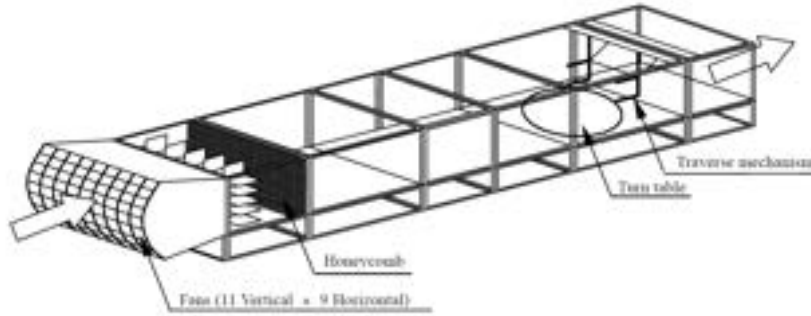


FIGURE 6.5: Scheme of Multiple-fan wind tunnel of Miyazaki University, (S. Cao, Nishi, et al., 2002).

A step further has been proposed by (S. Cao, Nishi, et al., 2002), still from the same institution, who used a novel facility, namely a three-dimensional wind tunnel characterised by 99 controlled fans (arranged in a 9×11 matrix) and a contraction ratio of 1:1.8, which is able to reproduce various fluctuating flows through computer control (Figure 6.5) and to reach velocities up to $15 \left[\frac{m}{s} \right]$. They could observe that sharp velocity changes (accelerations in the order of $2.5 \left[\frac{m}{s^2} \right]$) could be accurately reproduced in the novel facility. The test section is $15.5 [m]$ long at its maximum, $2.6 [m]$ wide and $1.8 [m]$ high. Other pictures are presented in Figure 6.6.



(A) Wall of fans.



(B) Multiple-fan wind tunnel and control room.

FIGURE 6.6: Multiple-fan wind tunnel of Miyazaki University; source: <http://geraldine.fjfi.cvut.cz> .

In the studies, it was observed that the integral scale in the vertical direction is the quantity that is the most challenging to be reproduced in the multiple-fan wind tunnel, and consequently numerous efforts have been addressed to improve this flaw. In particular, studies from 2006 and 2007 (Ozono, Nishi, and H. Miyagi, 2006; Ozono, H. Miyagi, and Wada, 2007) proposed a comparison between the results obtained with the classical uniformly active mode (in which all the fans are set to reproduce the same signal, which is fed through the inverse Fourier transform of a reference spectrum) and a quasi-grid mode (alternating inactivated fans

with activated ones), which instead should be supposed to generate a strong shear immediately past the entrance to the test section, causing a vigorous mixing. In fact, the turbulence which is generated in this way shows a high level of isotropy immediately downstream of the test section inlet, if compared to the anisotropy between the horizontal and vertical directions in the uniformly active mode. However, after the initial turbulent state, the flow soon returns to a pulsatile regime, as in the original condition. Another outcome of these studies was that a shorter test section length and higher mean velocities are advantageous for frequency response.

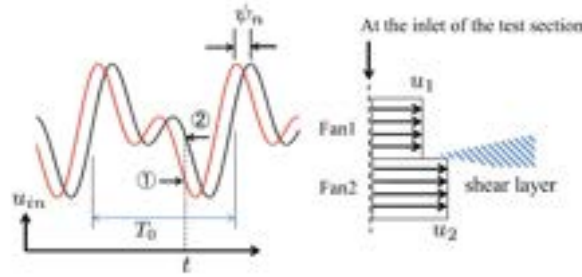


FIGURE 6.7: Random phase assigned to signals associated with different fans, (Takemure and Ozono, 2007).

Still seeking improvements on the set-up of the multiple-fan wind tunnel, Ozono, collaborating with other researchers (Ozono and Ikeda, 2018; Takemure and Ozono, 2007), focused on the shear layers generated between the outflows from adjacent ducts, assigning to each input signal a different phase (but keeping the same wave form and amplitude), aiming at a favorable interaction between the different shear layers in order to aid the development of turbulence downstream (Figure 6.7). The scope was finally achieved, obtaining a good isotropy between the vertical and the horizontal turbulence; furthermore, a high-intensity and large-scale turbulence was obtained.

The prototype of Miyazaky University was taken as reference to build novel facilities. The first one is the wind tunnel of Tongji University (Shanghai), characterised by the presence of 120 independently controlled high sensitive fans (arranged in a 12×10 matrix, Figure 6.8), which act on a 1.8×1.5 [m] test section, producing velocities up to $20 \left[\frac{m}{s} \right]$. The contraction ratio of this facility is 1:4.



FIGURE 6.8: Wall of fans of the Multiple-fan wind tunnel of Tongji University, (S. Cao and J. Cao, 2017).

The third multiple-fan wind tunnel is in Taipei, at the Tamkang University. An accurate description of this facility is provided in Section 6.3.

Besides, the concept of a multiple-fan wind tunnel has been exported also on smaller scale, e.g. (Kikuchi et al., 2019), employing 100 common (especially if compared with a traditional wind tunnel fan) PC cooling fans, which are controlled by an original embedded system.

It is noteworthy to stress again that the main scope with which these facilities were built is the reproduction of ABL profiles in a limited amount of space, aiming at the reproduction of high-intensity and turbulence scales. Nonetheless, they are also capable of simulating accelerating flows thanks to the reduced inertia of the fans, which makes them suitable facilities to study the effects of thunderstorm outflows on structures.

A separate discussion is deserved for multiple-fan wind tunnels whose main aim is the reproduction of hurricanes, extra-tropical cyclones and thunderstorms on full-scale buildings, as the Florida International University or the Insurance Institute for Business & Home Safety (IBHS) Research Center Full-Scale Test Facility. Concerning the latter one, the test chamber is $44.2 \times 44.2 \times 18.3$ [m], in which wind flow is produced by 105 1.68 [m] diameter vane-axial fans (Smith, 2011); also a 1:10 prototype exists and is documented in (Smith et al., 2012).

6.3 The Tamkang University Multiple-fan wind tunnel (TKU-MFWT), Taipei

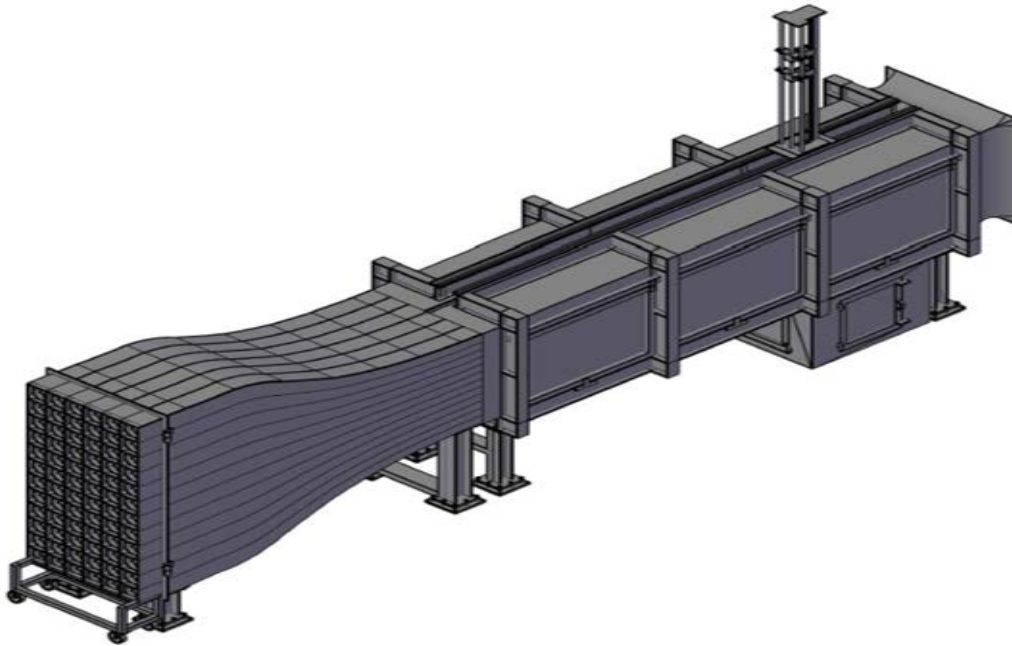


FIGURE 6.9: Render of the TKU-MFWT, courtesy of Tamkang University and Dr. Yuan-Lung Lo.

The Tamkang University Multiple-fan wind tunnel (TKU-MFWT) (Figure 6.9) is an actively controlled wind tunnel equipped with 72 individually controlled fans to drive the flow (Figure 6.10A), arranged in a 12×6 matrix.

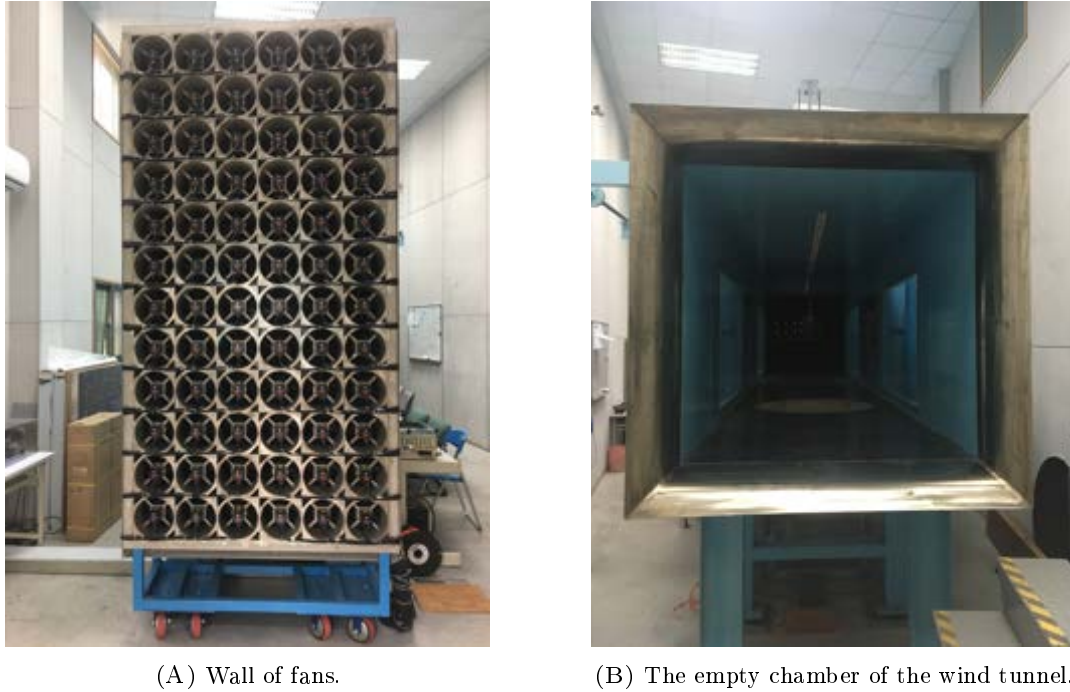


FIGURE 6.10: TKU-MFWT.

The test section is 1.32×1.32 [m] in cross section. No roughness elements are used to develop the velocity profile and all the internal surfaces are smooth (Figure 6.10B). The contraction rate is 1:2 and is obtained by reducing only the vertical dimension. The nominal mean wind velocity range in the tunnel is $2 < \bar{U} < 16$ [$\frac{m}{s}$].

The total length of the facility is 10.43 [m] and the contraction beyond the wall of fans covers 4.39 [m] of this dimension. In Section 6.4, there is Figure 6.12, which provides a scheme of the TKU-MFWT, furnishing the relevant dimensions, which also clarify the definition of the test section.

The presence of a high number of fans allows different vertical wind profiles to be reproduced, and this topic has been addressed in a recent work presented at the International Conference of Wind Engineering in Beijing (M. S. Mason and Lo, 2019; Lo and M. S. Mason, 2019). In that work, an investigation was carried out to study the effects induced by the change of the velocity profile (uniform, standard atmospheric boundary layer, nose-like shape) on the pressure coefficient distribution during the transitions.

6.4 The wind tunnel model

The wind tunnel model is a sectional model of a square cylinder equipped with 94 pressure taps (Figure 6.11A).



(A) Sectional model and tubes.



(B) Installation in the TKU-MFWT.

FIGURE 6.11: The wind tunnel model.

The model covers the entire width of the test section (Figure 6.13, Figure 6.14 and Figure 6.11B), which is placed 3.66 [m] downwind of the entrance to the test chamber. Figure 6.12 shows a drawing of the TKU-MFWT, in which the lengths to define the position of the sectional model in the facility are indicated.

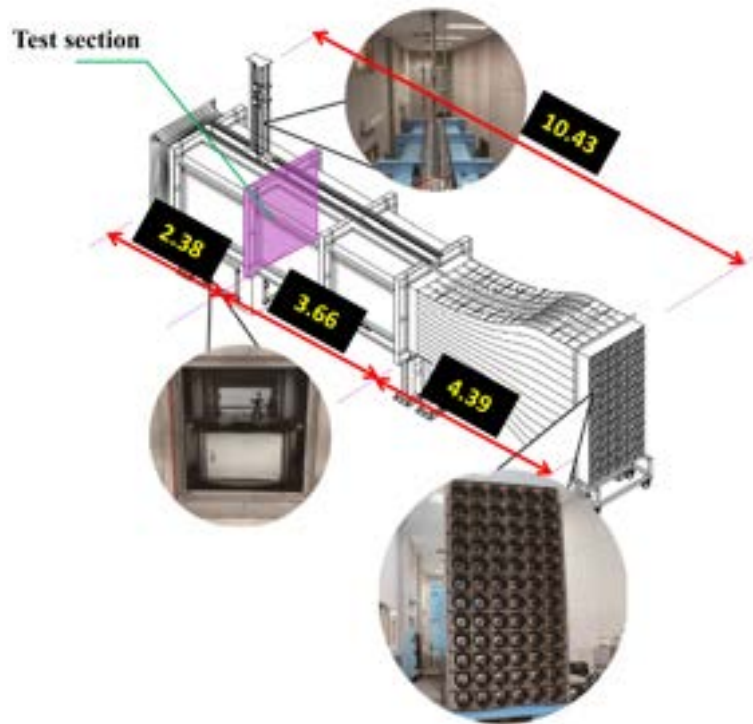


FIGURE 6.12: Scheme with dimensions (in [m]) of the TKU-MFWT.

The side b of its cross-section is 6 [cm], therefore the resultant blockage ratio is less than 5 %.

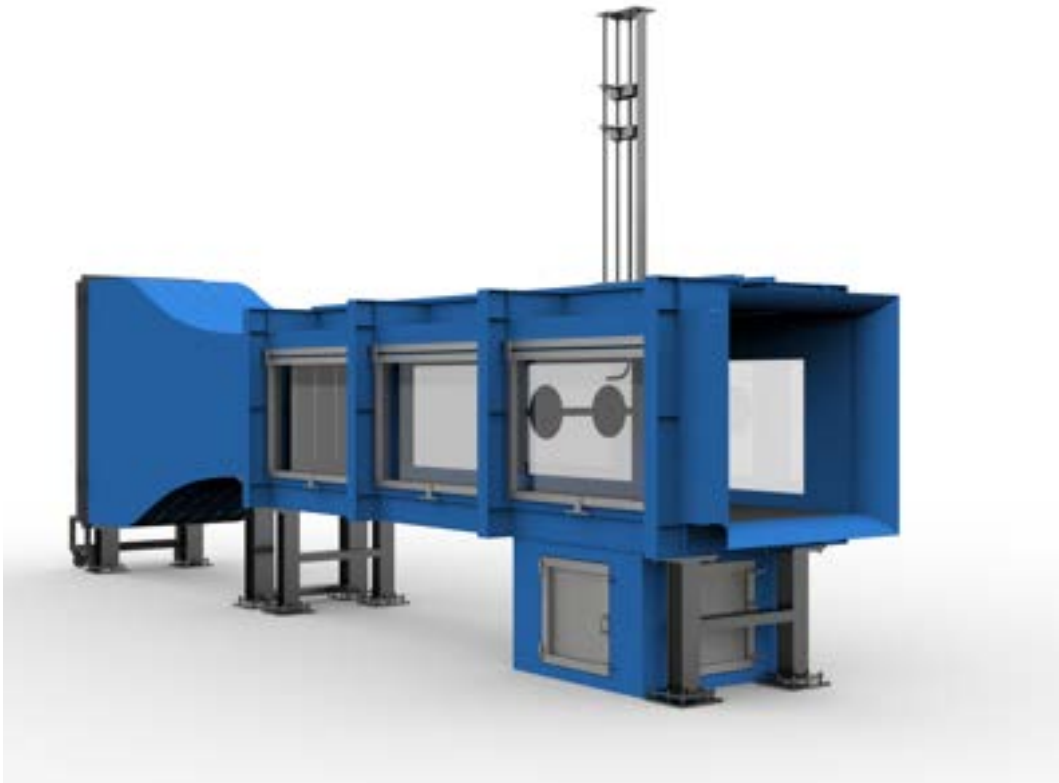


FIGURE 6.13: Render of the TKU-MFWT with the model installed.

An internal view is still proposed through the rendering in Figure 6.14.

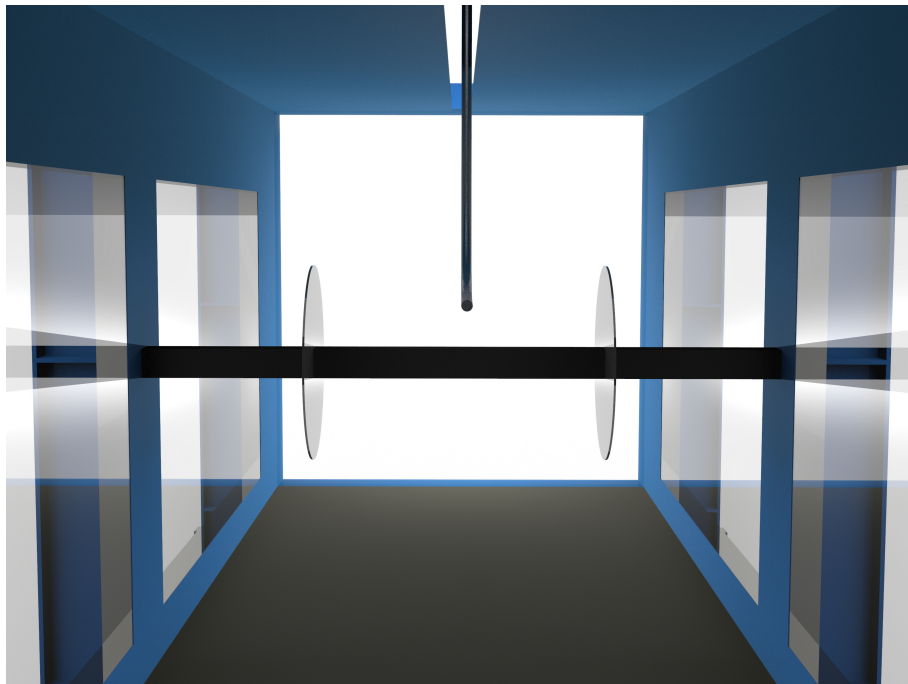


FIGURE 6.14: Internal view of the render, close-up of the wind tunnel model.

Out of the 94 pressure taps, 46 are placed in the mid-span section, where the distance

between the taps is 5 [mm], except for the pressure taps in the upper and lower face that are closest to the edges, from which they are 2.5 [mm] far. The model is studied for zero incidence only and this is the configuration to which Figure 6.15 refers to, drawing the external envelope of the model in black and the pressure taps as red dots; the Z -direction represents the axis of the model, as in the previous chapters (Chapter 3 and Chapter 4).

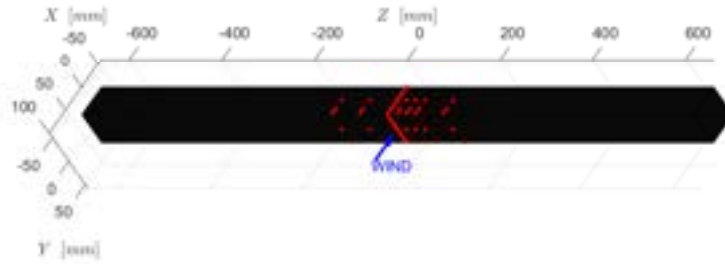
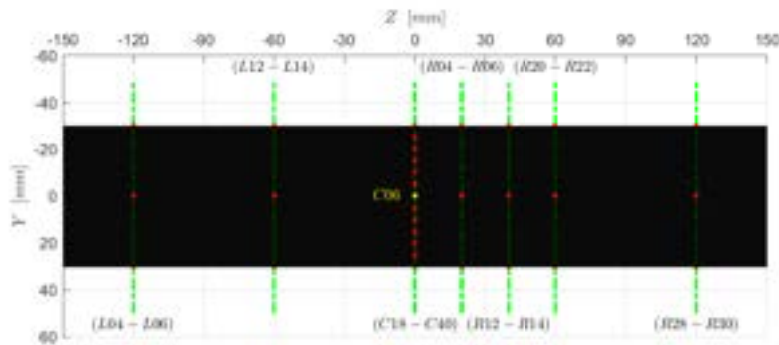
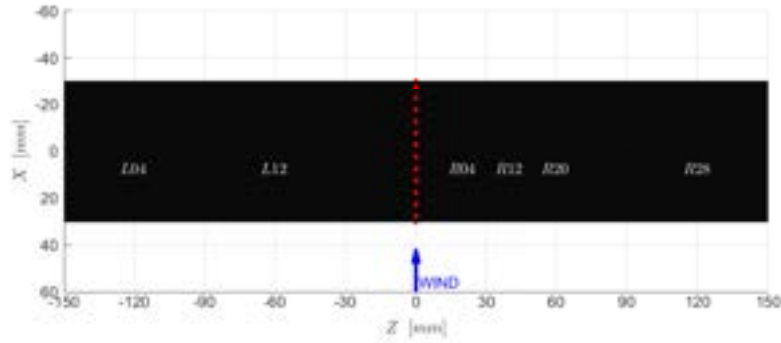


FIGURE 6.15: 3D Model of the wind tunnel model with the indication of the incident wind.

Figure 6.16A and Figure 6.16B, respectively, show the front and the top views of the wind tunnel model, specifying the notation for the pressure taps. In particular, Figure 6.16B describes the position of the pressure taps on the upper face and the direction of the incoming wind. On the other hand, Figure 6.16A refers to the lateral sections, which are highlighted by dashed green lines and are the objects of the chapter devoted to the vortex-shedding phenomenon (Chapter 8). Furthermore, the pressure tap at the stagnation point of the mid-span section, $C06$, is indicated in yellow.



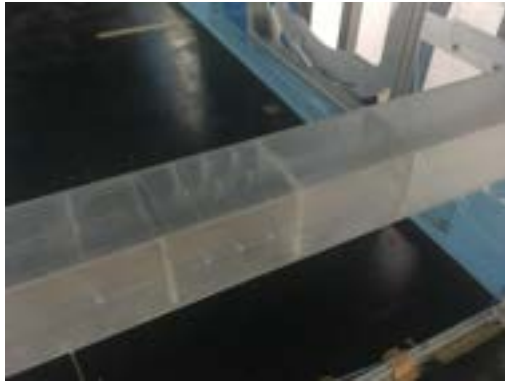
(A) Front view.



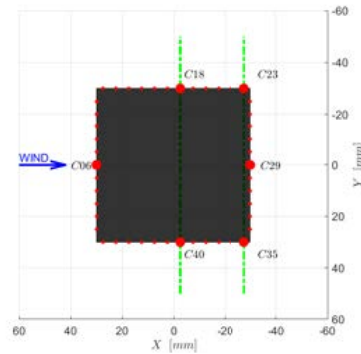
(B) Top view.

FIGURE 6.16: Views of the wind tunnel model.

Figure 6.17 shows the mid-section of the model, reporting the incident wind and the 46 pressure taps that have been mentioned before. Six of these taps have been highlighted with bigger dots, since the associated signals are of great interest to study the effects induced on the structure by accelerating or decelerating flows. These are $C06$, which, as mentioned before, is located at the stagnation point of the section, $C29$, whose signal difference with $C06$ is representative of the resistance of the body, and the two couples $C18 - C40$ and $C23 - C35$, which are representative of the vertical load induced by vortex-shedding. The dashed green lines passing through the latter two couples indicate, as before, that these two sections are investigated in the following, precisely in Chapter 8.



(A) Close-up.



(B) Scheme.

FIGURE 6.17: Mid-span section of the wind tunnel model.

The X -axis is directed in the opposite direction of the incoming wind and the Y -axis is positive for the lower part of the model. Hence, the system (X, Y, Z) is a suitable right-handed tern.

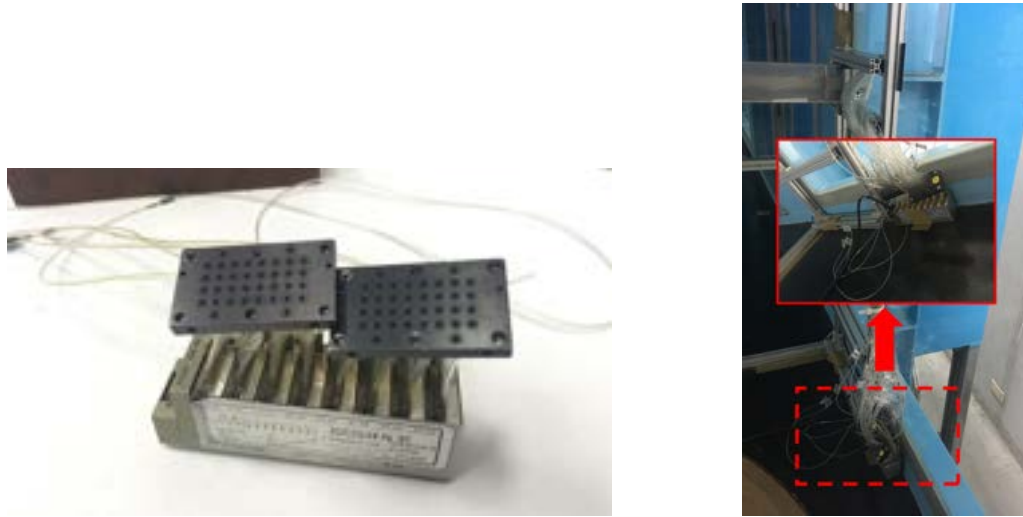
6.5 The wind tunnel instrumentation

The wind tunnel model is supported by an aluminium frame which is installed inside the TKU-MFWT. Two circular end-plates, whose diameter is 40 [cm] ($\sim 7b$) are installed 600

[*cm*] apart, leading the model to a slender ratio equal to 10, as in the case after (Yang and Matthew S. Mason, 2019).

The instrumentation installed in the wind tunnel has the scope of capturing the pressure and the wind field generated around the wind tunnel model. Section 6.5.1 is dedicated to the pressure field, whereas Section 6.5.2 concerns the wind field generated by the fans.

6.5.1 Pressure field



(A) A single pressure transducer.

(B) Installation in the TKU-MFWT.

FIGURE 6.18: *Scanivalve* ZOC33 multi-pressures scanning device.

To acquire the pressures experienced by the 94 surface pressure taps, two 64 channels ZOC 33 pressure transducers (*Scanivalve* Corporation) (Figure 6.18A) are employed, each one incorporating a high speed multiplexer (45 [*kHz*]). The sampling frequency is set at 300 [*Hz*]. They are placed on the ground of the TKU-MFWT, covered from the action of the wind by the supporting frame (Figure 6.18B, in the zoom). The precision of such instrument is declared as the 0.15 % of the full scale, which is 2500 [*Pa*], so that the accuracy is ± 3.75 [*Pa*]. All model taps are connected to the corresponding pressure transducer with a 1.5 [*m*] PVC tubing, which has an internal diameter of 1.5 [*mm*]. Considering the length of the tubes, the raw pressure measurements are treated with frequency correction technique for both amplitude and phase distortions (Irwin, Cooper, and Girard, 1979). All the recorded signals are actually differential pressures between the ones acquired on the tap and the reference pressure, which is taken from an adjacent room.

6.5.2 Wind field

Empty tunnel

To study the vertical wind profile inside the TKU-MFWT, a *Turbulent Flow Series 100* Cobra probe has been installed in the empty test chamber.



FIGURE 6.19: Set-up for vertical profiling in the TKU-MFWT.

The Cobra probe, thanks to the simultaneous reading from its 4 holes, is able to separately furnish the three velocity components (in general terms, longitudinal u' , lateral v' and vertical w' component) together with the static pressure. It is placed in correspondence of the section where the windward face of the wind tunnel model is located during the tests (see Figure 6.19), along the mid-section of the tunnel, which corresponds to the section presented in Figure 6.17B. The device, which is hereinafter denoted as *CPI*, has been moved at different heights, precisely $h = 40, 140, 240, 340, 390, 490, 540, 570, 600, 610, 620, 630, 640, 650, 660, 670, 680, 690, 700, 710, 720, 750, 780, 830, 880$ and 930 [mm] from the ground.

Wind field around the wind tunnel model

To study the induced wind field around the model, three Pitot-static tubes and (initially) three Cobra probes are used. The three Pitot-static tubes are used to estimate the total and the static pressure, and - consequently - the dynamic pressure - which act on the model. At variance with the Cobra probe, the Pitot-static tube does not furnish the velocity, but provides the dynamic pressure P_{dyn} . Moreover, such device is not able to separate the different components, providing only one global value of the dynamic pressure. To convert it to velocity, the dynamic pressure is divided by (0.5ρ) and the square root is carried out. ρ is constantly assumed equal to $1.2 \left[\frac{Kg}{m^3} \right]$ and this choice derives from the fact that the temperature of the facility is kept constant at about 20 [C].

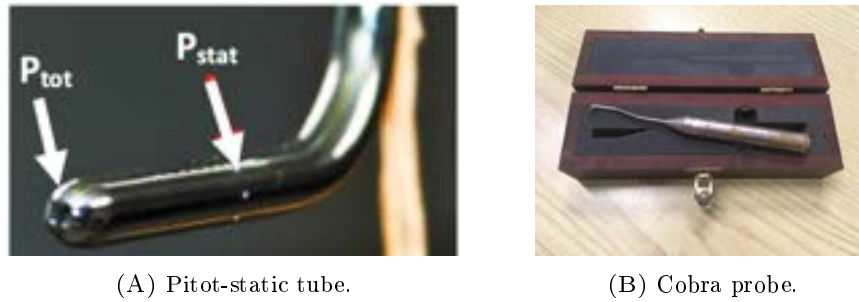
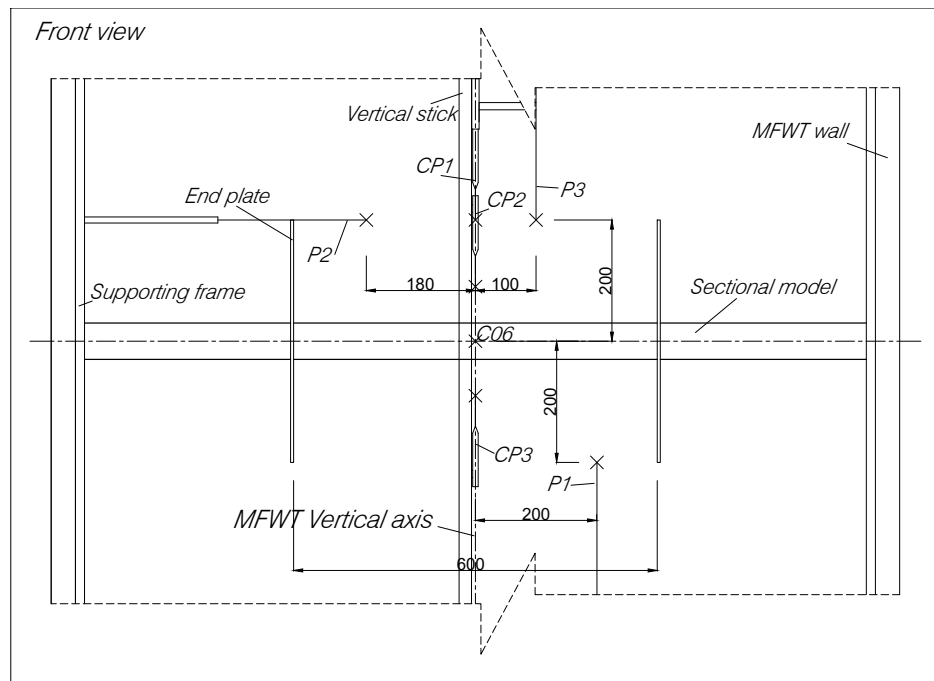
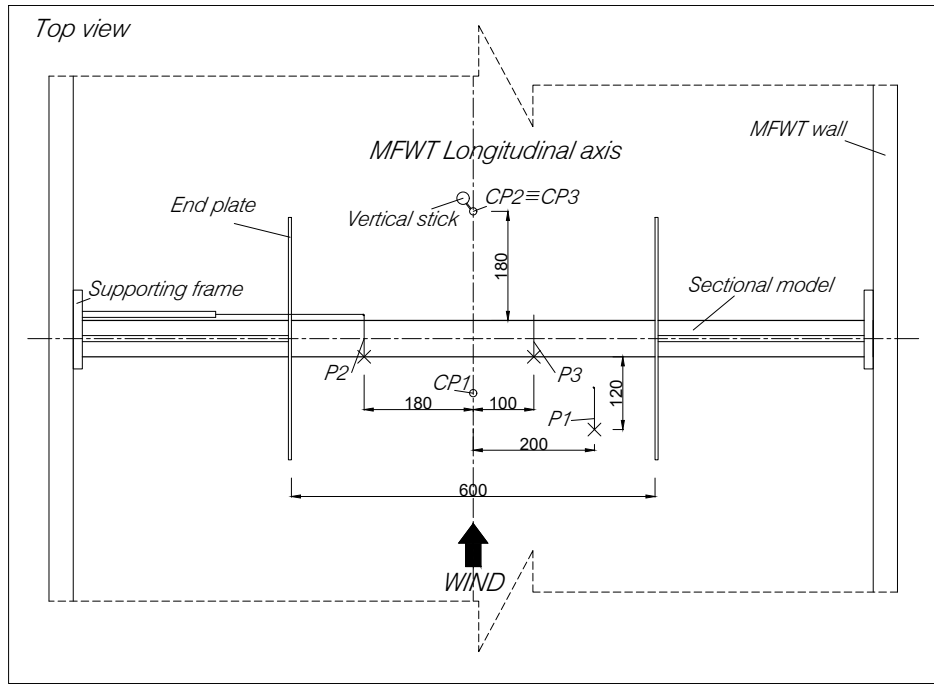


FIGURE 6.20: Devices to measure wind field.

It is standard practice for wind tunnel testing in steady flows to have two Pitot-static tubes placed one above the model and the other a few (i.e. 4) body reference dimensions upwind. This disposition has to be firstly tested in the empty tunnel, in order to observe the ratio between the velocities recorded by one and the other without the blockage induced by the wind tunnel model. Secondly, when the model is installed, this ratio can be employed on the records from the second Pitot-static tube (not affected by the presence of the model) to compare the results of this operation with the raw records of the first Pitot-static tube. This technique cannot be simply extended when reproducing accelerating flows, since it is important that the increase (or the decrease) of the wind speed simultaneously refers both to the windward face of the model and to the devices employed to study the dynamic pressure.



(A) Front view.



(B) Top view.

FIGURE 6.21: 2D schemes of the TKU-MFWT arrangement.

This is why the reading holes of two of these Pitot-static tubes are placed in the same vertical plane of the windward face, as sketched in Figure 6.21A and Figure 6.22, which show the positioning of the devices, hereinafter called $P1$, $P2$ and $P3$. Respectively, they read the total pressure at $1b$ (towards the inlet section), $0b$ and $0b$ along the X -axis, hence $P2$ and $P3$ exactly act on the same vertical plane of the windward section. Figure 6.21A specifies that $P1$ is 200 [mm] ($\sim 3b$) far from the mid-span section along the Z -axis and still 200 [mm] is the distance between $C06$ and $P1$ along the Y -axis. This distance is the same for the three Pitot tubes, being $P2$ and $P3$ over the model and $P1$ below it. $P2$ is 180 [mm] far from the mid-span section along the Z -axis, on the opposite side of $P1$, while $P3$ is placed at 100 [mm], on the same side of $P1$. The three Pitot-static tubes are connected to the same ZOC33 Scanivalve Corporation transducers already mentioned for the pressure taps on the model. Concerning the Cobra probes, the first one is still in the same position described in the previous paragraph, but moved of $1b$ closer to the inlet section. Two additional *Turbulent Flow Series 100* Cobra probes have been installed behind the model to study the wake generated around the body: their heads are placed at a distance equal to 18 [cm] ($3b$) along the X -axis and 9 [cm] ($1.5b$) along the Y -axis (Figure 6.22).

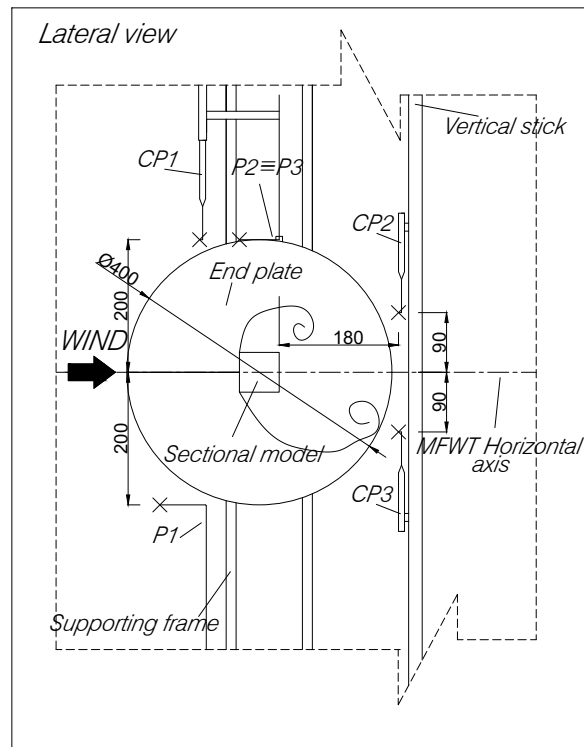
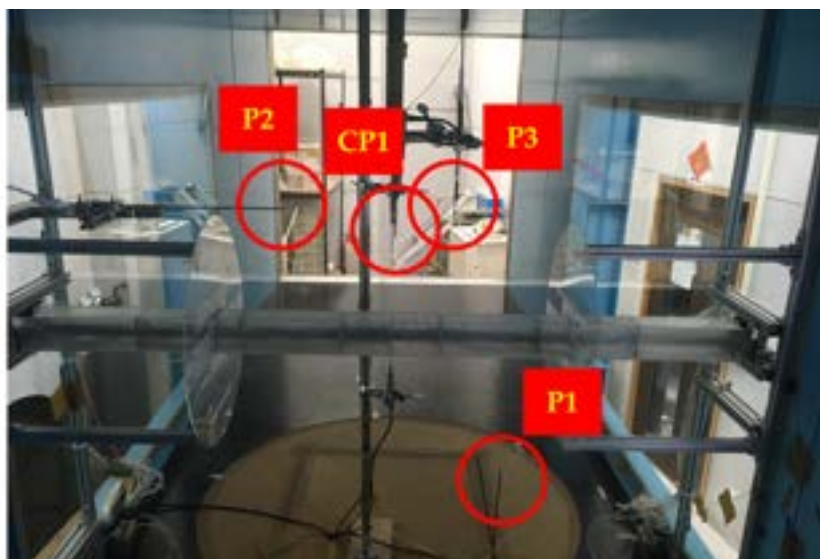
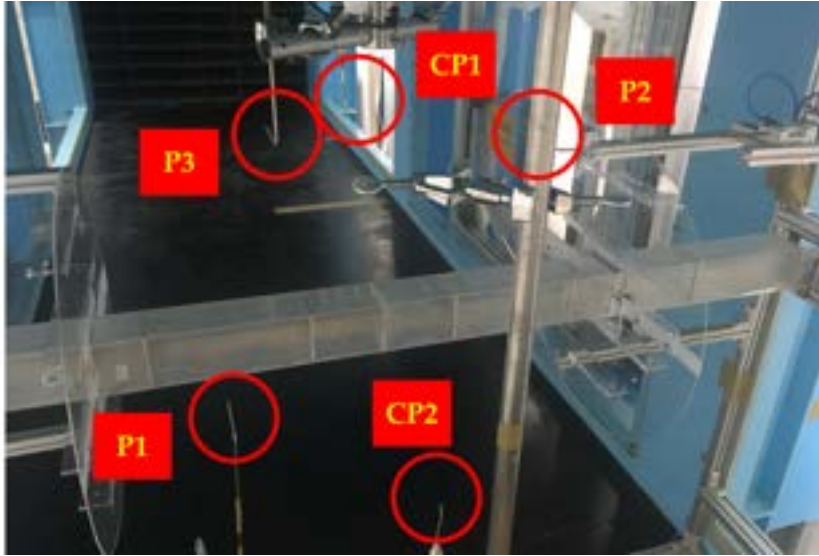


FIGURE 6.22: Scheme of the lateral view of the TKU-MFWT arrangement.

The presence of the two Cobra probes behind the model was assured during the first phase of the wind tunnel tests, but one of them, *CP2*, broke during the operations and only *CP3* was left. At variance with the pressure signals, the data from the Cobra probes are acquired through the *National Instrument* acquisition system, so their registrations are not completely coherent in time with the data from the ZOC 33 transducers. Figure 6.23 reports pictures of the wind tunnel set-up, labeling the previously listed devices.



(A) Front view.



(B) Top view.

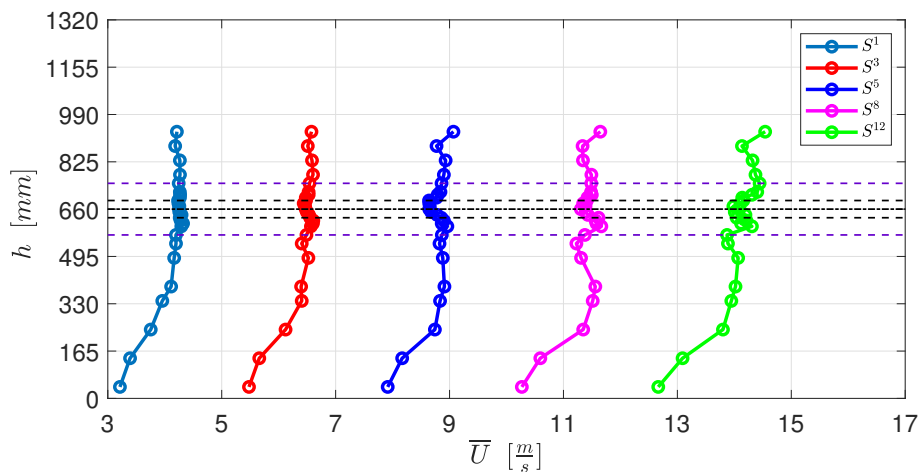
FIGURE 6.23: Wind tunnel set-up.

6.6 Overview of the wind tunnel tests

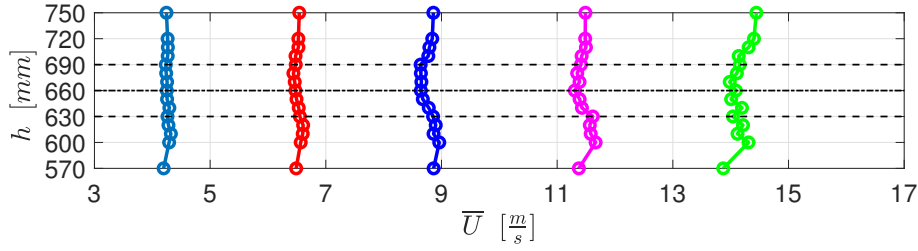
In this section, a general description is given of the wind tunnel tests that have been carried out in the TKU-MFWT. To have an adequate set of reference data to which the effects induced by the acceleration (or deceleration) have to be compared, it is necessary to reproduce in the wind tunnel both steady and unsteady flows. Hence, after the preliminary tests carried out in the empty tunnel, steady and unsteady flow pressure tests are carried out.

6.6.1 Preliminary tests

Firstly, twelve different settings of the TKU-MFWT have been picked as references to be employed in the wind tunnel test campaign.



(A) View considering the whole height of the TKU-MFWT.



(B) Zoom on the height of interest for the sectional model.

FIGURE 6.24: Vertical wind speed profiles for 5 settings of the fan in the TKU-MFWT.

These 12 settings, called hereinafter as S^1 - S^{12} , have been defined in order to have an uniformly distributed wind speed range. As explained in previous paragraphs, measurements of the velocity profile have been performed along a vertical line in the mid-span section of the TKU-MFWT; every measurement is composed of 2^{15} samples acquired at $300 [Hz]$ of sampling frequency. Figure 6.24 shows the mean value of the measurements concerning S^1 , S^3 , S^5 , S^8 and S^{12} , reporting in abscissa the values of the mean wind speed and in ordinate the vertical height from the ground. In the same picture, in order to clarify the position of the model with respect to the profile, the model axis is reported with a dashed-dot line, the contour lines of the square cylinder with a dashed black line, and the lines at $1.5b$ from the model axis with a dashed purple line. The mean speed along the vertical axis exhibits a variation from its average in the order of 5 %, especially for higher wind speeds. This variation is higher than the value commonly suggested for traditional general-purpose tunnels, e.g. (Barlow, Rae Jr., and Pope, 1999). On the other hand, the presence of 72 fans made the achievement of a better result challenging. Therefore, these settings have been eventually considered as satisfactory and employed for the analyses. Nonetheless, the variation here highlighted is considered in the analyses of results in the following.

6.6.2 Steady flow pressure tests

The steady flow pressure tests have been carried out in correspondence of the twelve different settings which have been mentioned before. After examining several possibilities, the adopted reference dynamic pressure has been defined as the difference between the pressure recorded by the *C06* pressure tap and the average mean static pressure recorded by *P2* and *P3*.

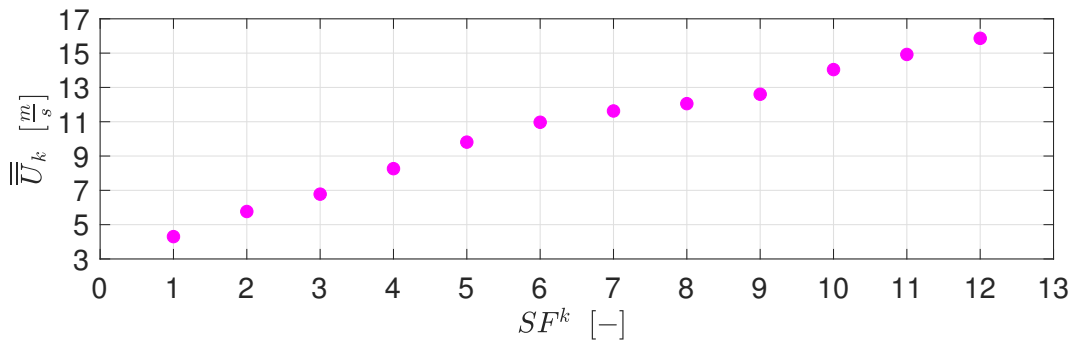


FIGURE 6.25: Values of the mean reference wind speed for the twelve considered settings.

This calibration has been chosen after an accurate analysis of different methods (i.e. considering a single Pitot-static tube), since its estimation was found to be robust. Indeed, the

results obtained through this procedure were highly repeatable and all the three taps (*C06*, *P2*, *P3*) acquire pressures from the same vertical plane. Actually, the holes of the Pitot-static tube that measure the static pressures are 4 centimetres downstream of that vertical plane, but this distance has been considered to have a limited influence. Furthermore, the static pressure distribution appears to be non-uniform in the chamber, and the choice of an average value from two different devices seems to take this spatial change into account. As regards this matter, Table 6.3 shows the variation of the static pressure P_s recorded by the different Pitot-static tubes for the whole set of tests. The nomenclature $\overline{\overline{P}}_{s,P_c}$ (where $c = 1, 2, 3$, since the devices are three) means that the value is the mean of several quantities $\overline{P}_{s,P_c}$, each obtained through a temporal mean on a single repeat.

Name of the test	$\overline{\overline{P}}_{s,P1}[Pa]$	$\overline{\overline{P}}_{s,P2}[Pa]$	$\overline{\overline{P}}_{s,P3}[Pa]$
SF^1	0.3	-1.6	-0.9
SF^2	-0.3	-3.7	-2.1
SF^3	-0.8	-5.5	-3.6
SF^4	-0.1	-6.8	-3.4
SF^5	-2.1	-11.4	-7.8
SF^6	-1.4	-13.4	-7.3
SF^7	-4.4	-18.1	-11.1
SF^8	-4.0	-18.7	-12.8
SF^9	-5.0	-21.4	-12.9
SF^{10}	-5.5	-24.6	-14.7
SF^{11}	-2.7	-23.8	-12.7
SF^{12}	-5.8	-28.6	-19.2

TABLE 6.3: Mean values of the registered static pressures P_s from the three Pitot-static tubes *P1*, *P2* and *P3*.

Furthermore, this choice permits to obtain completely consistent measurements of the pressure field around the body with the wind velocity, since all the components are simultaneously recorded by the pressure transducers.

Name of the test	$\overline{U}_k$	N° repeats	$\overline{\overline{U}}_k \left[\frac{m}{s} \right]$
SF^1	$\overline{U}_1$	32	4.30
SF^2	$\overline{U}_2$	25	5.77
SF^3	$\overline{U}_3$	32	6.78
SF^4	$\overline{U}_4$	25	8.26
SF^5	$\overline{U}_5$	32	9.81
SF^6	$\overline{U}_6$	25	10.97
SF^7	$\overline{U}_7$	25	11.63
SF^8	$\overline{U}_8$	32	12.05
SF^9	$\overline{U}_9$	25	12.60
SF^{10}	$\overline{U}_{10}$	25	14.04
SF^{11}	$\overline{U}_{11}$	25	14.92
SF^{12}	$\overline{U}_{12}$	33	15.86

TABLE 6.4: Steady flow test matrix.

The associated mean reference wind velocities are hereinafter denoted as $\overline{U}_1 - \overline{U}_{12}$, and their values against the number of fan setting $S^1 - S^{12}$ are shown in Figure 6.25. Their

quantification is reported in Table 6.4, in the forth column. This permits to estimate the Reynolds range which characterises this campaign, which is 17200 – 63440. In Figure 6.26A a wind speed time history from one repeat of test SF^8 is reported, while its harmonic content is pictured in Figure 6.26B.

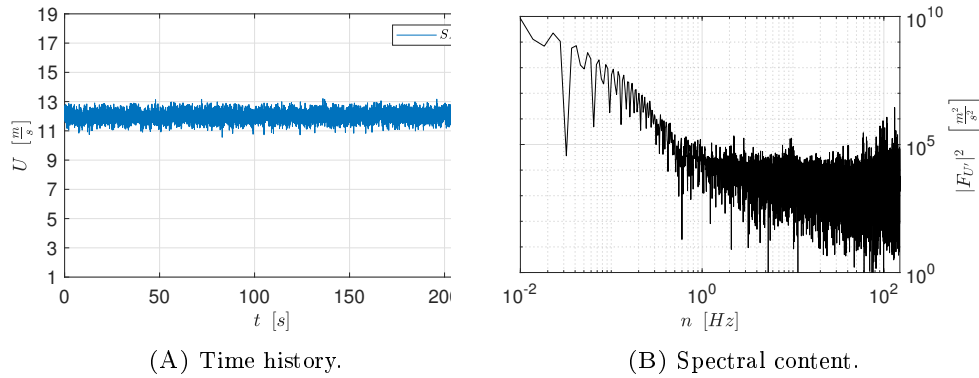


FIGURE 6.26: Reference wind speed from one repeat of SF8.

The number of repeats reported in Table 6.4 permits to obtain an ensemble mean of the mean value of the aerodynamic drag which is almost independent on the addition of new data, and a deeper discussion is provided in Chapter 7.

Figure 6.27A and Figure 6.27B, respectively, display the variation of $\sqrt{\overline{U'^2}}$ and of $\frac{\sqrt{\overline{U'^2}}}{\overline{U}}$ with the mean wind speed $\overline{U}$.

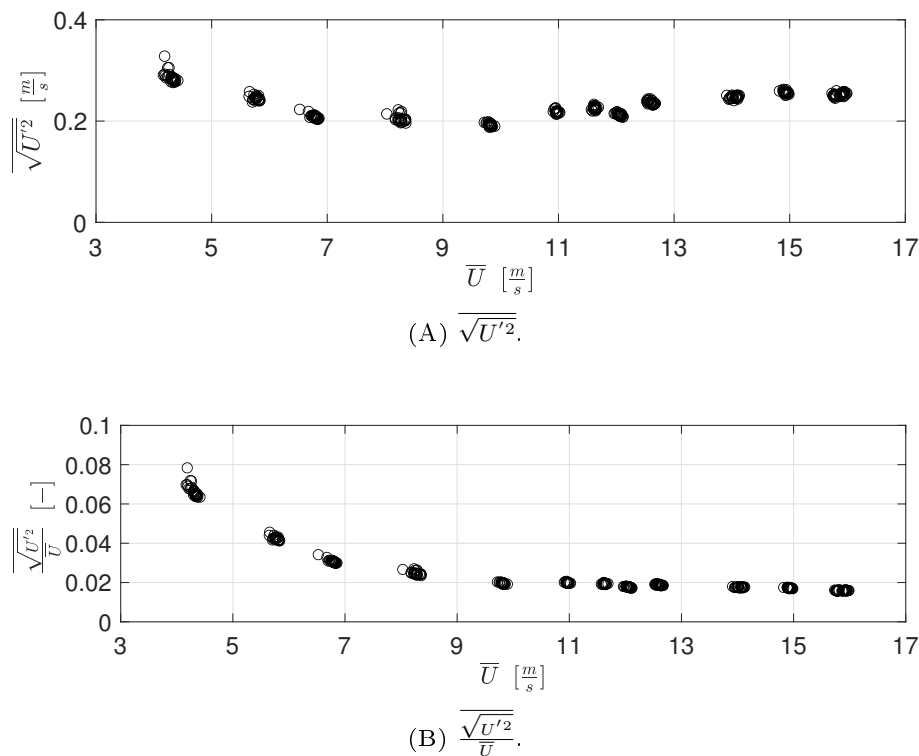


FIGURE 6.27: Variation of quantities associated with turbulence with the mean wind speed $\overline{U}$.

The level of $\frac{\sqrt{U'^2}}{U}$ appears to be higher than 1.6 % under any wind speed, which makes the flow turbulent. This has already been anticipated in Section 6.2 and is a typical feature of multiple-fan wind tunnels.

6.6.3 Unsteady flow pressure tests

The second phase of the wind tunnel test campaign has been devoted to reproduce unsteady flows.

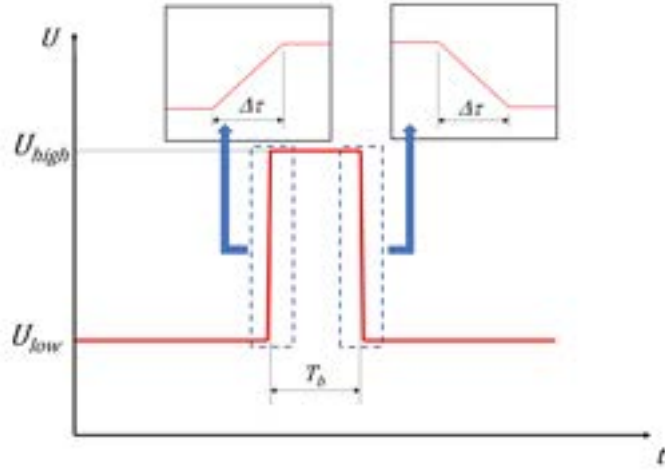


FIGURE 6.28: Scheme of a wind speed time history under unsteady flow conditions.

To describe the simulated wind speed time history, it is no longer possible to define, as done in the previous paragraph, the mean wind speed of the time history and the flow turbulence, but it is necessary to defined other parameters, summarised in Figure 6.28.

Name of the test	U_{low}	U_{high}	$\Delta\tau[s]$	$T_b[s]$	N° repeats
UF_1	S^1	S^{12}	2	60	90
UF_2	S^3	S^{12}	1.5	60	30
UF_3	S^5	S^{12}	1	60	30
UF_4	S^8	S^{12}	0.5	60	32
UF_5	S^3	S^8	1	60	30
UF_6	S^1	S^{12}	5	60	30
UF_7	S^3	S^{12}	2	60	30
UF_8	S^5	S^{12}	2	60	30
UF_9	S^5	S^{12}	5	60	30
UF_{10}	S^1	S^{12}	2	30	41
UF_{11}	S^1	S^{12}	2	10	30
UF_{12}	S^1	S^{12}	2	5	30
UF_{13}	S^1	S^{12}	2	1	30

TABLE 6.5: Unsteady flow test matrix.

In particular, U_{low} and U_{high} are the velocities associated with the fan settings illustrated by Table 6.4; applying the relevant nomenclature, it is possible to define the test matrix in

Table 6.5, which reports the type of the test ($UF = \text{Unsteady Flow}$) followed by the quantities described in Figure 6.28.

It is noted that the quantities $\Delta\tau$ and T_b indicated in Table 6.5 are nominal quantities and are given as input in the Excel file which governs the rotation of the fans of the TKU-MFWT. All the time histories which have been recorded are composed of 2^{16} samples recorded with a sampling frequency of 300 [Hz] , as for steady flows. Figure 6.29 shows a time history of the reference wind speed from one repeat of UF_1 and the two zooms focus on the ramp-up and the ramp-down.

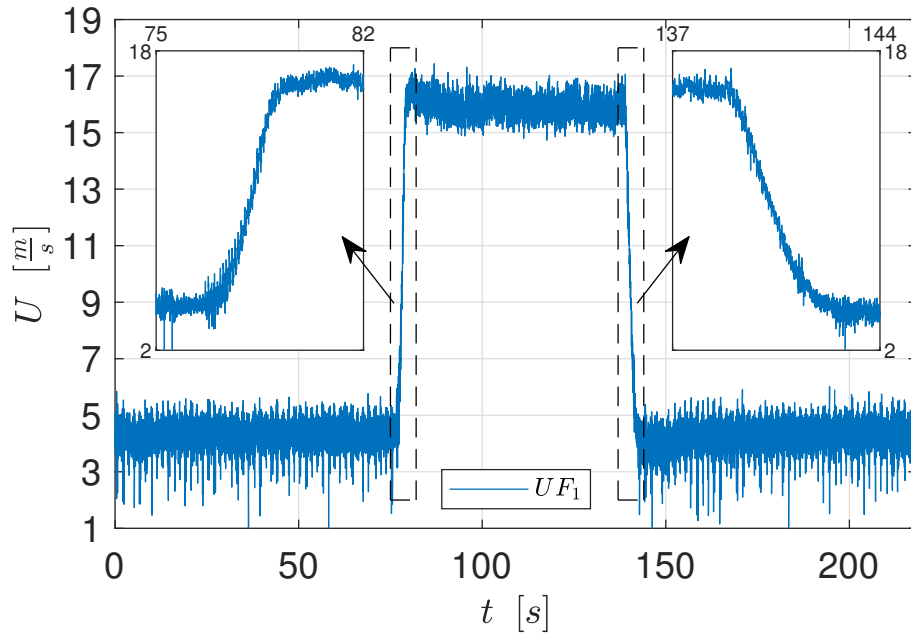


FIGURE 6.29: Time history of the reference wind speed for one repeat of UF_1 .

The next figures show a comparison between time histories coming from different tests. The first figure (Figure 6.30) shows the comparison between time histories of tests (UF_1 , UF_2 , UF_3 and UF_4) which differ by the choice of U_{low} .

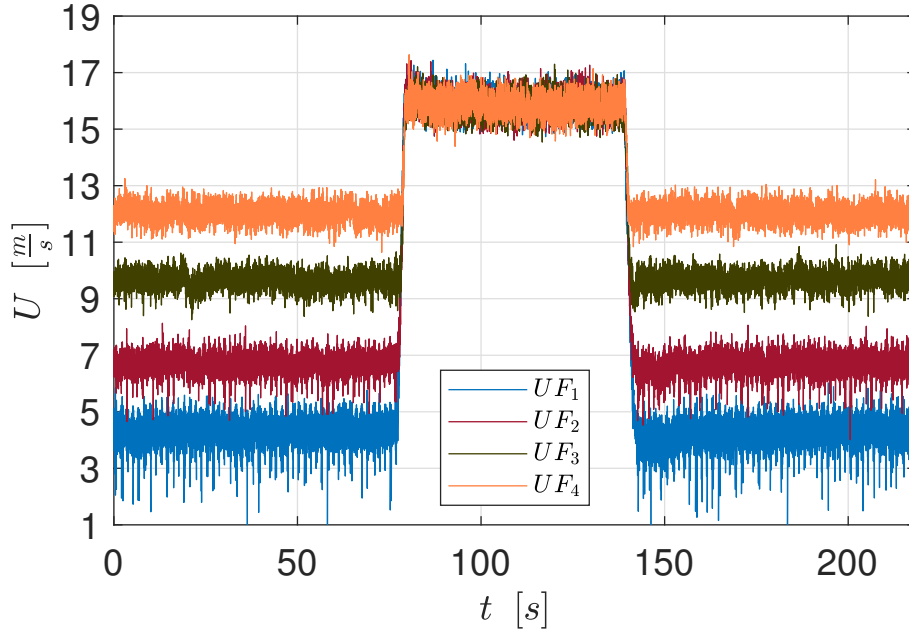


FIGURE 6.30: Comparison between time histories of the reference wind speed for one repeat of UF_1 , UF_2 , UF_3 and UF_4 (different U_{low}).

Conversely, Figure 6.31 focuses on the dependence on U_{high} and reports time histories from UF_2 and UF_5 .

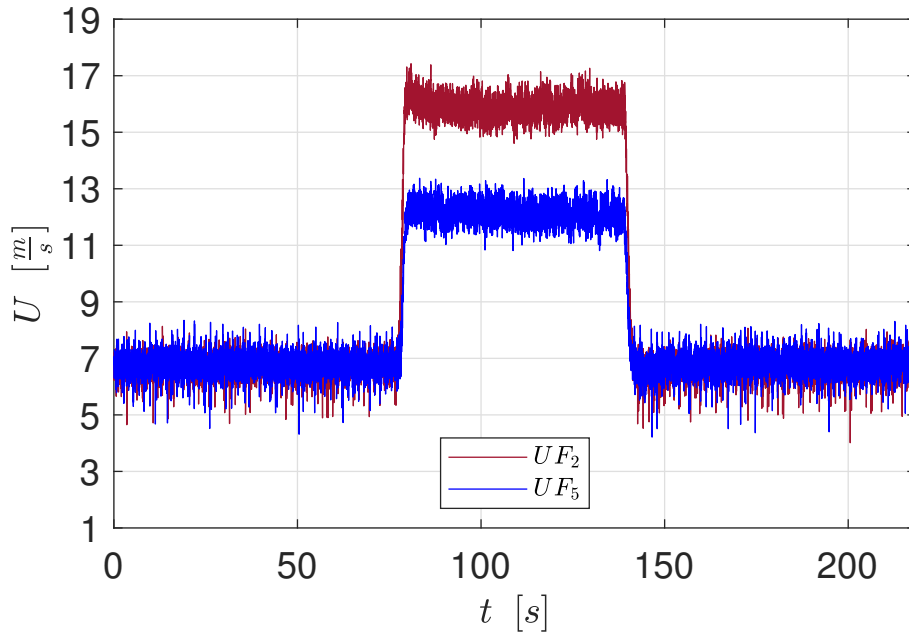
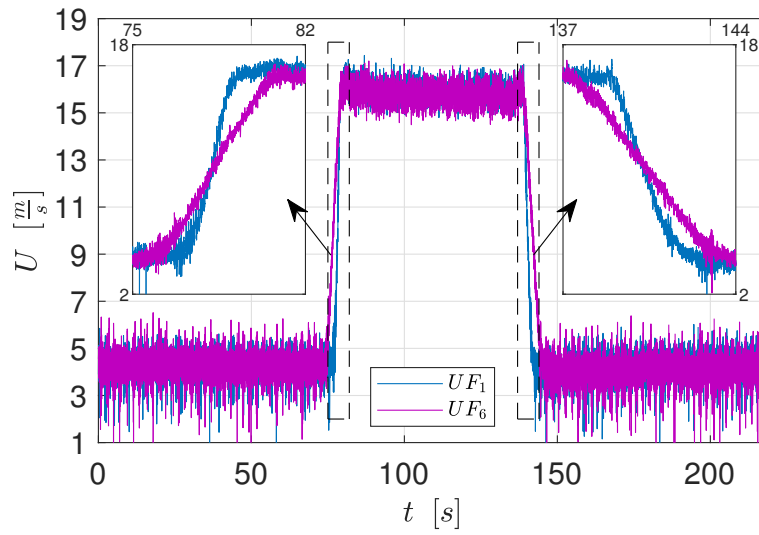
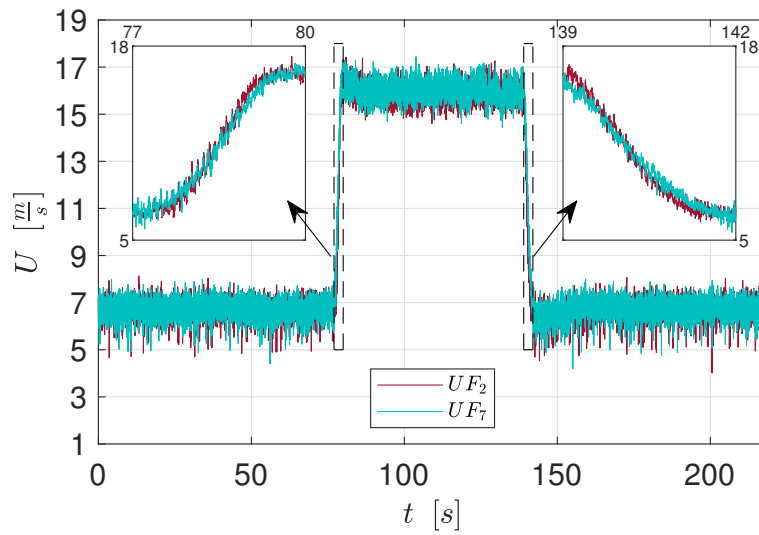
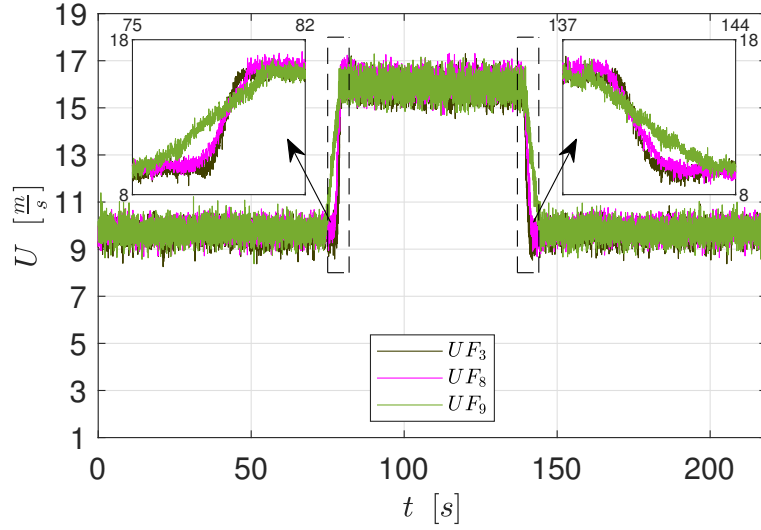


FIGURE 6.31: Comparison between time histories of the reference wind speed for one repeat of UF_2 , and UF_5 (different U_{high}).

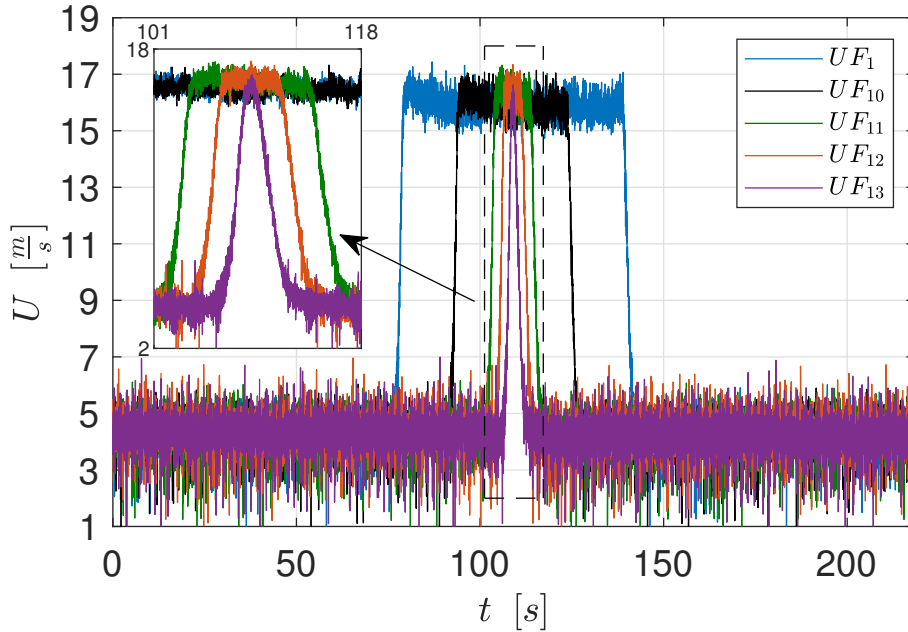
Figure 6.32 shows comparisons between time histories coming from tests characterised by a different $\Delta\tau$. In particular, it compares UF_1 and UF_6 (Figure 6.32A), UF_2 and UF_7 (Figure 6.32B) and UF_3 , UF_8 and UF_9 (Figure 6.32C).

(A) UF_1 and UF_6 .(B) UF_2 and UF_7 .

(C) UF_3 , UF_8 and UF_9 .FIGURE 6.32: Comparison between time histories of the reference wind speed (different $\Delta\tau$) for different tests.

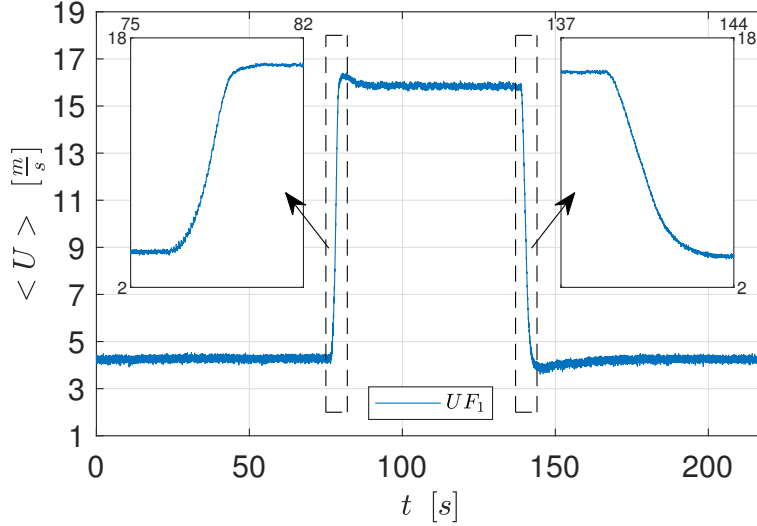
Conversely, in Figure 6.33 five time histories coming from UF_1 , UF_9 , UF_{10} , UF_{11} and UF_{12} are reported, which differ because of the choice of T_b . This picture clarifies that when T_b is shorter than the original (UF_9 , UF_{10} , UF_{11} and UF_{12}), a higher number of samples characterised by the lower wind speed U_{low} is considered, to have consistency with the total number of samples (2^{16}).

The path here proposed, identifying possible comparisons between the tests according to the dependence on U_{low} , U_{high} , T_b and $\Delta\tau$, traces a scheme which is recalled in Chapters 7 and 8 to comment the results.

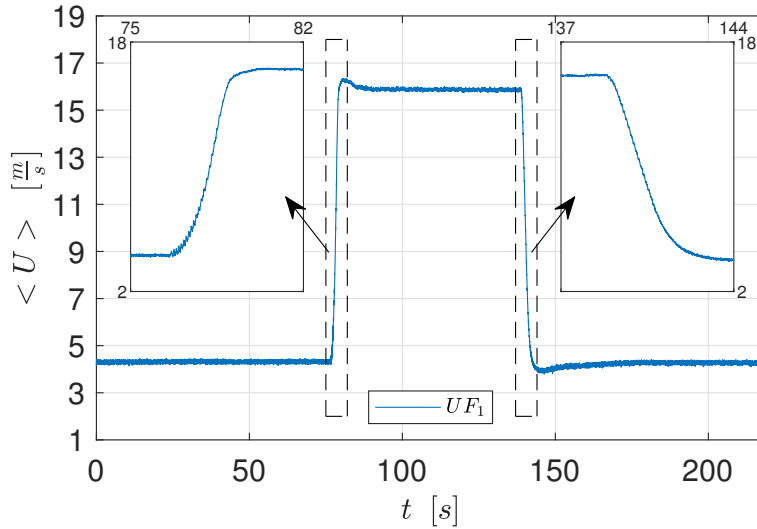
FIGURE 6.33: Comparison between time histories of the reference wind speed for one repeat of UF_1 , UF_9 , UF_{10} , UF_{11} and UF_{12} (different T_b).

6.7 Methodology of analysis of the dynamic pressure in unsteady conditions

To study specified quantities (such as drag or lift coefficient) in unsteady conditions, at variance with steady flows, it is not possible to study the temporal mean, making necessary to proceed with ensemble means of the signals (which, in this manuscript, are indicated through the operator $\langle \rangle$), after an appropriate alignment (Yang and Matthew S. Mason, 2019).



(A) Ensemble mean on 30 repeats.



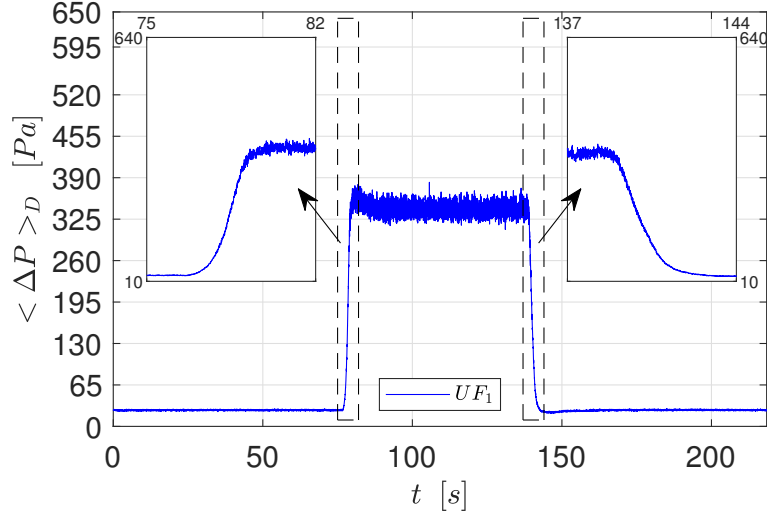
(B) Ensemble mean on 90 repeats.

FIGURE 6.34: Ensemble mean of the reference wind speed U for the test UF_1 .

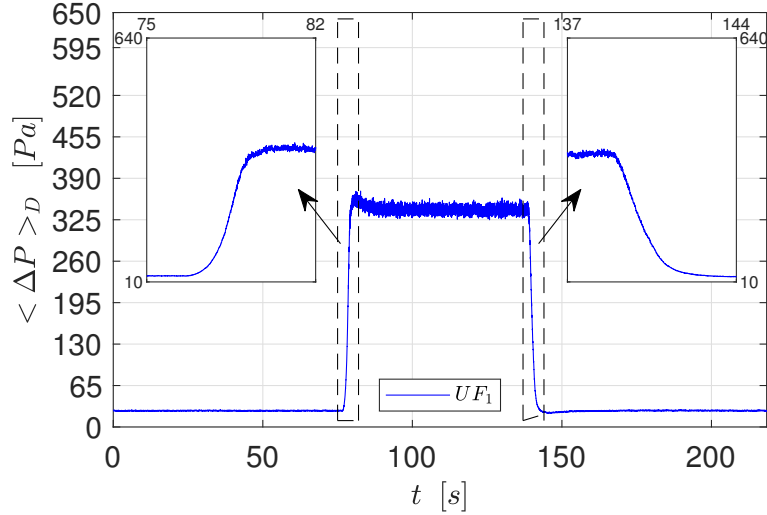
However, because of the turbulence present in the tunnel, it was observed that even a high number of repeats does not seem sufficient to reach a clear and well-defined signal of the reference wind velocity, not influenced by turbulence, as shown by Figures 6.34A and 6.34B, which, respectively, display the ensemble means on 30 and 90 repeats of U .

In spite of the high number of repeats, the ensemble mean does not converge to well-defined values as in the cases reported by the researchers of The University of Queensland, where the open-circuit suction wind tunnel assures a limited level of turbulence. Analogously, Figure

6.35A and Figure 6.35B show the ensemble mean of ΔP_D , which is the signal of the difference between *C06* and *C29* and is an indicator of the aerodynamic drag.



(A) Ensemble mean on 30 repeats.



(B) Ensemble mean on 90 repeats.

FIGURE 6.35: Ensemble mean of the difference between *C06* and *C29*, ΔP_D for the test UF_1 .

Having obtained the previous results, it is possible to evaluate the resistance coefficient $c_{\Delta P_D}$, obtained as the ratio between $\langle \Delta P_D \rangle$ and the reference dynamic pressure $\langle P_{dyn} \rangle$, from which $\langle U \rangle$ is estimated. The outcome of this operation, for 90 repeats, is reported in Figure 6.36, which also offers specific zooms on the ramps. These still highlights the difficulties to proceed with this technique.

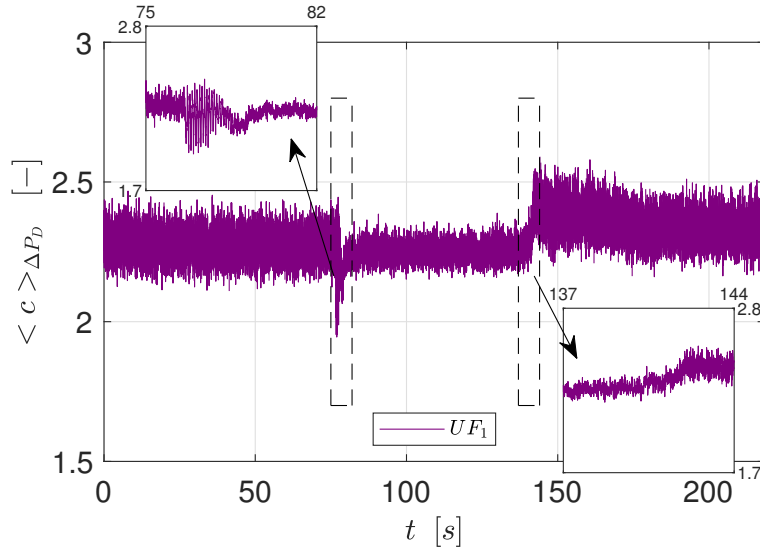


FIGURE 6.36: Ensemble mean of the resistance coefficient $c_{\Delta P_D}$ for the test UF_1 .

In order to overcome this issue, a filtering technique based on the continuous wavelet transform, CWT , (already introduced in Chapter 5) is adopted and applied on every signal (one for each repeat) associated with the reference dynamic pressure, P_{dyn} , to the signal difference between $C06$ and $C29$, ΔP_D , and to the drag force per unit length, f_D , evaluated by projecting in the alongwind direction the integration of pressures over the perimeter. In particular, from the 2^{16} samples of the original signals, the regions of the ramp-up and of the ramp-down are specifically individuated and extracted, to carry out the tailored technique only on selected portions of the signal. The description of the procedure is explained in the following, distinguishing the cases for which the ramp-up and the ramp-down can be treated as independent (Section 6.7.1), and for which they have to be studied together (Section 6.7.2), since T_b is shortened (Figure 6.33). Finally, Section 6.7.3 shows the ensemble mean of the wind speed U_W and acceleration a_W for the entire set of tests, distinguishing them by the parameters defined in Section 6.6.3.

6.7.1 Ramp-up and ramp-down studied as independent

In the tests UF_1 - UF_{10} , T_b is higher than 30 [s], and this time length is considered sufficient to allow the formation of a well-defined wake beyond the model; this permits to consider the analyses of the ramp-up and the ramp-down as independent. Hence, from each signal, it is possible to extract two sub-signals focusing on the ramp-up and the ramp-down, being each of them composed of 2^{15} samples. Figure 6.37 shows the identification of the two sub-signals (Figure 6.37A for the ramp-up and Figure 6.37C for the ramp-down) from the original time-history of the dynamic pressure P_{dyn} (Figure 6.37B) of one repeat of UF_1 .

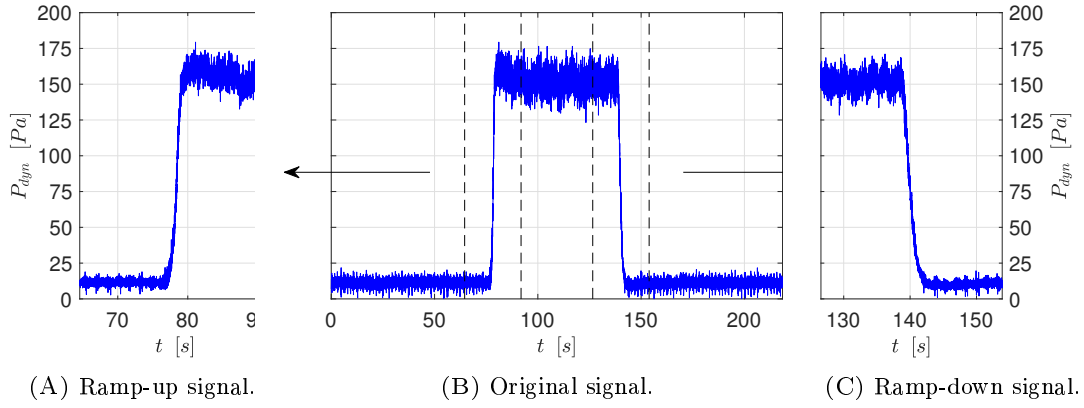


FIGURE 6.37: Selection of sub-signals from a time history of the reference dynamic pressure P_{dyn} of one repeat of UF_1 .

The two sub-signals (Figure 6.37A for the ramp-up and Figure 6.37C for the ramp-down) may be treated with the $L2$ continuous wavelet transform, after the definition of the mother wavelet (a Morlet with $\omega_0 = 2\pi$, which realises the best balance between time and frequency resolution, Chapter 5). To this end, 501 scales are squeezed in the range 0.01 - 2.51 [Hz], allowing an optimal frequency discretisation to be obtained. The filtering procedure is carried out imposing a thresholding parameter λ equal to 5 % of the mean value of the energy map (sensitivity studies about this parameter are presented in the next paragraph). The cut-off frequency $n_{co,U}$ coincides with 2.51 [Hz], and allows the removal of any sort of influence of the vortex-shedding, since that is seen to be acting at 9.4 [Hz] for the lowest tested velocity. This procedure is consistent with the definition of a time-varying mean of the signal, regardless whether that is P_{dyn} , ΔP_D or f_D ; moreover, it is noted that this precaution is taken since all the signals of interest are influenced by the vortex-shedding. Indeed, also P_{dyn} is affected by the static pressure from $P2$ and $P3$, which are reading on the same vertical plane as the windward face of the square cylinder, at 20 [cm] ($\sim 3b$) from the model axis, so that their measurements are affected by the vortices shed by the body. Figure 6.38 shows the application of the procedure for P_{dyn} : after the definition of the signals of interest (Figure 6.38A and Figure 6.38B), the energy maps are filtered and displayed (Figure 6.38C and Figure 6.38D). The filtered real and imaginary parts of the transform undergo the inverse continuous wavelet transform and the filtered signals are displayed (Figure 6.38E and Figure 6.38F), and are indicated with a subscript w . P'_{dyn} is the residual ($P_{dyn} - P_{dyn,w}$) and is indicated in black.

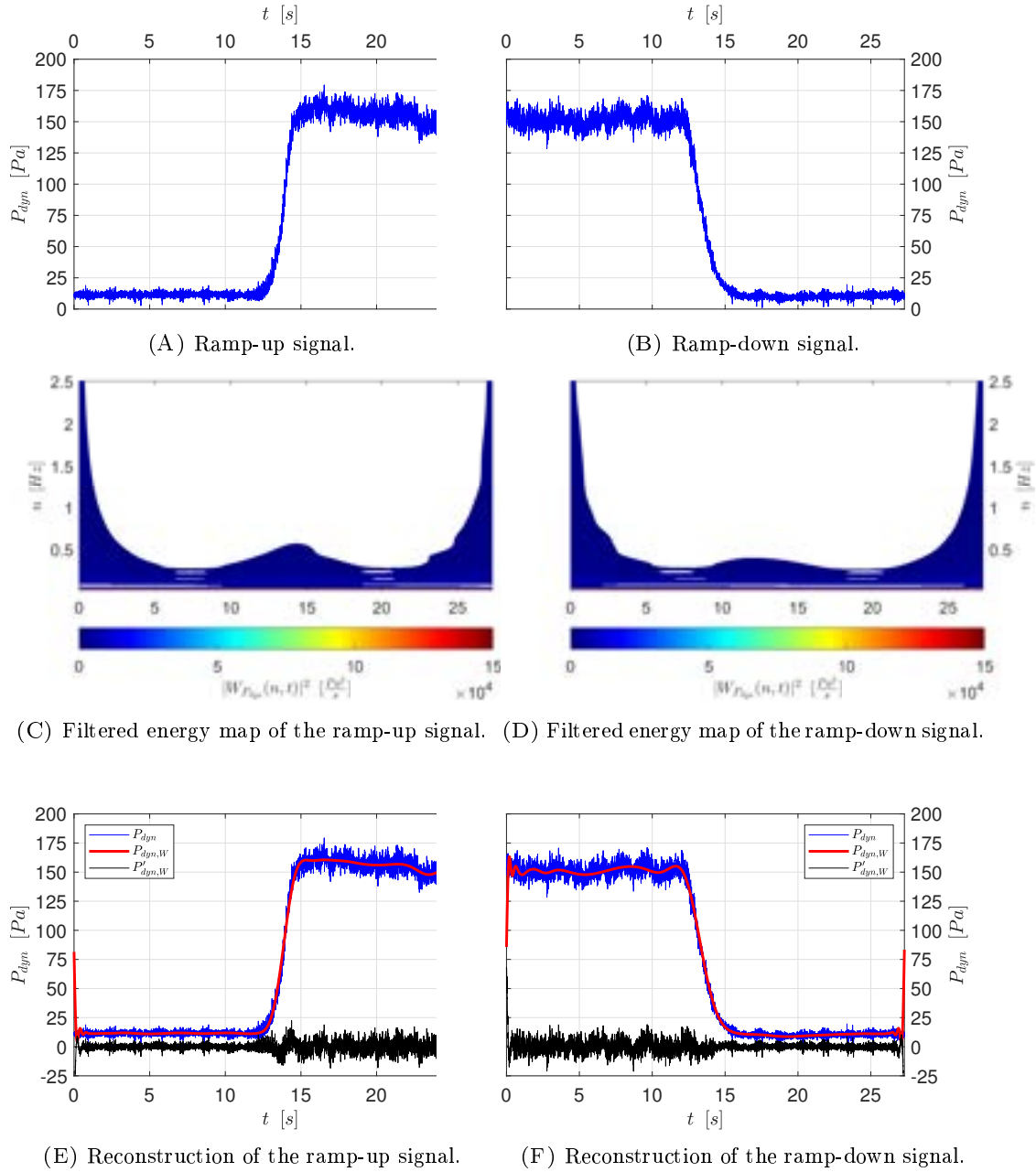


FIGURE 6.38: Procedure of the filtering based on CWT for signals of P_{dyn} extracted from a time history of UF_1 .

As stated before, from the time history of P_{dyn} it is possible to easily evaluate the reference wind velocity U , assuming a non-varying density $\rho = 1.2 \left[\frac{Kg}{m^3} \right]$. The same might be done to pass from its time-varying mobile quantity, $P_{dyn,W}$, to the time-varying mobile wind speed U_W . From the derivative of the latter quantity, obtained using a numerical method (central finite difference at the 4th order), it is possible to determine the flow acceleration a_W . Furthermore, from the combination of these two quantities, the procedure to estimate the acceleration parameter $K_{a,W}$ is straightforward, as shown in Eq. 6.1. It is remarked that this time-history is estimated for each repeat.

$$K_{a,W} = \frac{a_W}{U_W^2} d \quad (6.1)$$

where the reference length d is the depth of the body, equal to b for square cylinders. Figure 6.39 shows the procedure on a repeat, for the ramp-up conditions: Figure 6.39A reports U_W and Figure 6.39B shows a_W , while Figure 6.39C shows the acceleration parameter $K_{a,W}$.

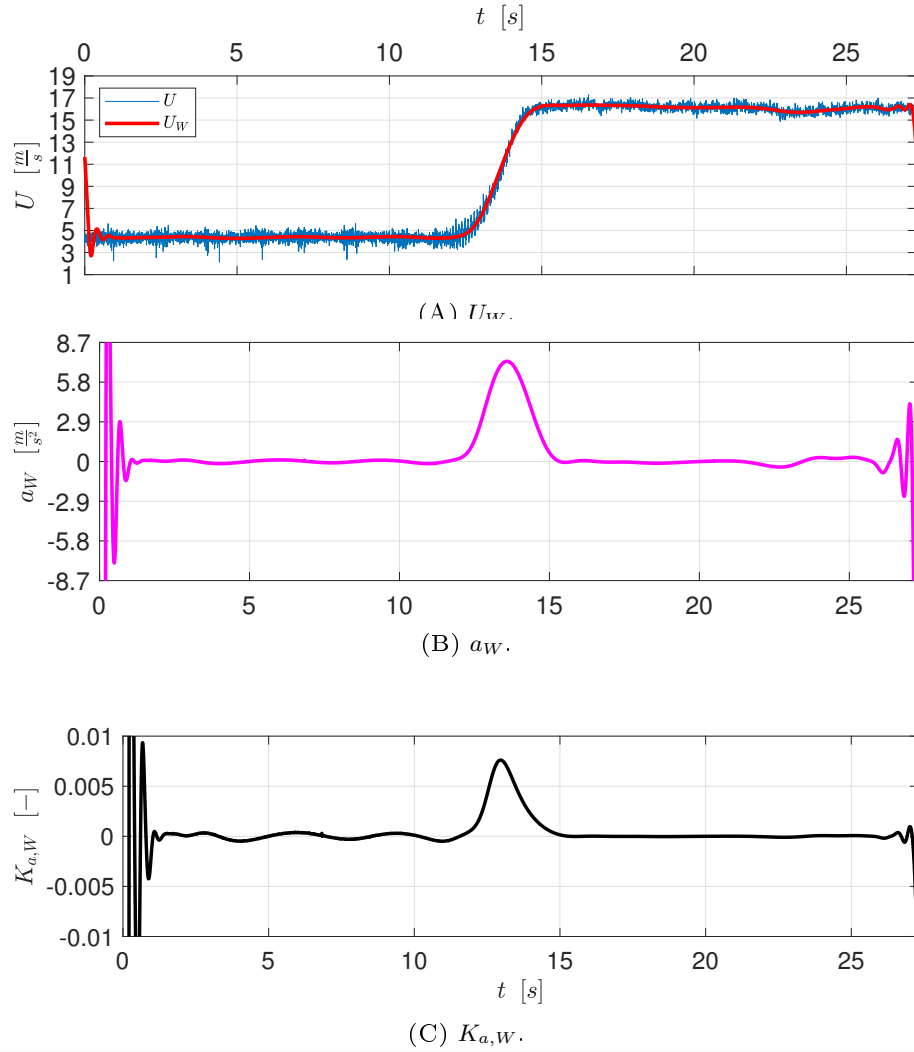
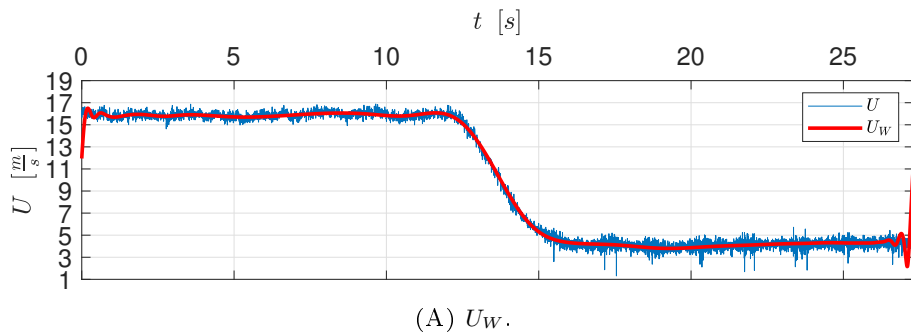


FIGURE 6.39: Estimation of the reference wind velocity and flow acceleration in ramp-up conditions for one repeat of UF_1 .

Figure 6.40 likewise pictures the ramp-down case, showing U_W (Figure 6.40A), a_W (Figure 6.40B) and $K_{a,W}$ (Figure 6.40C).



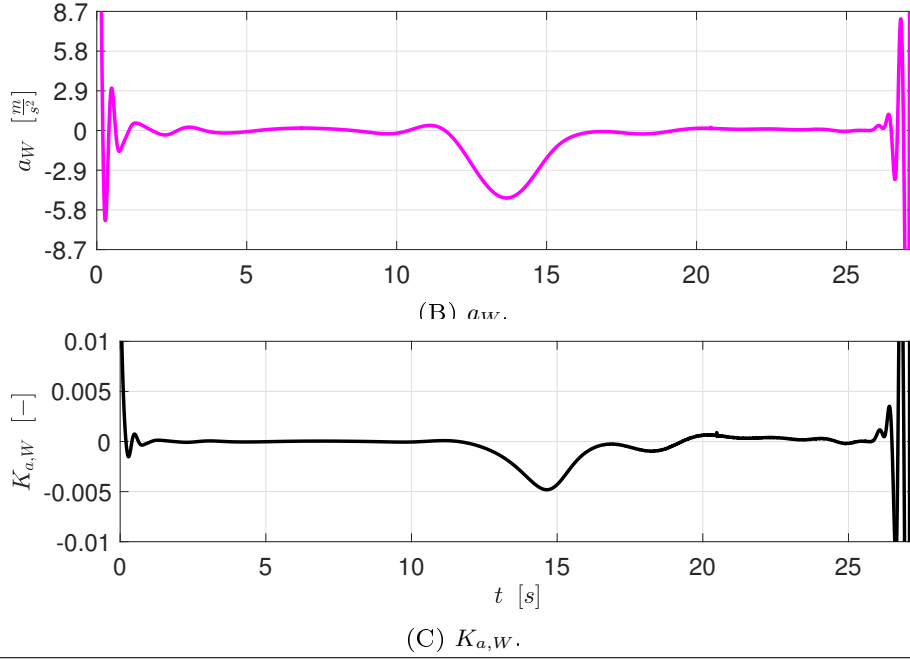


FIGURE 6.40: Estimation of the reference wind velocity and flow acceleration in ramp-down conditions for one repeat of UF_1 .

Observing the signals of a_W , it is evident that the flow acceleration during the ramp-up is higher than the corresponding deceleration in the ramp-down. In fact, the estimations of their maximum value are, respectively, 7.32 and $(-4.93) \left[\frac{m}{s^2} \right]$. This fact has been observed for all the tests (see also Section 6.7.3). Moreover, it is possible to note that the maximum, when considering the ramp-up, and the minimum, when studying the ramp-down, of $K_{a,W}$ do not occur in correspondence of the maximum, or the minimum, of a_W , but in both cases these quantities are translated to the area of lower wind speeds U_W . This has already been noted also in Chapter 5 analysing anemometric signals. The maximum value of $K_{a,W}$ is around 0.007 , whereas the minimum is close to -0.005 . These translate into values of $\frac{a_W}{U_W^2}$ (named as R_a in Chapter 5) in the order of $0.11 / -0.083 \left[\frac{1}{m} \right]$ which are plausible values concerning thunderstorm outflows. In particular, they appear consistent with the measurements reported in Figure 5.15, therefore the effects around the wind tunnel model might well be representative of the behaviour of a square structure of similar dimensions exposed to thunderstorm-induced action.

Sensitivity to the thresholding parameter

The choice of the thresholding parameter λ equal to 5 % of the mean energy of the map derives after a deep analysis, in which many other values have been explored. Herein, two additional cases of λ , precisely $\lambda = 0$ and $\lambda = 0.10$, are reported for the ramp-up case only, for sake of comparison. Figure 6.41, following the scheme adopted before, shows the results obtained by use of $\lambda = 0$ (energy map in Figure 6.41B and rebuilt signal in Figure 6.41D) and $\lambda = 0.10$ (energy map in Figure 6.41C and rebuilt signal in Figure 6.41E). It is noteworthy indicating that the former case leads to using the continuous wavelet transform as a simple low-pass filter.

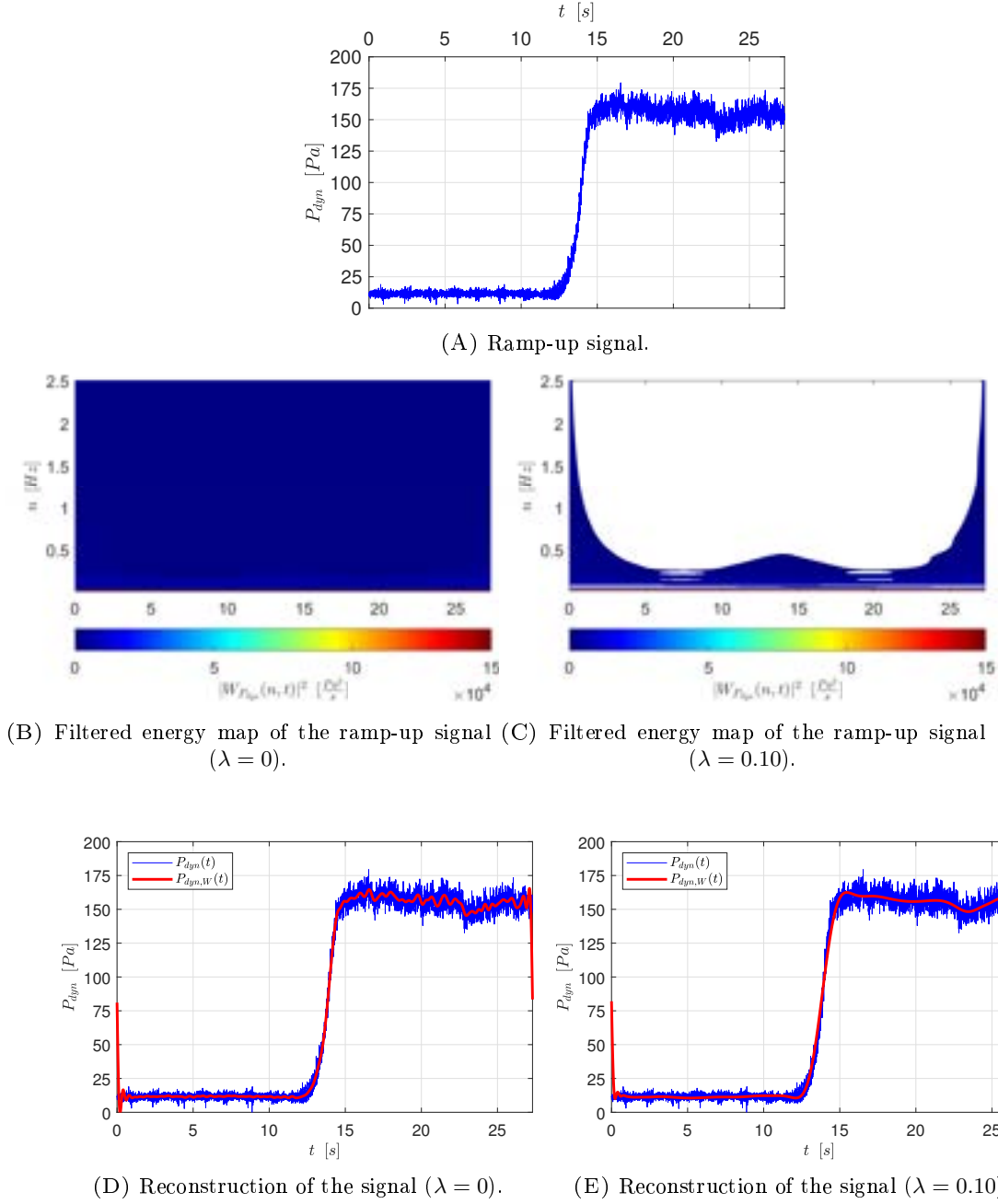


FIGURE 6.41: Procedure of filtering of the ramp-up signal of P_{dyn} with different thresholding parameter λ .

If, on one hand, the rebuilt signal shown in Figure 6.41D appears to be far too much detailed, presenting avoidable oscillations at the high velocity, on the other the signal presented in Figure 6.41E seems to be too steep in correspondence of the beginning of the ramp. This is the reason why, eventually, the choice of $\lambda = 0.05$ has been set as definitive.

6.7.2 Ramp-up and ramp-down studied together

As far as the tests UF_{11} , UF_{12} and UF_{13} are concerned, the quantity T_b is too limited to treat the ramp-up and the ramp-down as independent, and so the analyses conducted for these cases enclose both ramps. In analogy with Figure 6.37, Figure 6.42 shows the isolation of

a 2^{13} samples from the original signal of P_{dyn} (Figure 6.42A) of one repeat of UF_{13} (Figure 6.42B).

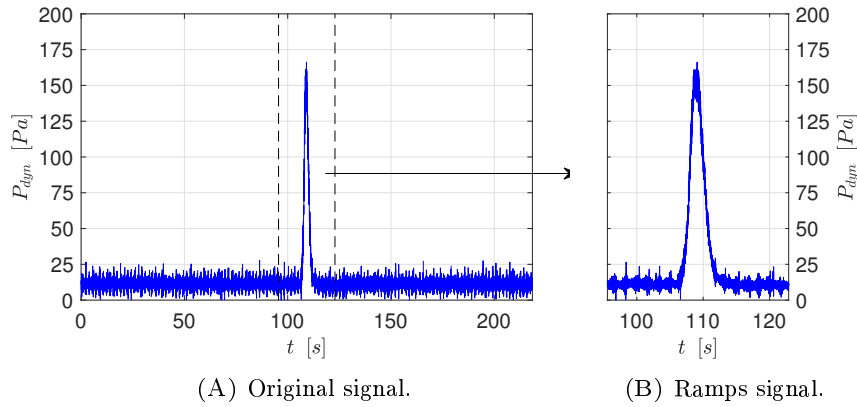
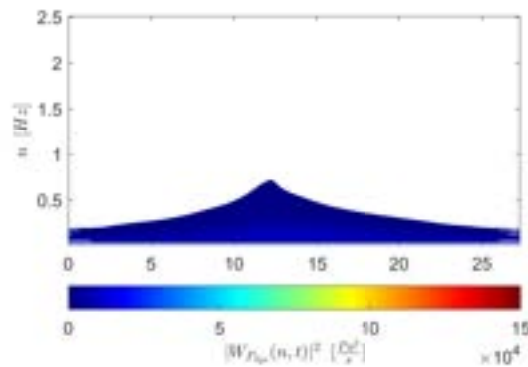
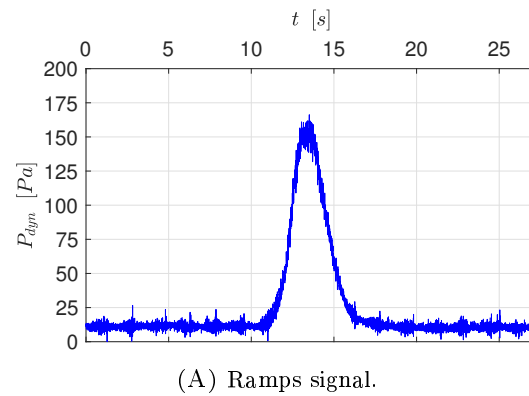
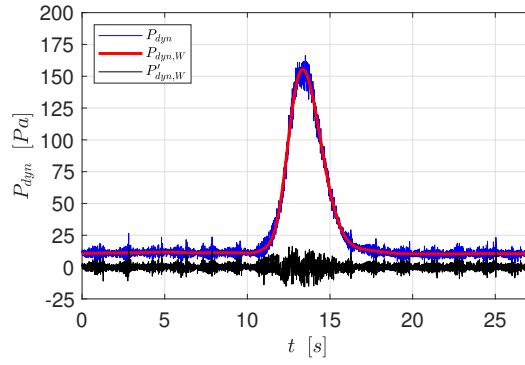


FIGURE 6.42: Selection of a sub-signal from a time history of the reference dynamic pressure P_{dyn} of one repeat of UF_{13} .

The signals associated with P_{dyn} , ΔP_D and f_D are treated in the same way described in Section 6.7.1 and Figure 6.43 shows the procedure, in analogy with Figure 6.37.

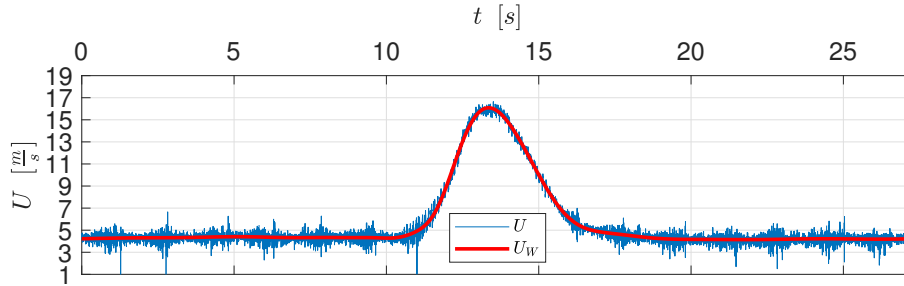
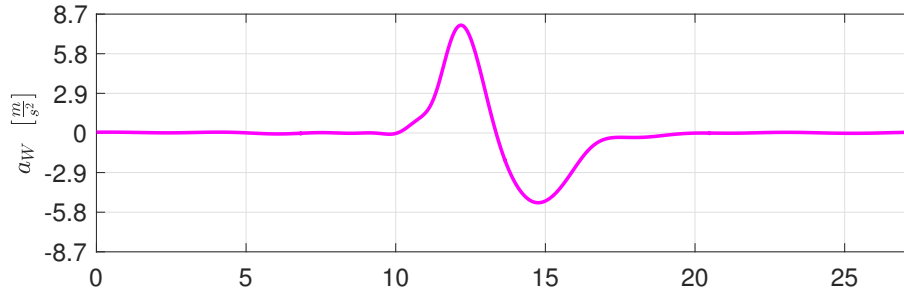
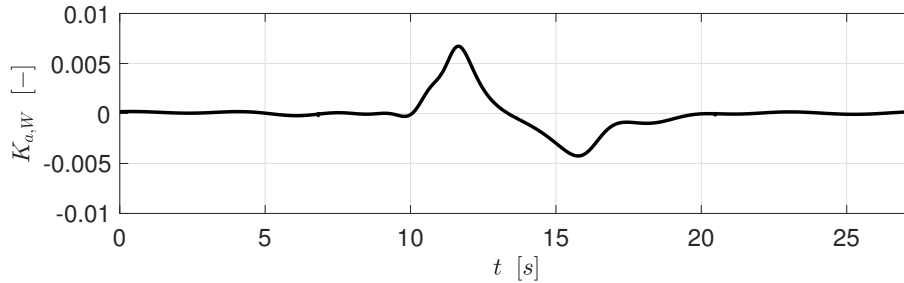




(C) Reconstruction of the ramps signal.

FIGURE 6.43: Procedure of the filtering based on CWT for signals of P_{dyn} extracted from a time history of UF_{13} .

Finally, following the procedure to determine U_W from $P_{dyn,W}$, the associated acceleration a_W and acceleration parameter $K_{a,W}$, Figure 6.44 shows these quantities for the repeat of UF_{13} .

(A) U_W .(B) a_W .(C) $K_{a,W}$.FIGURE 6.44: Estimation of the reference wind velocity and flow acceleration in ramp-down conditions for one repeat of UF_{13} .

The definition of the reference wind speed U_W is highly employed to study how acceleration affects the aerodynamic drag (Chapter 7) and vortex-shedding around the body (Chapter 8).

6.7.3 Characteristics of the unsteady flows

The definition of the *CWT* filtering technique allows the ensemble mean of the wind speed to be easily defined. At the same time, the definition of the ensemble mean of the acceleration is made available as well. Moreover, it is possible to gather statistical information about them. This section aims of quantifying the accelerations generated by the thirteen unsteady flows, providing data about the maximum acceleration and deceleration, and about their mean quantities during the ramps. As already done in Section 6.6.3, the unsteady flows are now separated into families, grouping tests which differ between each other because of one parameter only (Figure 6.28).

The following plots show the ensemble mean of the wind speed U_W and the acceleration a_W in correspondence of the ramps (isolated as shown in Figures 6.37 and 6.42).

Figure 6.45 focuses on tests which are different because of U_{low} (UF_1 , UF_2 , UF_3 and UF_4), whereas Figure 6.46 shows tests with different U_{high} (UF_2 , UF_5). Figures 6.47, 6.48 and 6.49 are related to tests which differ because of the choice of $\Delta\tau$, which are UF_1 and UF_6 , UF_2 and UF_7 and UF_3 , UF_7 and UF_8 . In the end, the last two plots report tests characterised by different T_b , respectively UF_1 and UF_{10} (Figure 6.50) and UF_{11} , UF_{12} and UF_{13} (Figure 6.51).

Finally, a table (partially) converts these plots in numbers, reporting the maximum value of the acceleration and deceleration, and appropriate mean values.

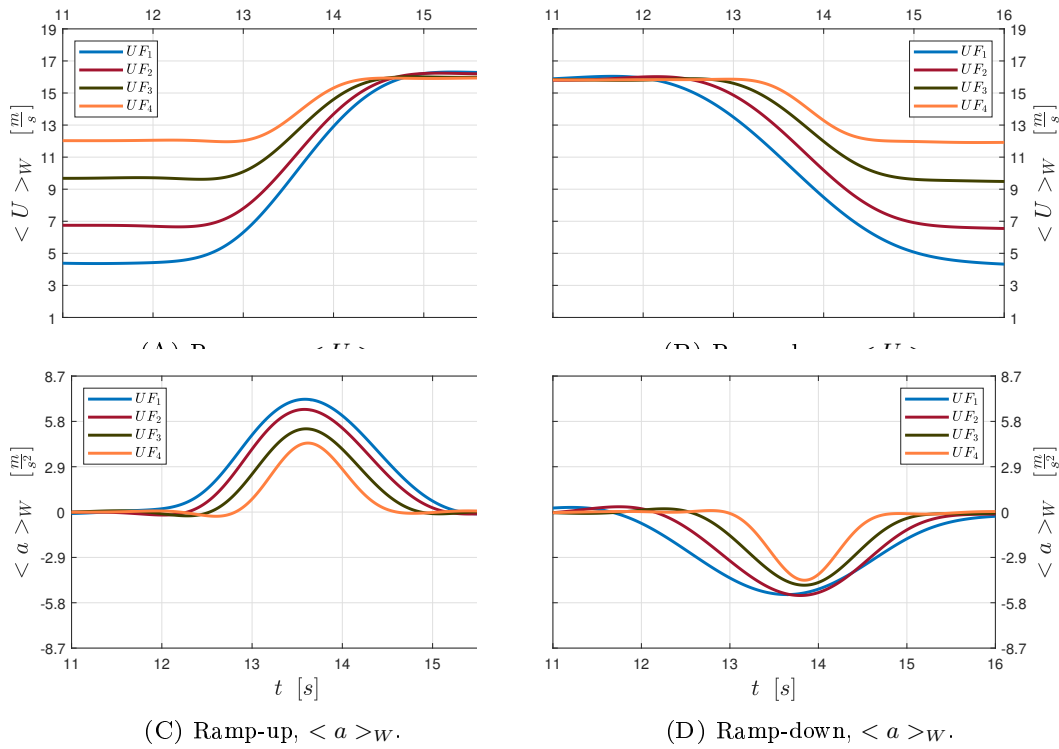


FIGURE 6.45: Ensemble mean of wind speed and acceleration of unsteady flows which differ because of the choice of U_{low} (UF_1 , UF_2 , UF_3 and UF_4).

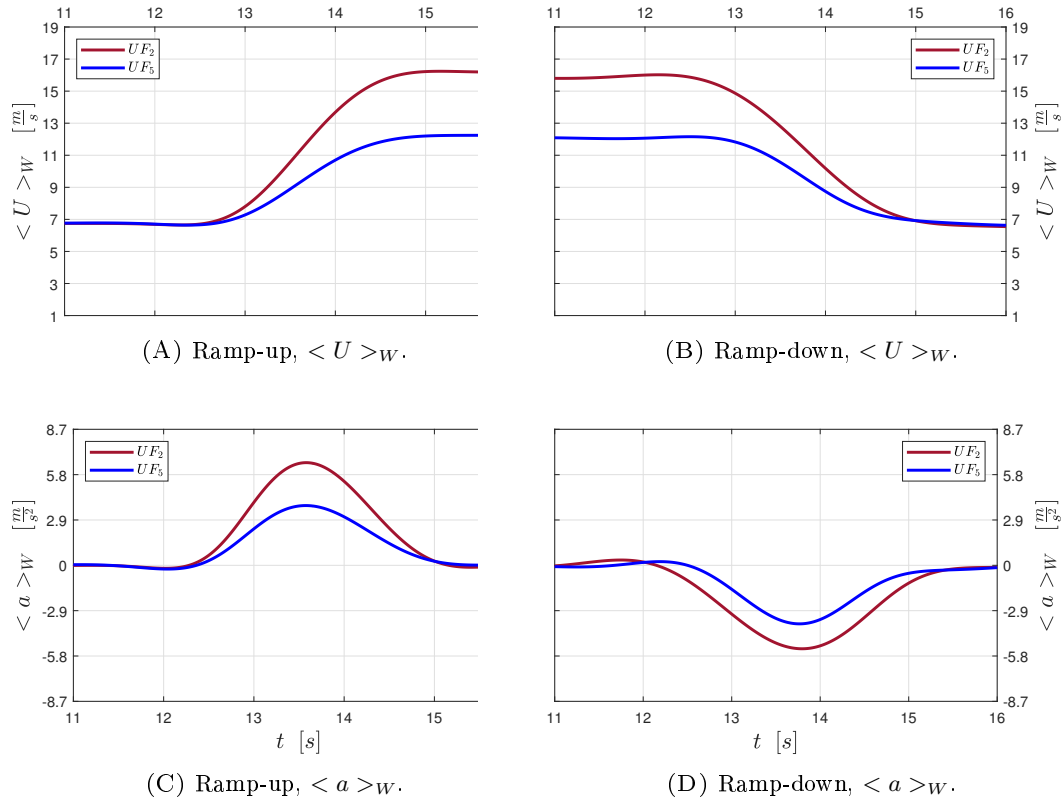


FIGURE 6.46: Ensemble mean of wind speed and acceleration of unsteady flows which differ because of the choice of U_{high} (UF_2 and UF_5).

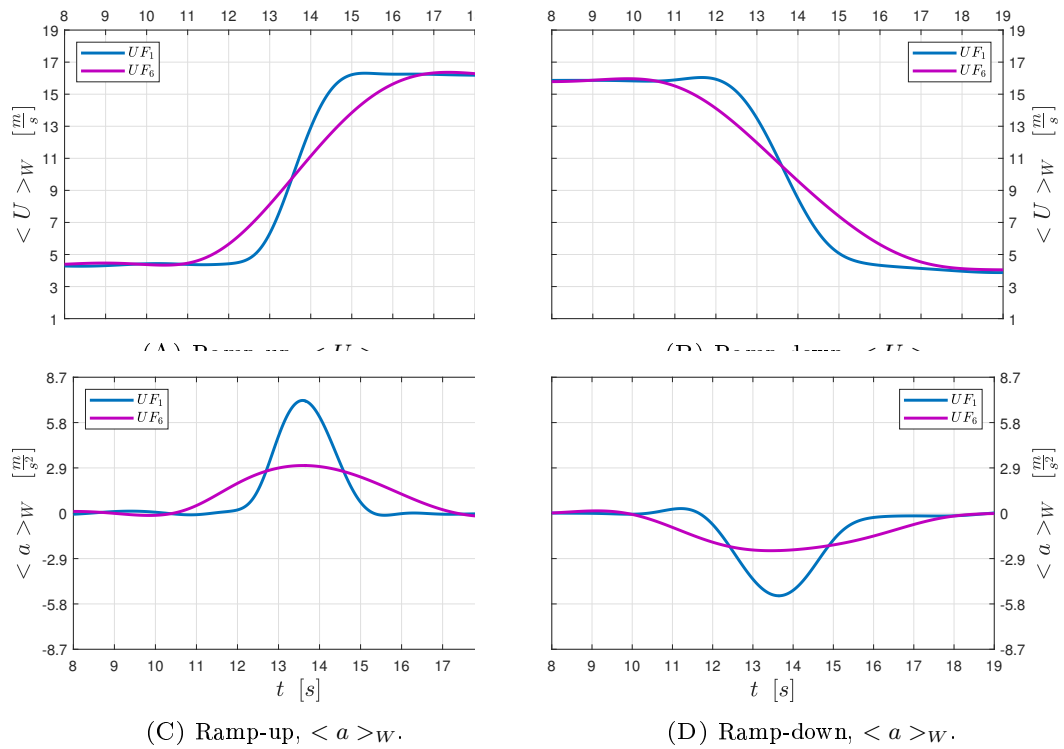


FIGURE 6.47: Ensemble mean of wind speed and acceleration of unsteady flows which differ because of the choice of $\Delta\tau$ (UF_1 and UF_6).

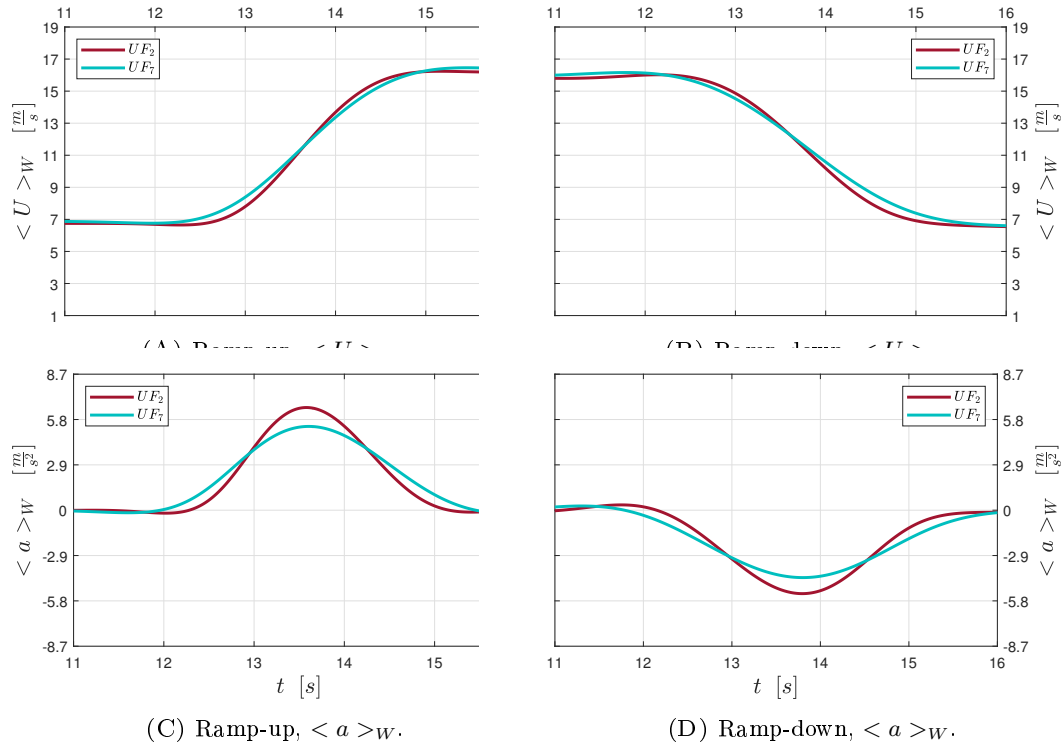


FIGURE 6.48: Ensemble mean of wind speed and acceleration of unsteady flows which differ because of the choice of $\Delta\tau$ (UF_2 and UF_7).

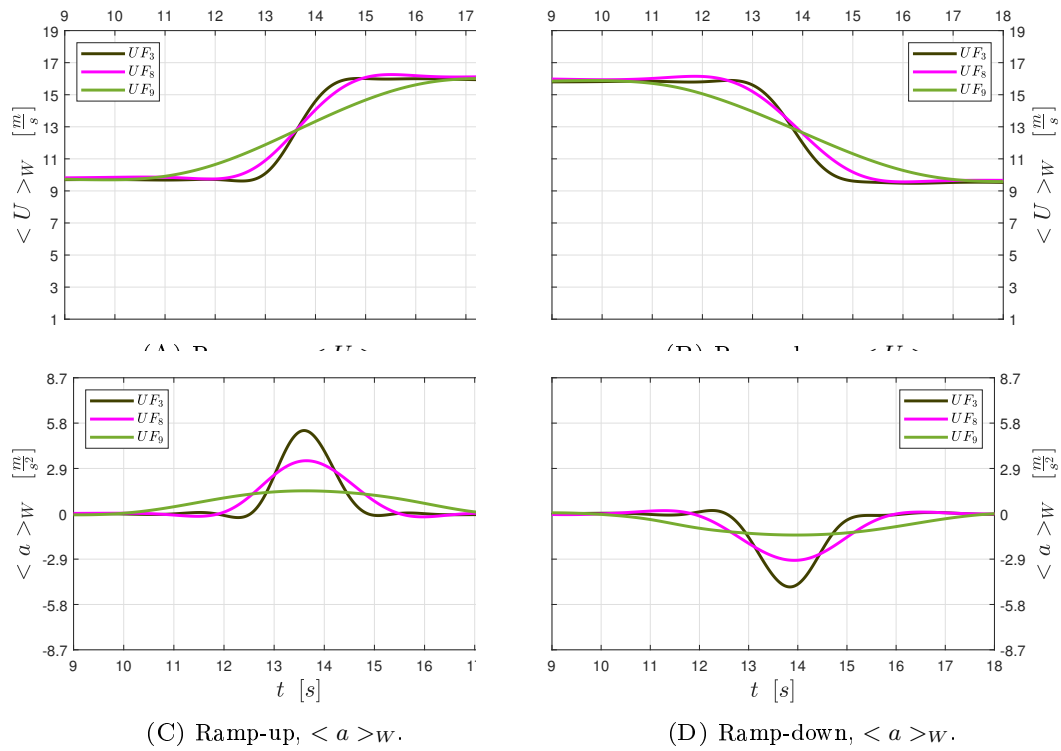


FIGURE 6.49: Ensemble mean of wind speed and acceleration of unsteady flows which differ because of the choice of $\Delta\tau$ (UF_3 , UF_8 and UF_9).

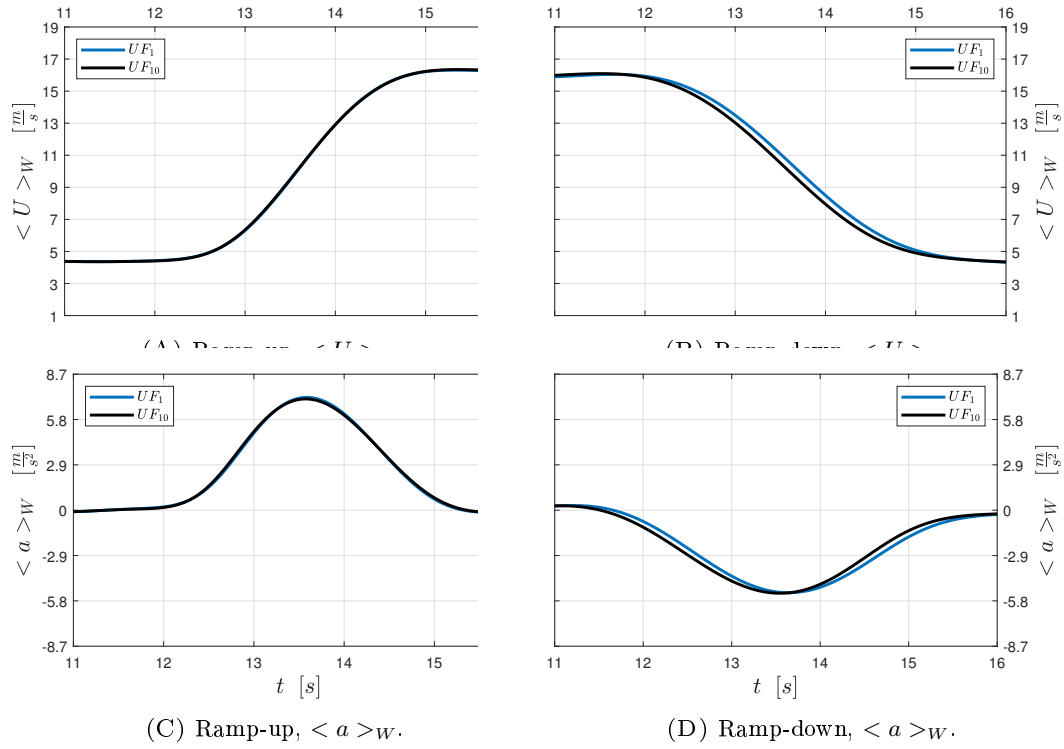


FIGURE 6.50: Ensemble mean of wind speed and acceleration of unsteady flows which differ because of the choice of T_b (UF_1 and UF_{10}).

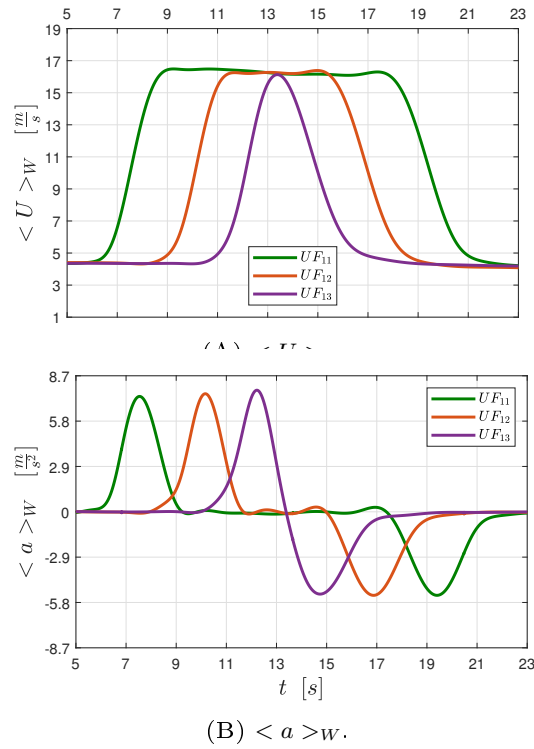


FIGURE 6.51: Ensemble mean of wind speed and acceleration of unsteady flows which differ because of the choice of T_b (UF_{11} , UF_{12} and UF_{13}).

To conclude the Chapter, the following table 6.6 lists, from left to right, the maximum value of the acceleration (ramp-up), of the deceleration (ramp-down) ($\langle a \rangle_W|_{RU,max}$, and $\langle a \rangle_W|_{RD,min}$, where RU and RD respectively shorten the terms ramp-up and ramp-down), and their mean values in the ramps ($\overline{\langle a \rangle_W}|_{RU}$ and $\overline{\langle a \rangle_W}|_{RD}$). These are evaluated by picking the time instants relevant to the beginning and the end of the ramps, sought by imposing $\langle a \rangle_W = 0.25 [\frac{m}{s^2}]$, for the beginning and the end of the ramp-up, or $\langle a \rangle_W = -0.25 [\frac{m}{s^2}]$, concerning the ramp-down. These latter two values are furnished for the whole set of tests, except UF_{11} , UF_{12} and UF_{13} , for which the ramps are not considered independent.

Name of the test	$\langle a \rangle_W _{RU,max} [\frac{m}{s^2}]$	$\langle a \rangle_W _{RD,min} [\frac{m}{s^2}]$	$\overline{\langle a \rangle_W} _{RU} [\frac{m}{s^2}]$	$\overline{\langle a \rangle_W} _{RD} [\frac{m}{s^2}]$
UF_1	7.21	-5.28	3.80	-2.75
UF_2	6.56	-5.33	3.64	-2.92
UF_3	5.32	-4.68	3.00	-2.58
UF_4	4.41	-4.36	2.50	-2.37
UF_5	3.82	-3.74	2.19	-1.79
UF_6	3.05	-2.39	1.93	-1.55
UF_7	5.36	-4.31	3.05	-2.44
UF_8	3.39	-2.98	2.02	-1.79
UF_9	1.47	-1.36	1.01	-0.95
UF_{10}	7.11	-5.31	3.82	-2.74
UF_{11}	7.38	-5.34	—	—
UF_{12}	7.55	-5.34	—	—
UF_{13}	7.78	-5.26	—	—

TABLE 6.6: Unsteady flow test matrix.

Commenting the estimation of a_W on a single repeat of UF_1 , it was noted that the accelerations in the ramp-up is higher than their corresponding decelerations. By looking at Table 6.6, this finding appears to be confirmed throughout the whole set of unsteady flow tests. Moreover, it is possible to appreciate how the acceleration pattern recalls a Gaussian curve, both in the ramp-up and ramp-down.

Chapter 7

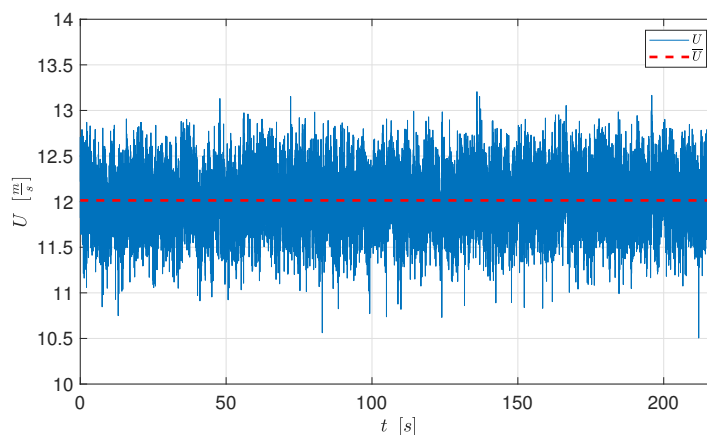
Aerodynamic drag of a square cylinder in steady and unsteady conditions

This chapter focuses on the estimation of the resistance and drag coefficient, $c_{\Delta P_D}$ and c_D , in steady and unsteady conditions. It is articulated as follows: Section 7.1 illustrates the procedures to be carried out under steady flow conditions, which are straightforward. The study of unsteady flows is tackled in Section 7.2, which describes how these parameters are evaluated in transient conditions. The determined quantities are then gathered and analysed by ensemble means in Section 7.3, which presents the results in terms of coefficients, selected mean pressure coefficients and mean pressure coefficient distributions. Moreover, comments about the variation of the static pressure in unsteady conditions are provided. Section 7.4 critically analyses the adopted methodology, presenting the results obtained through alternative techniques. Finally, Section 7.5 summarises and comments the main results that were obtained.

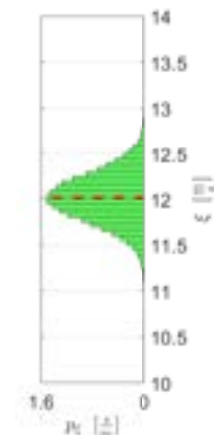
7.1 Steady flows

In this Section, the steady references concerning the aerodynamic drag (Section 7.1.1) (i.e. $c_{\Delta P_D}$ and c_D) and the pressure distributions (Section 7.1.2) are defined. All the results are introduced with reference to the case represented by SF^8 , from which a selected repeat is singularly analysed. The illustrated procedures are then extended to the entire set of steady flow pressure tests.

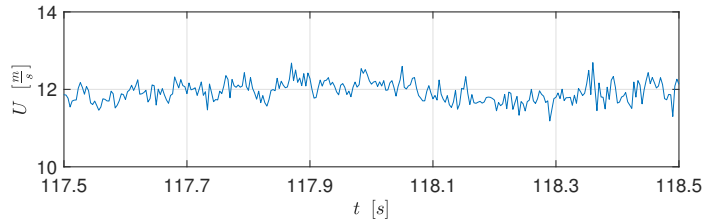
7.1.1 Aerodynamic drag



(A) Time history.



(B) PDF.

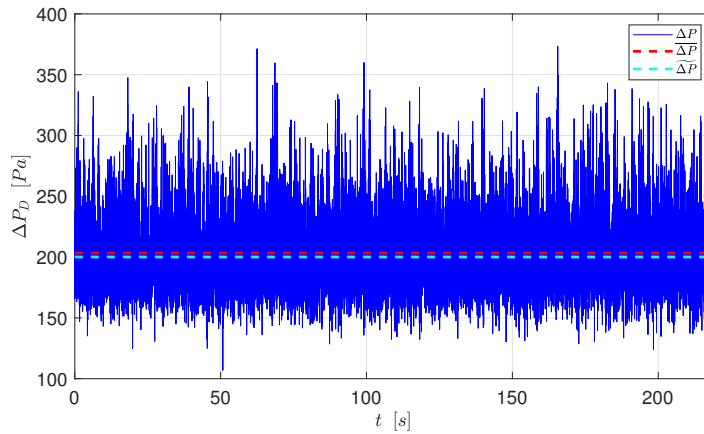


(C) Zoom on a time range of 1 [s].

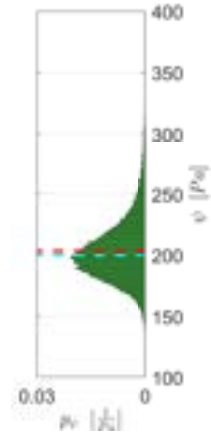
FIGURE 7.1: Reference wind speed of one repeat of SF^8 .

Focusing on the reference wind speed, Figure 7.1 shows a time history (Figure 7.1A) of one repeat and its PDF (Figure 7.1B). Moreover, the time history is zoomed between 117.5 [s] and 118.5 [s] in Figure 7.1C. As expected, the properties of the reference wind speed are almost Gaussian, presenting a skewness equal to -0.03 and a kurtosis equal to 3.2. The median and the mean of the time history are similar, being both equal to 12.0 $\left[\frac{m}{s}\right]$.

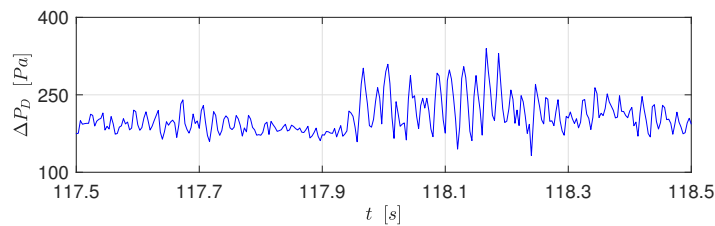
Analogously, Figure 7.2 shows one repeat of the difference of pressure between $C06$ and $C29$, called ΔP_D in Chapter 6. The time history is presented in Figure 7.2A, while its PDF is shown in Figure 7.2B. Finally, the zoom of the time history between 117.5 [s] and 118.5 [s] is pictured in Figure 7.2C.



(A) Time history.



(B) PDF.



(C) Zoom on a time range of 1 [s].

FIGURE 7.2: Pressure difference between $C06$ and $C29$, ΔP_D , of one repeat of SF^8 .

This figure shows that this signal, representative of the drag force, does not retain the properties of the reference wind speed, being no longer Gaussian (its skewness and kurtosis are, respectively, 1 and 5.16). This is associated with the signal acquired by $C29$, strongly affected by the wake, which gives rise to remarkable oscillations of pressure. However, the difference between the mean and the median is still limited, since they are, respectively, 203.3

and 200.1 [Pa]. The reduced difference between the mean and median is noted for the whole set of cases, allowing the mean to be considered as representative of the phenomenon. Its magnitude ($\overline{\Delta P}_{SF^8}$) is collected for the entire set of repeats (32) of SF^8 . Figure 7.3 shows the collection of these values, which are compared with the progressive mean $\overline{\overline{\Delta P}}_{SF^8}$, which varies with the repeat, and its accuracy, given by the quantity $\overline{\overline{\Delta P}}_{SF^8} \pm 2\sigma_{\overline{\Delta P}|_S}$ (where the nomenclature $|_S$ shortens the term SF^8). $\sigma_{\overline{\Delta P}|_S}$ is the standard deviation of the distribution $\overline{\Delta P}_{SF^8}$ divided by the square root of the number of repeats. This value constitutes an estimator of the variance of the distribution and, in doing so, implicitly assumes the random variable $\overline{\Delta P}_{SF^8}$ to be Gaussian, which is a plausible choice. The number of repeats can be considered satisfactory if the value of $\sigma_{\overline{\Delta P}|_S}$ is lower than the tolerance of the *Scanivalve* pressure transducers, which has been declared in Chapter 6 as ± 3.75 [Pa]. As far as SF^8 is concerned, after 32 repeats, $\overline{\overline{\Delta P}}_{SF^8} = 204.3$ [Pa], $\sigma_{\overline{\Delta P}|_S} = 0.10$ [Pa]. Besides, this latter number also seems to give confidence about the small influence played by the variation of the mean wind speed profile (Figure 6.24), since the quantity ± 3.75 [Pa] always represents the tolerance of the pressure transducers, regardless of the uniformity of the mean wind speed profile.

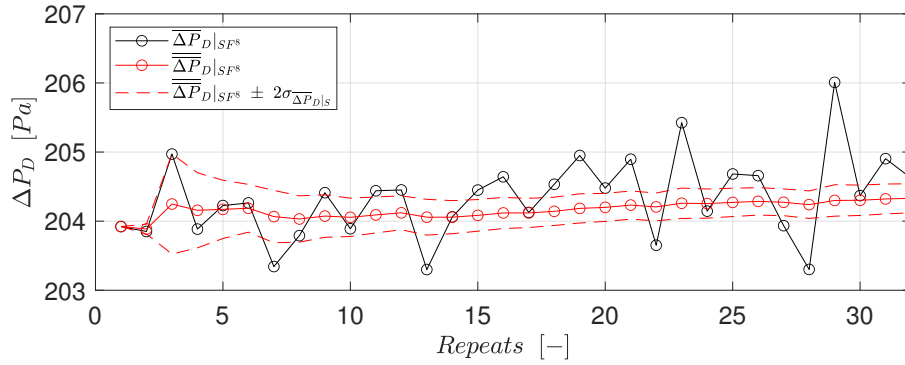


FIGURE 7.3: Variation of ($\overline{\Delta P}_D|_{SF^8}$), of its progressive mean value ($\overline{\overline{\Delta P}}_D|_{SF^8}$) and its accuracy ($\overline{\overline{\Delta P}}_D|_{SF^8} \pm 2\sigma_{\overline{\Delta P}|_S}$).

The procedure of extraction of the mean value is carried out for the drag force per unit length f_D as well, evaluating again 32 values of $\overline{f}_D|_{SF^8}$. What explained concerning SF^8 is intended to be easily extended to any other steady flow pressure tests.

Once defined, for every repeat, ΔP_D and $\overline{f}_D$, and the corresponding value of $\overline{p}_{dyn}$ and $\overline{U}$, the estimates of the mean resistance coefficient $\overline{c}_{\Delta P_D}$ and the mean drag coefficient $\overline{c}_D$ are carried out:

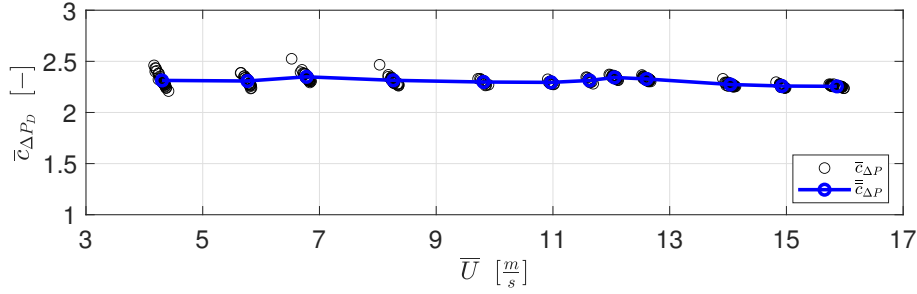
$$\begin{aligned}\overline{c}_{\Delta P_D} &= \frac{\overline{\Delta P}_D}{\overline{p}_{dyn}} \\ \overline{c}_D &= \frac{\overline{f}_D}{\overline{p}_{dyn} b}\end{aligned}\tag{7.1}$$

For SF^8 , the mean value of the 32 $\overline{c}_{\Delta P_D}$ ($\overline{\overline{c}}_{\Delta P_D}|_{SF^8}$) is 2.34. Concerning the drag coefficient $\overline{c}_D$ ($\overline{\overline{c}}_D|_{SF^8}$), it is 2.08.

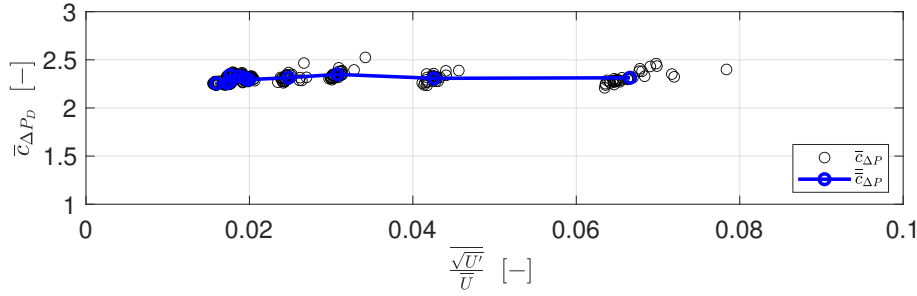
Steady reference values

The concepts proposed in the previous paragraph are hereinafter extended to the whole set of steady-flow measurements. This enables to depict the variation of $\overline{\overline{c}}_{\Delta P_D}$ and $\overline{\overline{c}}_D$ with the

wind speed and with the turbulence. Focusing on the former quantity, Figure 7.4 shows the variation of $\bar{c}_{\Delta P_D}$, reporting a black point for every repeat. Their mean value $\bar{\bar{c}}_{\Delta P_D}$, for each steady flow pressure tests is reported with blue dots. A thick blue line links the whole set of $\bar{\bar{c}}_{\Delta P_D}$. Figure 7.4A shows the dependence of the coefficient on the mean wind speed $\bar{U}$, while the effect of the non-dimensional turbulence $\frac{\sqrt{U'^2}}{\bar{U}}$ is described in Figure 7.4B.



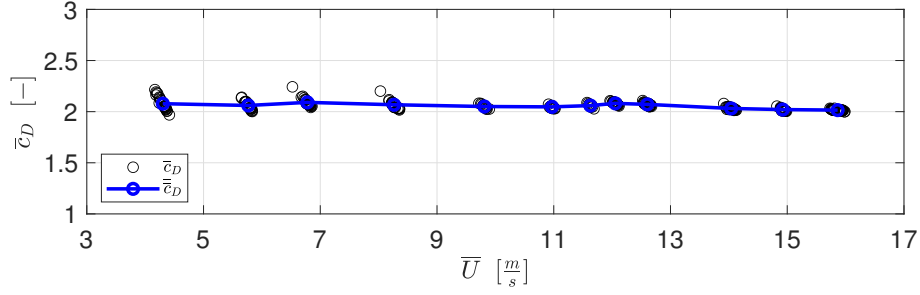
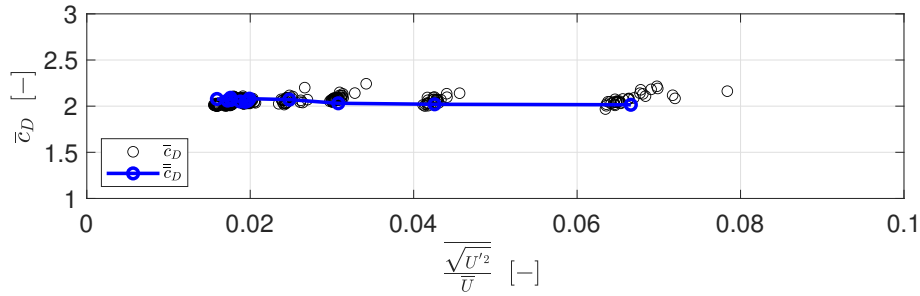
(A) Variation with the mean wind speed $\bar{U}$.



(B) Variation with the non-dimensional turbulence $\frac{\sqrt{U'^2}}{\bar{U}}$.

FIGURE 7.4: Variation of $\bar{c}_P$.

In the same way, Figure 7.5 shows the variation of $\bar{c}_D$ and $\bar{\bar{c}}_D$ with the mean wind speed $\bar{U}$ (Figure 7.5A) and the non-dimensional turbulence $\frac{\sqrt{U'^2}}{\bar{U}}$ (Figure 7.5B). The mean value (evaluated on the entire set of data) of $\bar{\bar{c}}_D$ is 2.06, which is consistent with the data listed in Chapter 6 and the presence of turbulence (already discussed in Chapter 6). In particular, the minimum of this coefficient is 2.01 and its maximum is 2.09. The oscillations and spread against the wind speed appear modest and mainly driven by the instrumentation accuracy (which is higher for higher wind speeds) and by the flow turbulence. In fact, the plots concerning the non-dimensional turbulence (Figures 7.4B and 7.5B) highlight that the highest spread arises in correspondence of the most turbulent tests, which occur at the lower wind speeds (Figure 6.27B).

(A) Variation with the mean wind speed $\bar{U}$.(B) Variation with the non-dimensional turbulence $\frac{\sqrt{U'^2}}{\bar{U}}$.FIGURE 7.5: Variation of $\bar{c}_D$.

If, on one hand, the mean drag coefficient $\bar{c}_D$ is by far the most well-known parameter to characterise the body resistance, on the other it depends on the integration of the pressures over the perimeter of the body. Therefore, another advisable quantity of interest might well be the aforementioned mean resistance coefficient $\bar{c}_{\Delta P_D}$, which is simply obtained thanks to the difference between two pressure signals and its division over the reference dynamic pressure. Its mean value is 2.30, being enclosed between 2.26 and 2.35, and its spread seems to follow the same pattern of $\bar{c}_D$. In the following, both quantities are estimated in unsteady conditions and compared with the steady cases. However, the main focus of the analyses presented hereinafter is on the resistance coefficient. Finally, it is pointed out that both $\bar{c}_D$ and $\bar{c}_{\Delta P_D}$ are not functions of the static pressure, being inherently obtained as difference of pressures. This is no longer true when dealing with pressure coefficients, which are the object of the next section.

7.1.2 Pressure coefficient distribution

Steady reference values

Analysing the signals from the entire set of pressure taps of the mid-span ring (Figure 6.17B), it is possible to draw the distributions of the mean ($\bar{c}_P$) and the RMS pressure coefficients (σ_{c_P}). This is carried out for each repeat, thanks to the following Equation:

$$\bar{c}_{P,j} = \frac{\bar{P}_j - \bar{P}_s}{\bar{P}_{dyn}} \quad (7.2)$$

$$\sigma_{c_{P,j}} = \frac{\sqrt{E[(P_j - \bar{P}_j)^2] - \bar{P}_s}}{\bar{P}_{dyn}}$$

The subscript j indicates the j^{th} tap ($j = 1 - 46$) of the mid-span section. Moreover, the operator $E \left[(A - \bar{A})^2 \right]$ is the central moment of order 2 of A (the variance), so its square root is its standard deviation. P_s is the static pressure, which is the mean value between the one acquired by $P2$ and $P3$, as mentioned in Chapter 6.

Then, again, the pressure coefficients are collected from each repeat and averaged, obtaining the quantities $(\bar{c}_P)$ and $\bar{\sigma}_{c_P}$ for each steady flow pressure tests. Still employing SF^8 as example, Figure 7.6 shows the two pressure distributions: Figure 7.6A concerns $\bar{c}_P$ and Figure 7.6B shows $\bar{\sigma}_{c_P}$. As before, the accuracy of the measurements is represented by two times the standard deviation of the distribution. In both cases, the non-dimensional abscissa $\frac{s}{b}$ represents the perimeter of the mid-span section of the body, in which the mid-point "0" symbolises the stagnation point ($C06$). The most negative and positive values actually coincide and represent the tap $C29$.

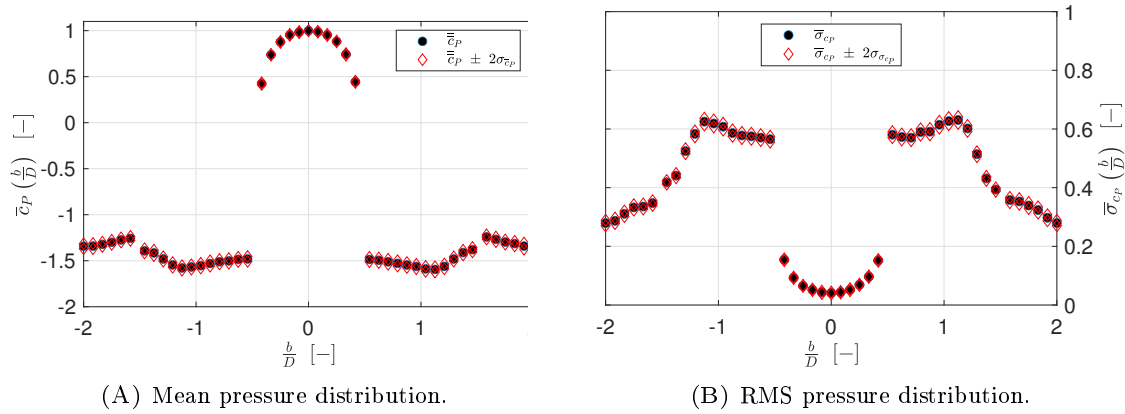


FIGURE 7.6: Reference steady pressure distributions for SF^8 .

Considering the whole set of tests, the mean base-pressure coefficient ($\bar{c}_{P,29}$) is -1.30 , oscillating between -1.34 and -1.26 . This result is again in line with the literature references reported in Chapter 6. In particular, this quantity is similar indeed to what reported by Lee in 1975 (Lee, 1975). The ratio of the mean drag coefficient and the base suction pressure coefficient is approximately 1.58, which is again similar to the outcomes by Lee and is slightly higher than what reported by Sohankar (Sohankar, 2006). At variance with $\bar{c}_D$ and $\bar{c}_{\Delta P_D}$, $\bar{c}_P$ and $\bar{\sigma}_{c_P}$ do depend on the estimated static pressure. Considerations about this quantity, especially as regards its variation under unsteady conditions, are made in Section 7.3.4).

7.2 Unsteady flows

While the procedure to define $c_{\Delta P_D}$ and c_D for steady flows is straightforward, for unsteady flows it is impossible to use temporal means and the use of ensemble means is necessary. On top of that, because of the presence of a high level of turbulence, the raw data of interest (P_{dyn} , ΔP_D , f_D) are firstly treated by CWT to obtain filtered signals, representative of the mean trend of the quantity. These can be employed to estimate time-histories of the coefficients $c_{\Delta P_D}$ and c_D in unsteady conditions. In analogy with the quantities P_{dyn} , ΔP_D , f_D , the variation of the coefficients with time for unsteady flows are marked with the same subscript w , so that these are called $c_{\Delta P_D,w}$ and $c_{D,w}$. These might well be suitable candidates to represent the unsteady counterparts of, respectively, $\bar{c}_{\Delta P_D}$ and $\bar{c}_D$, or, taking the number of repeats into account, of $\bar{c}_{\Delta P_D}$ and $\bar{c}_D$. Section 7.2.1 follows what described in Section 6.7, showing an example of extraction and filtering of appropriate sub-signals from the original time-history of the load (while Section 6.7 deals with P_{dyn}). In particular, this procedure is

applied to the whole set of pressure signals coming from the 46 taps of the mid-span section, on ΔP_D , and on the resultant drag force per unit length f_D . Section 7.2.2 shows how the filtered signals are analysed, and how the relevant quantities are collected from every repeat. Finally, it shows a preliminary result, comparing the reference of $\overline{\Delta P_D}|_{SF8}$ with the collection of several instantaneous values of the corresponding quantity, this time evaluated in unsteady conditions. Results concerning the pressure coefficients are not furnished in this Section. As in Section 6.7, the procedure is articulated in two cases, being the first a repeat of UF_1 , which is characterised by a T_b which is long enough to assure the independence of the ramp-up and the ramp-down. The second case is a repeat of UF_{13} , for which T_b is shortened and the two ramps are not treated separately.

7.2.1 Methodology of analysis of the aerodynamic drag in unsteady conditions

The procedure defined in Section 6.7 to filter the reference dynamic pressure, in order to obtain a slowly-varying mean of that quantity, is replicated on the signals associated with the aerodynamic drag, ΔP_D and f_D . Focusing on the former quantity, this Section reports the procedure for the tests in which the ramp-up and ramp-down are studied as independent ($UF_1 - UF_{10}$), followed by the description for the tests characterised by a shorter T_b ($UF_{11} - UF_{13}$).

Ramp-up and ramp-down studied as independent

In analogy with Figure 6.37, Figure 7.7 displays the selection of two sub-signals of 2^{15} samples each (Figures 7.7A and 7.7C) from the original time history (Figure 7.7B) of one repeat of UF_1 , this time associated with ΔP_D . Obviously, these signals are simultaneous with the ones of the reference dynamic pressure. Pictures concerning f_D are not shown for sake of brevity.

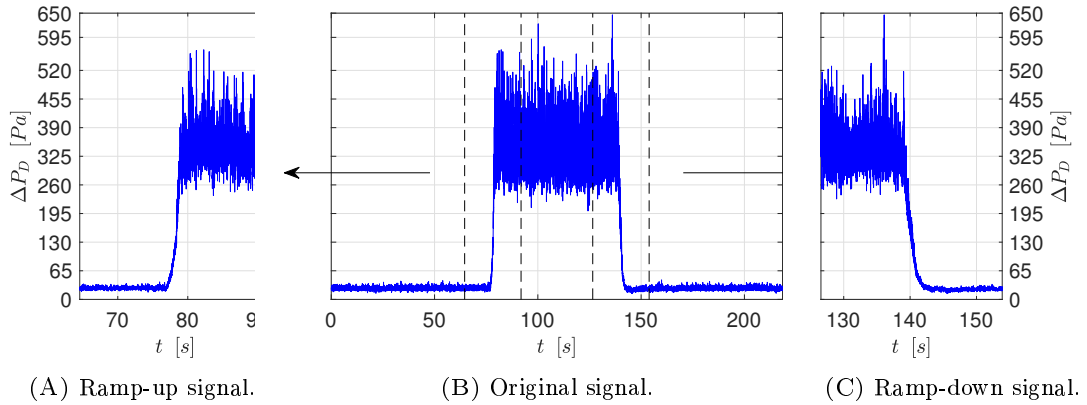


FIGURE 7.7: Selection of sub-signals from a time history of the reference dynamic pressure ΔP_D of one repeat of UF_1 .

Following the scheme traced by Figure 6.38 concerning P_{dyn} , Figure 7.8 describes the steps to be undertaken to filter the quantity ΔP_D . The filtering technique, coherently with what applied on the reference dynamic pressure, is still based on $L2$ CWT, adopting a Morlet wavelet with $\omega_0 = 2\pi$, and the introduction of 501 scales in the range 0.01 - 2.51 [Hz]; the thresholding parameter is again assumed as $\lambda = 5$ % of the mean energy. This technique permits to end up with a signal $\Delta P_{D,W}$, when working on ΔP_D , or with $f_{D,W}$, if acting on f_D . Starting from the selected sub-signals (Figures 7.8A and 7.8B), the corresponding energy maps are evaluated and filtered (Figures 7.8C and 7.8D), and the filtered signals are obtained

and compared with the original ones (Figures 7.8E and 7.8F). In these two latter graphs, the residual quantity $P'_{\Delta P_D, W} = (P_{\Delta P_D} - P_{\Delta P_D, W})$ is also drawn in black.

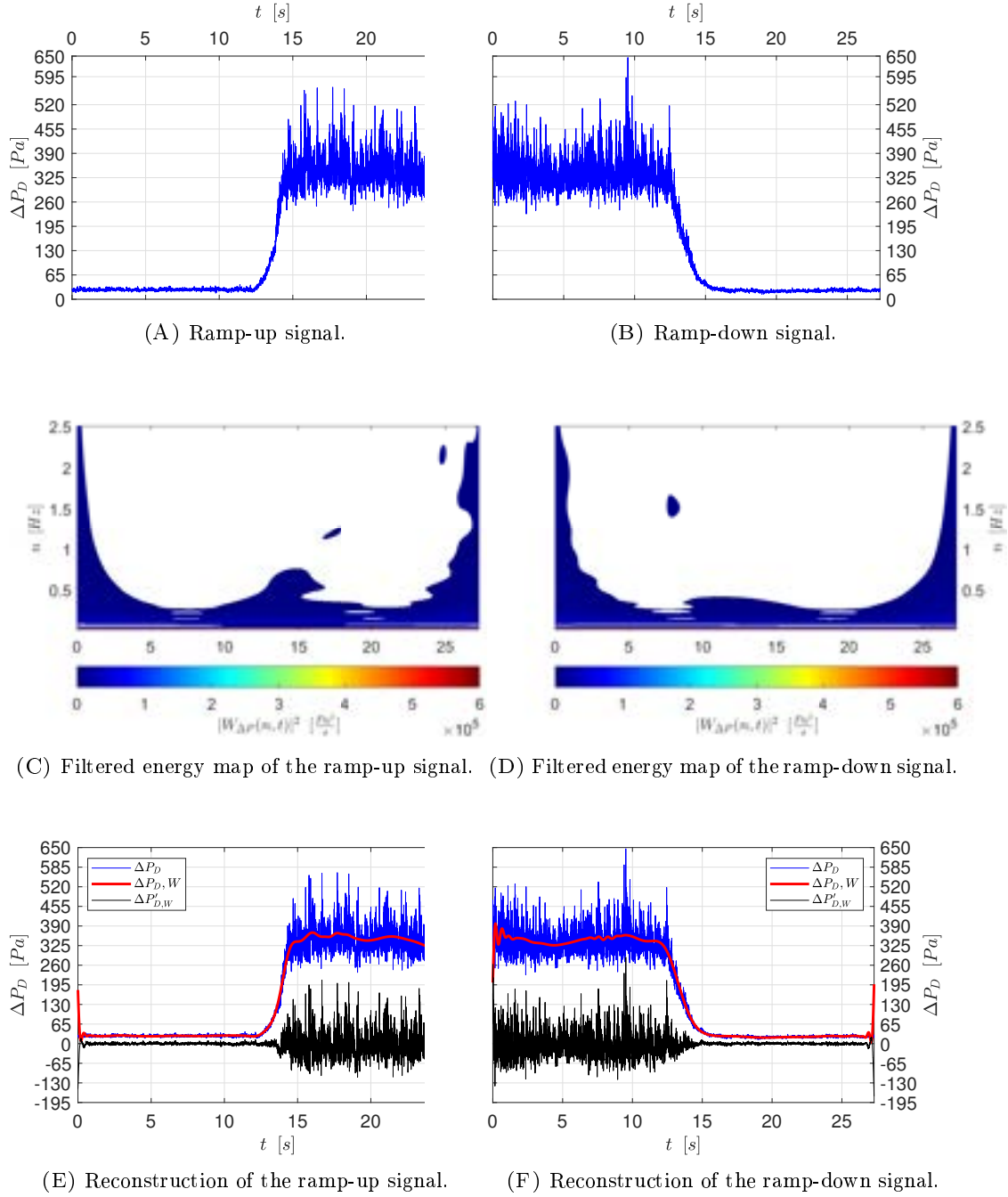


FIGURE 7.8: Procedure of the filtering based on *CWT* for signals of ΔP_D extracted from a time history of UF_1 .

Ramp-up and ramp-down studied together

When T_b is short, and the ramps are not considered as independent, the methods to treat P_{dyn} are again extended to ΔP_D and f_D . Following Figure 6.43, Figure 7.9 shows the definition of 2^{15} samples from the full time history of ΔP_D , which are deeply analysed in the following paragraphs.

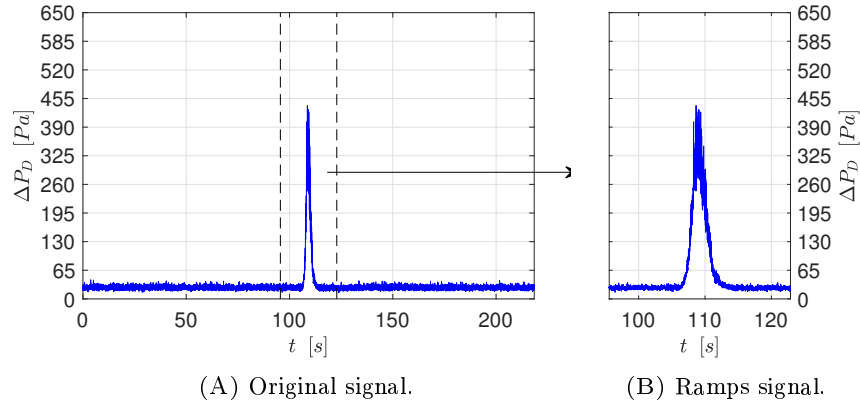
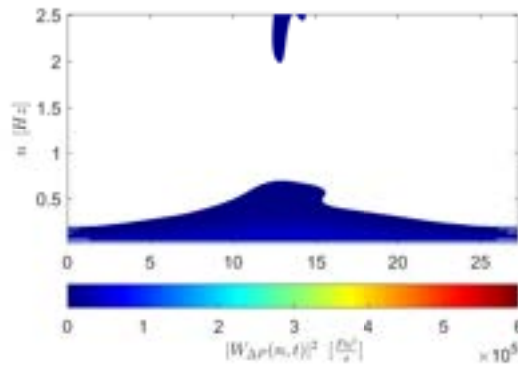
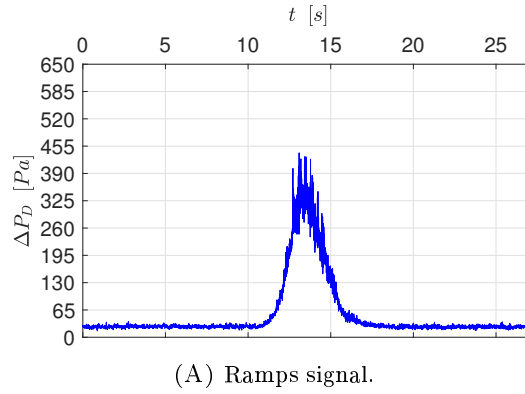
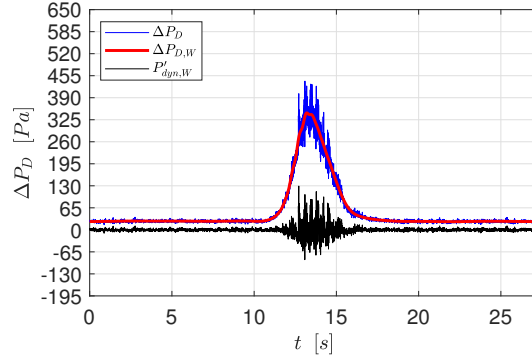


FIGURE 7.9: Selection of a sub-signal from a time history of the reference dynamic pressure ΔP_D of one repeat of UF_{13} .

Describing what illustrated in Figure 7.10, this signal (Figure 7.10A) is, again, treated with the *CWT*, obtaining the energy map, which is filtered (Figure 7.10B). Eventually, the inverse transform allows the filtered signal to be rebuilt (Figure 7.10C).



(B) Filtered energy map of the ramps signal.



(C) Reconstruction of the ramps signal.

FIGURE 7.10: Procedure of the filtering based on *CWT* for signals of ΔP_D extracted from a time history of UF_{13} .

7.2.2 Aerodynamic drag

In the previous paragraph, it has been described how the original signals relevant to the aerodynamic drag have to be treated in unsteady conditions, with the aim of limiting the influence of turbulence. In this section, instead, the selection of the specific time instants of quantities ($\Delta P_{D,W}$, $f_{D,W}$) that have to be compared with the steady references (ΔP_D , f_D) is described. In particular, this procedure is dictated by the time-history of U_W , which easily permits to determine the time instant in which an unsteady flow crosses a value of velocity which is associated with one of the 12 steady flows. As in the previous section, this explanation is firstly provided for the tests in which the treatment of the ramp-up and the ramp-down as independent is possible (Section 7.2.2), showing an application on one repeat of UF_1 . Subsequently, the procedure is furnished for tests in which the ramps are treated together (Section 7.2.2), taking as reference case one repeat of UF_{13} .

Ramp-up and ramp-down studied as independent

Thanks to the simultaneous recordings of $P_{dyn,W}$ (Section 6.7.1) and $\Delta P_{D,W}$ (Section 7.2.1) (or $f_{D,W}$, not shown), it is possible to define the time-varying mean resistance coefficient $c_{\Delta P_{D,W}}$, or the time-varying mean drag coefficient $c_{D,W}$. The following equations are introduced:

$$\begin{aligned} c_{\Delta P_{D,W}} &= \frac{\Delta P_{D,W}}{P_{dyn,W}} \\ c_{D,W} &= \frac{f_{D,W}}{P_{dyn,W} b} \end{aligned} \quad (7.3)$$

The aforementioned quantities contain in their descriptions the term "mean", since they originate from signals which have been previously treated to remove their turbulent components. The next step is to pick selected instants from the time history of $c_{\Delta P_{D,W}}$ and $c_{D,W}$ to be compared with the steady references: these, for every time history, are extracted working on U_W , on which the values of the reference wind speeds $\bar{U}_k$ (Figure 6.25) are sought. This research has the aim of selecting the associated indexes in_k , which are employed to define the relevant loads $\Delta P_{D,W}(\bar{U}_k)$ and $f_{D,W}(\bar{U}_k)$. Consequently, determining the associated coefficients $c_{\Delta P_{D,W}}(\bar{U}_k)$ and $c_{D,W}(\bar{U}_k)$ is straightforward. Analogously, it is also possible to estimate the corresponding accelerations $a_W(\bar{U}_k)$. The number of k depends on the test: for instance, UF_1 covers the full range of wind speeds, since U_{low} is reproduced with the fan

setting SF^1 and U_{high} corresponds to SF^{12} (see Figure 6.28 and Table 6.5), so the whole set of steady reference velocities $\bar{U}_k$ ($k = 2 - 11$) is investigated. On the other hand, other tests do not comprise the entire range (e.g., for UF_2 , $k = 4 - 11$). It is remarked that this procedure is herein made for every repeat, thanks to the filtering technique which has been calibrated before. In a standard test, this would be made on the ensemble mean of the raw data only. An example is proposed for one repeat of UF_1 , firstly investigating the ramp-up, and secondly analysing the ramp-down. Tackling the former, Figure 7.11 shows the procedure: the 10 indexes ($k = 2 - 11$) are defined in Figure 7.11A, and the corresponding a_W , $\Delta P_{D,W}$ and $c_{\Delta P_{D,W}}$ are picked in Figures 7.11A, 7.11C and 7.11D by dragging dashed lines from the indexes. The text that is present in the plots should aid in the definition of the instantaneous quantities, which are collected for the whole set of repeats.

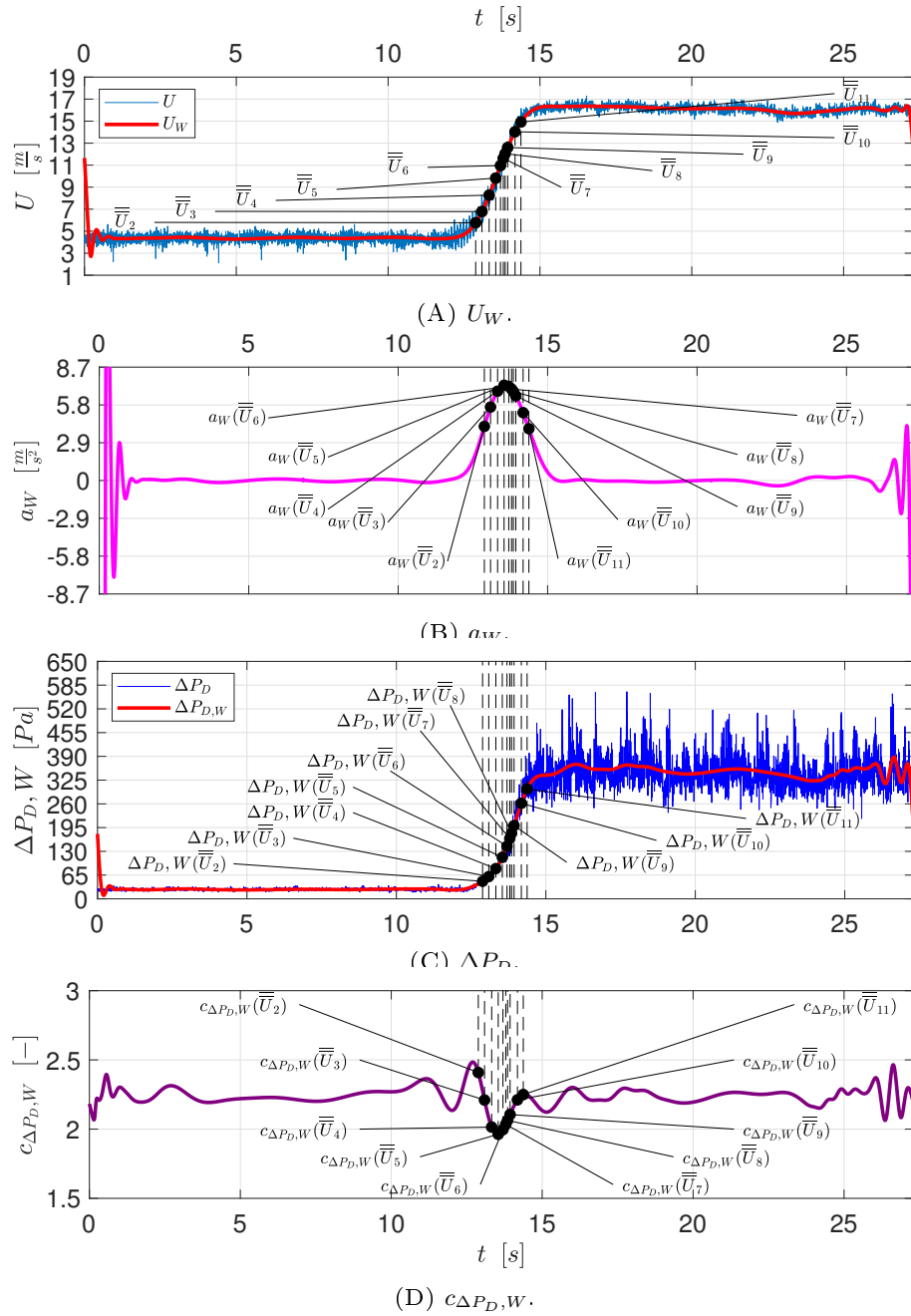


FIGURE 7.11: Selection of indexes to define the aerodynamic drag in unsteady conditions for one repeat of UF_1 (ramp-up).

Likewise, 7.12 displays the selection of the appropriate indexes for the corresponding ramp-down. The indexes are picked in Figure 7.12A, while the definition of the associated values of a_W , $\Delta P_{D,W}$ and $c_{\Delta P_{D,W}}$ are in Figure 7.12B, 7.12C and 7.12D. The dashed lines still represent the time instants at which the indexes in_k are picked.

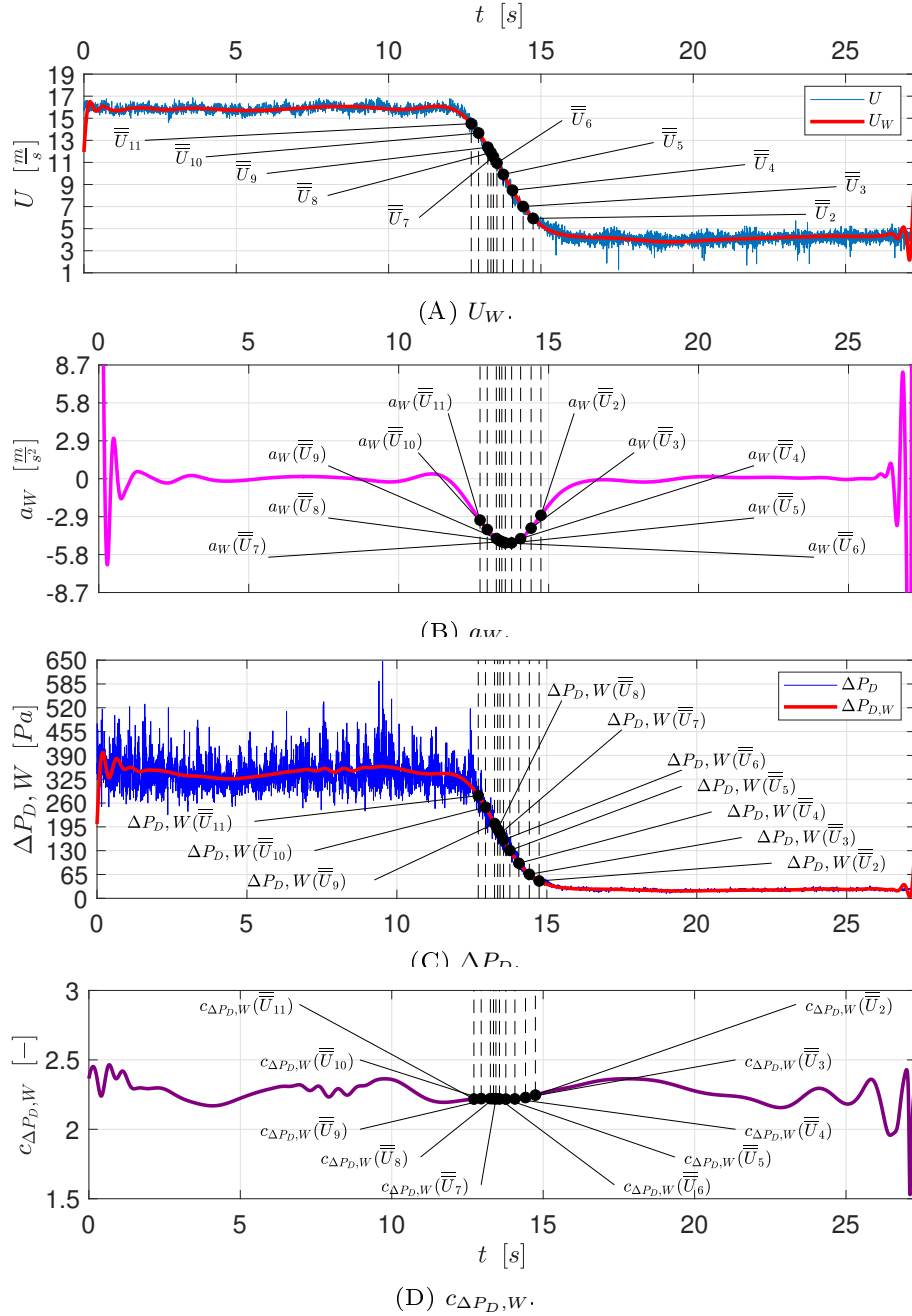


FIGURE 7.12: Selection of indexes to define the aerodynamic drag in unsteady conditions for one repeat of UF_1 (ramp-down).

Figure 7.13 reports the variation of $c_{D,W}$, again for the same repeat. Figure 7.13A shows its variation during the ramp-up, while Figure 7.13B focuses on the ramp-down.

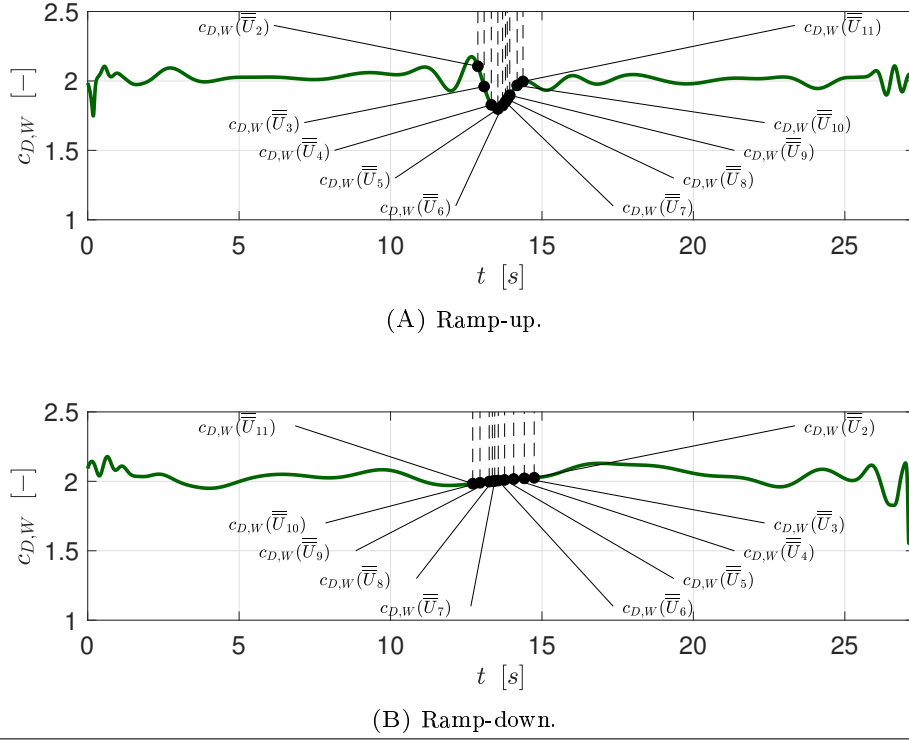
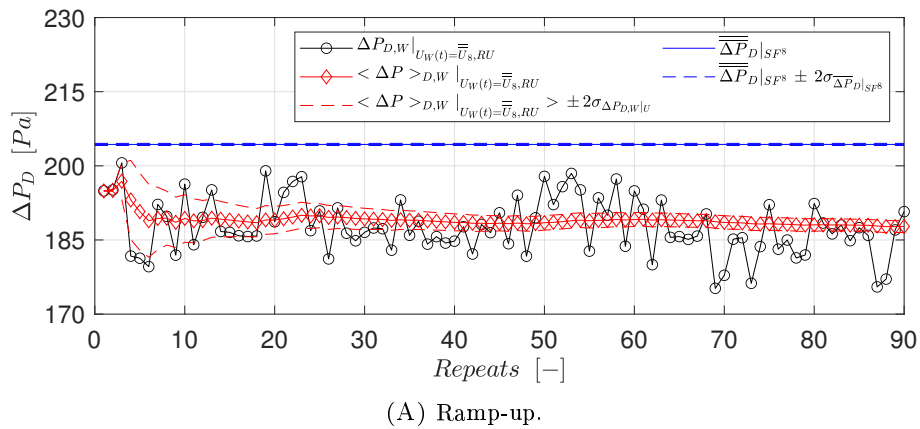


FIGURE 7.13: Time histories of $c_{D,W}$ for a repeat of UF_1 and selection of appropriate indexes.

Contrary to what occurs for steady flows, the collected values $\Delta P_{D,W}$ and $f_{D,W}$, or the corresponding coefficients $c_{\Delta P_{D,W}}$ and $c_{f_{D,W}}$, are not mean quantities, averaged over a long time interval. They are singular values which are collected by imposing an instantaneous up- or down-crossing of a reference wind speed (when $U_W = \bar{U}_k$). The final set of gathered numbers can be analysed from a statistical point of view, in order to clarify whether the number of repeats is sufficient to guarantee an adequate accuracy of the estimation. This procedure is illustrated in Figure 7.14, which indicates, for the ramp-up (Figure 7.14A) and the ramp-down (Figure 7.14B), the analysis for $\Delta P_{D,W}$ and its comparison with its steady counterpart relative to SF^8 . In each graph, the black line follows the values of $\Delta P_{D,W}|_{U_W(t)=\bar{U}_8}$ for each repeat, while the red one is the progressive ensemble mean. The red dotted line, in analogy with the steady flows, expresses the accuracy of the measurements through the quantity $\pm 2\sigma_{\Delta P_{D,W}|U}$ (where the nomenclature $|U$ shortens the term UF_1 , in this case).



(A) Ramp-up.

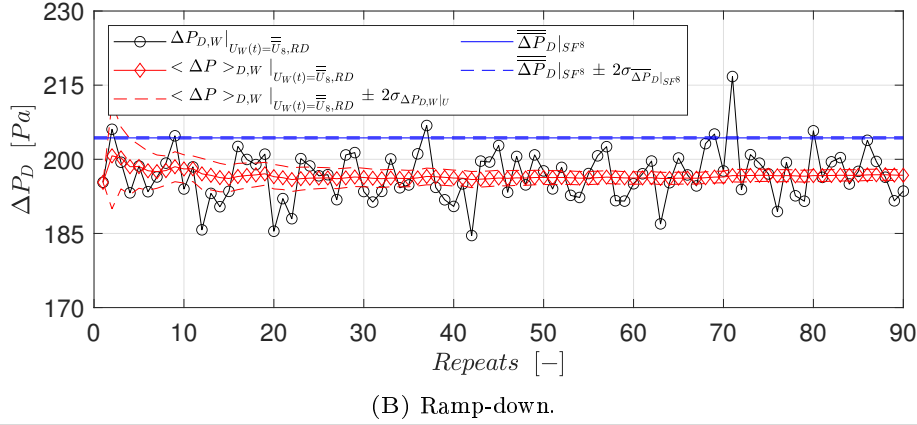


FIGURE 7.14: Collection of $\Delta P_{D,W}|_{U_W(t)=\bar{U}_s}$ in unsteady conditions for UF_1 , ensemble mean, accuracy and comparison with the steady reference (SF^8).

Implicitly assuming a Gaussian distribution of the random variable $\Delta P_{D,W}$ (as in steady flow), $\sigma_{\Delta P_{D,W}|U}$ is the standard deviation of the distribution divided by the square root of the number of repeats. The steady references are expressed by blue lines, which define the original value and its precision (in this case, the ones defined in Section 7.1 for SF^8). From the plots in Figure 7.14, it transpires that the aerodynamic drag in transient conditions, at least for the reference mean wind velocity $\bar{U}_8$, is lower than what defined in steady conditions. This occurs both in ramp-up and ramp-down conditions. In particular, if the steady reference pressure difference is 204.3 [Pa], the ensemble mean of the values gathered from the 90 repeats under ramp-up condition is 187.7 [Pa], with a standard deviation of 0.60 [Pa]. A moderately higher value is obtained for the ramp-down, for which the ensemble mean equals 196.8 [Pa], with a standard deviation of 0.55 [Pa]. In both cases, the value of $\sigma_{\Delta P_{D,W}|U=\bar{U}_8}$ seems low enough to rely on the result, which is a decrease of the aerodynamic drag, more pronounced for the ramp-up. However, it is recalled here that, as already observed in Chapter 6, the magnitude of the deceleration is lower than the acceleration. As a matter of fact, for UF^1 , the ensemble mean of the acceleration determined by imposing the up-crossing of $\bar{U}_8$ is 6.71 [$\frac{m}{s^2}$], while in ramp-down, that quantity is -4.98 [$\frac{m}{s^2}$].

Ramp-up and ramp-down studied together

This section follows the same path traced in the previous paragraph, this time for tests characterised by short T_b ($UF_{10} - UF_{13}$). The procedure illustrated before is simply extended by looking for the reference wind speeds $\bar{U}_k$ in both ramp-up and ramp-down in the same signal. Consequently, the associated a_W , $\Delta P_{D,W}$ and $c_{\Delta P_{D,W}}$ are immediately found and gathered. In analogy with Figure 7.11 and Figure 7.12 concerning UF_1 , Figure 7.15 depicts the steps for a repeat of UF_{13} . The 20 indexes (10 in the ramp-up and 10 in the ramp-down) are all indicated with dots along the time-history of U_W . From them, dashed lines are traced from top to bottom, going to intersect the corresponding values of a_W , $\Delta P_{D,W}$ and $c_{\Delta P_{D,W}}$.

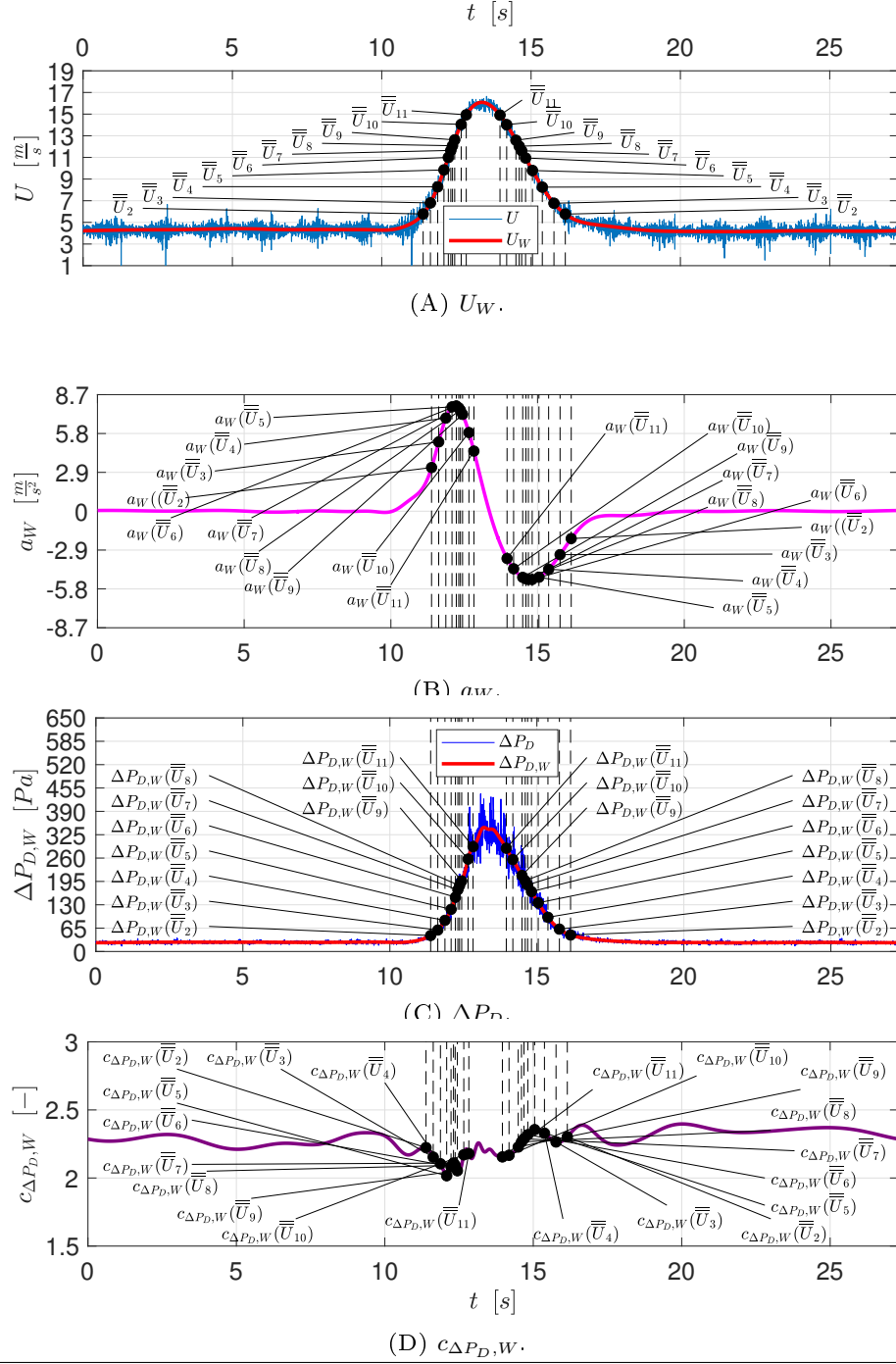


FIGURE 7.15: Selection of indexes to define the aerodynamic drag in unsteady conditions for one repeat of UF_{13} .

Moreover, Figure 7.16 displays the time-variation of $c_{D, W}$, highlighting the indexes of interest, as in Figure 7.13.

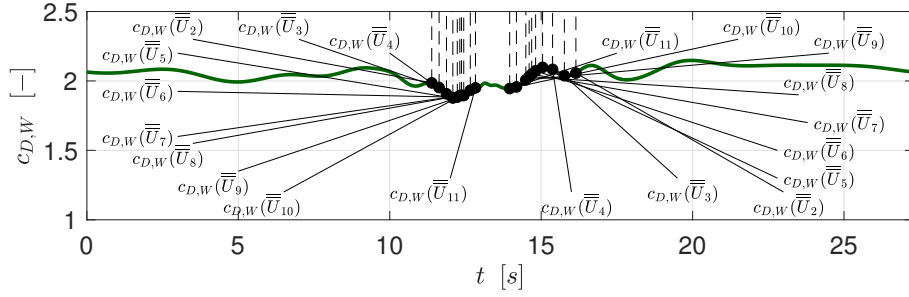
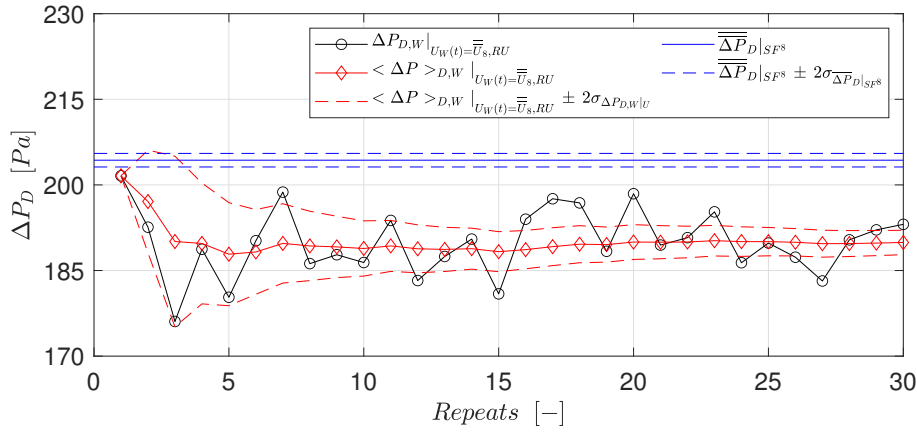
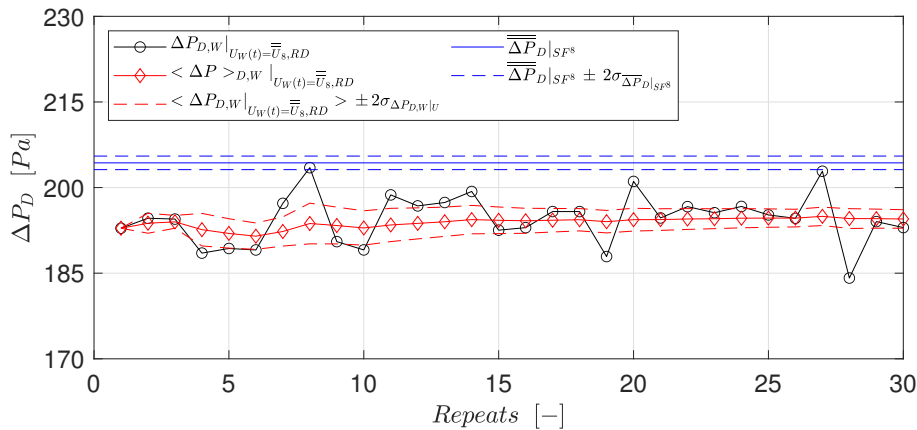


FIGURE 7.16: Time history of $c_{D,W}$ for a repeat of UF_{13} and selection of appropriate indexes.

In the spirit of checking the level of precision of the measures and to verify whether the number of repeats (30 for UF_{13}) is sufficient, Figure 7.17 compares, in complete analogy with 7.14, the variation of the instantaneous values of $\Delta P_{D,W}$ in correspondence of $U_W(t) = \bar{U}_8$, its progressive ensemble mean and the relative accuracy against the steady references. Figure 7.17A focuses on the ramp-up, while Figure 7.17B deals with the ramp-down.



(A) Ramp-up.



(B) Ramp-down.

FIGURE 7.17: Collection of $\Delta P_{D,W}|_{U_W(t)=\bar{U}_8}$ in unsteady conditions for UF_{13} , ensemble mean, accuracy and comparison with the steady reference (SF^8).

Then, again, it is possible to directly derive some indication concerning the aerodynamic drag in unsteady conditions, which seems again lower with respect the steady case, being equal to 189.9 [Pa] in ramp-up and 194.5 [Pa] in ramp-down. The resulting standard deviation of the distribution appears higher than the case of UF_1 , being equal to 1.07 [Pa] for the ramp-up and 0.81 [Pa] for the ramp-down. This is not surprising, since the number of repeats of UF_{13} is one third of the 90 repeats carried out for UF_1 . Nevertheless, these numbers still reflect a reduction of the aerodynamic drag compared to the steady case SF^8 . However, finding differences between the results of UF_1 and UF_{13} (which differ because of the choice of T_b) appears challenging. In fact, the discrepancies appear to be too limited when compared to the sensitivity of the pressure transducers.

7.3 Ensemble mean in unsteady conditions and comparison with steady references

Starting from the data collected in the previous section, their comparisons with the steady references are now described. Firstly, the aerodynamic drag is investigated (Section 7.3.1). Focusing on the pressure coefficients of the mid-span section, Section 7.3.2 deeply analyses six of them, while the whole set is investigated in Section 7.3.3. Finally, Section 7.3.4 gives some insight about the influence of the acceleration on the static pressure.

7.3.1 Aerodynamic drag

Having singularly analysed each repeat, it is possible to determine the time-histories of the ensemble means of the aforementioned quantities. Actually, these time-histories are not strictly necessary for the estimation of $c_{\Delta P_{D,W}}$ or $c_{D,W}$ at specified velocities, since this operation is pursued by seeking suitable indexes, as described in the previous Section. However, they allow a view at first glance of how the aerodynamic drag is affected by the acceleration or deceleration. Moreover, it is possible to analyse the ensemble means of the coefficients gathered for specific references against their steady counterparts, as already made for $\Delta P_{D,W}$ in Figures 7.14 and 7.17. This Section firstly shows the results of UF_1 , by reporting the ensemble mean of $c_{\Delta P_{D,W}}$ and $c_{D,W}$ for the ramp-up and the ramp-down. Subsequently, the variation of the coefficients evaluated in unsteady conditions against the steady quantities is estimated. Thus, the ensemble means of $c_{\Delta P_{D,W}}$ and $c_{D,W}$ are presented for UF_{13} as well. Besides, paragraphs are introduced to appreciate how the different parameters (which are U_{low} , U_{high} , $\Delta\tau$ and T_b , individuated in Section 6.6.3) affect the results.

Test UF_1

Concerning the test UF_1 (Figure 6.29) and focusing on the ramp-up, Figure 7.18 shows the ensemble mean of the quantities U_W (Figure 7.18A), a_W (Figure 7.18B) and $c_{\Delta P_{D,W}}$ (Figure 7.18C). The time interval of interest of the ramp-up is identified thanks to the plot of the acceleration $\langle a \rangle_W$: when $|\langle a \rangle_W|(t) = 0.25 \left[\frac{m}{s^2}\right]$, at the beginning and at the end of the ramps, two blue dots are indicated. From them, two vertical dashed line are traced, reaching the graph below, the one associated with $\langle c \rangle_{\Delta P_{D,W}}$. As regards this plot, $\langle c \rangle_{\Delta P_{D,W}}$ is drawn in purple, and its precision is indicated through dashed black lines, which represent the interval $\pm 2\sigma_{c_{\Delta P_{D,W}}|U}$. Moreover, the horizontal blue lines represent the corresponding steady references, indicating the mean value (solid line) and its accuracy, expressed through two times the standard deviation of the distribution (dashed lines). Obviously, this quantity is quite limited in correspondence of the highest velocity, whereas is much higher for lower wind speeds.

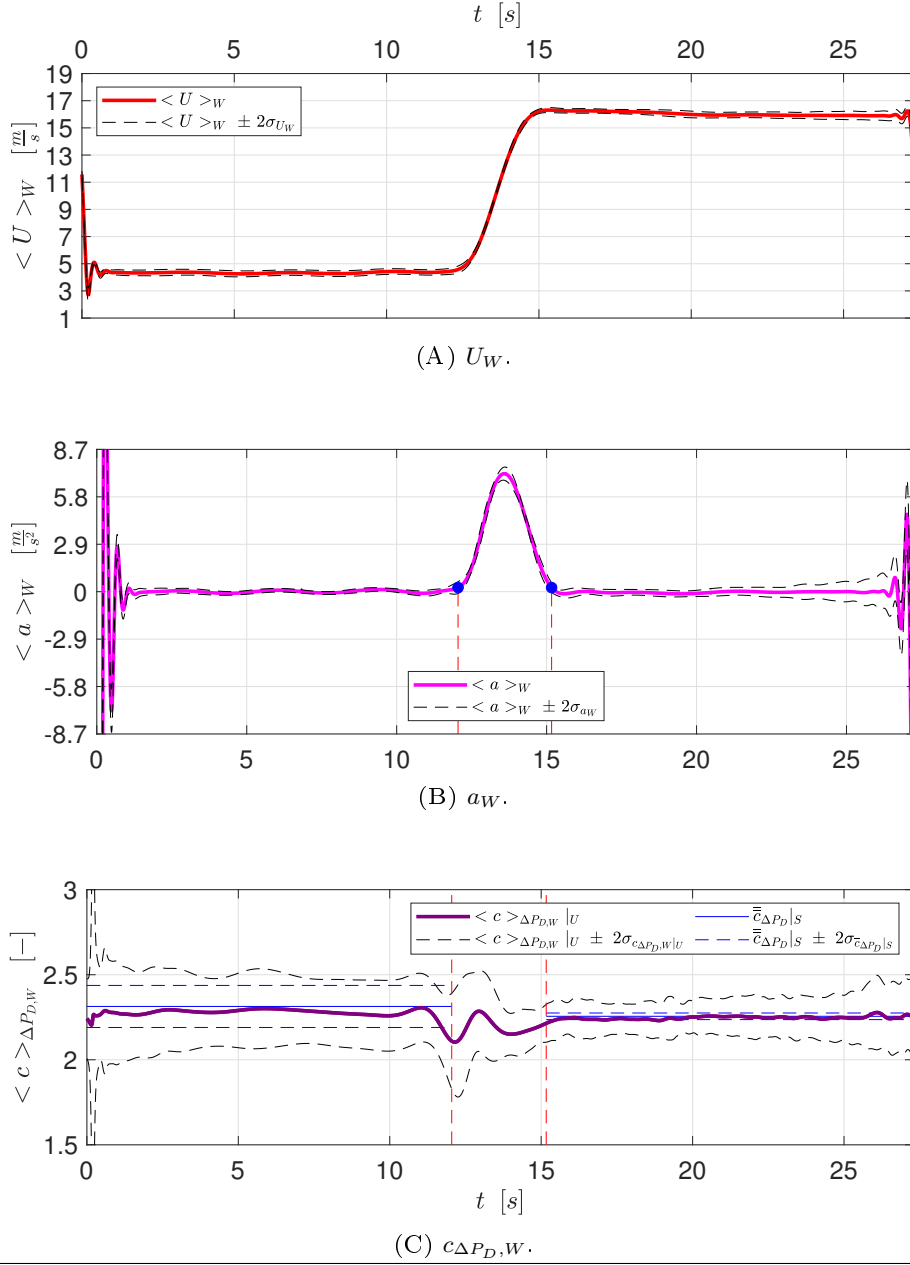


FIGURE 7.18: Time-histories of the ensemble mean on 90 repeats of UF_1 (ramp-up) of different quantities, with indication of the accuracy.

Figure 7.19 shows the variation of $\langle c \rangle_{D, W}$ with time in ramp-up conditions, which seems to follow the variation of $\langle c \rangle_{\Delta P_D, W}$. The two red dashed lines and the steady references assume the same meaning described for the previous picture.

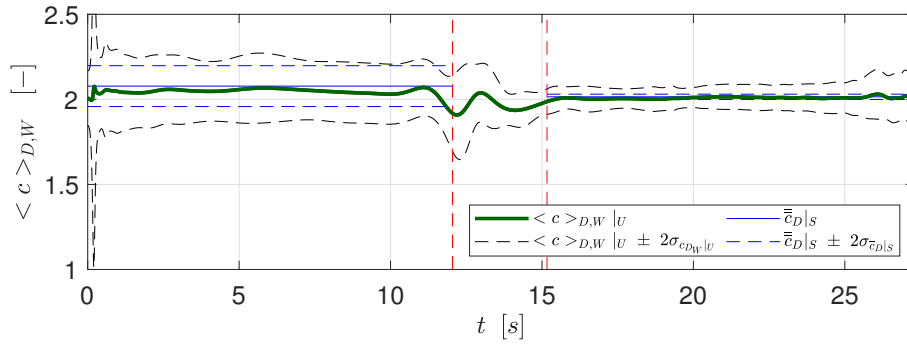
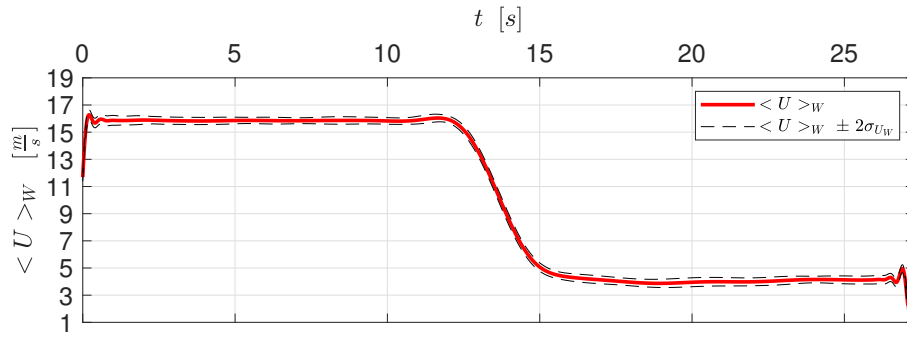
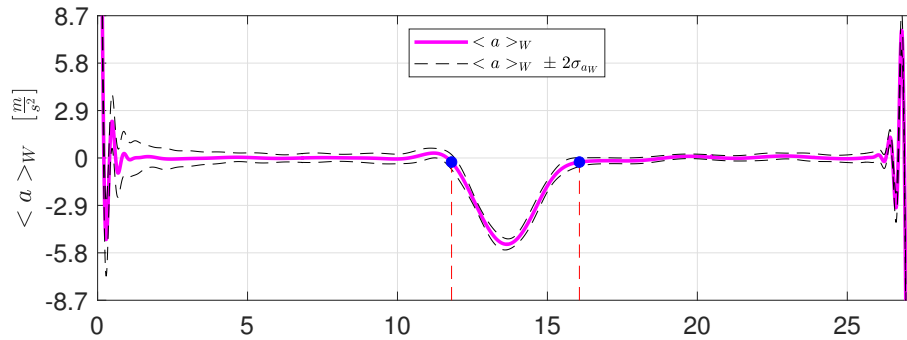


FIGURE 7.19: Time-history of the ensemble mean on 90 repeats of UF_1 (ramp-up) of $c_{D,W}$, with indication of the accuracy.

In the same way, Figure 7.20 depicts the variation of the same quantities of Figure 7.18, still for UF_1 , but in ramp-down conditions.



(A) U_W .



(B) a_W .

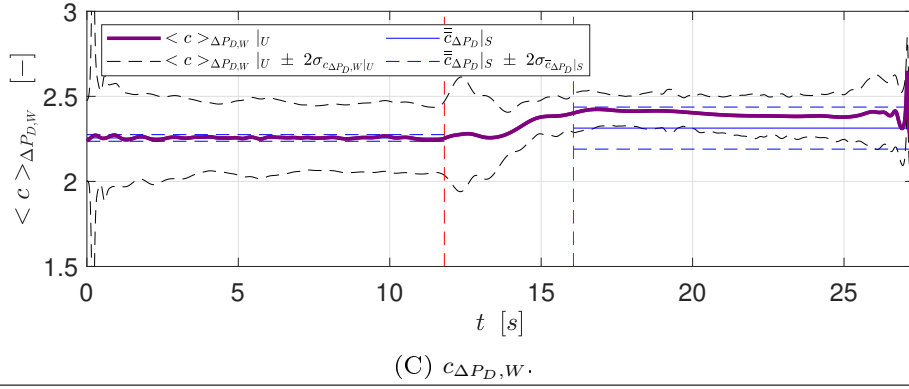


FIGURE 7.20: Time-histories of the ensemble mean on 90 repeats of UF_1 (ramp-down) of different quantities, with indication of the accuracy.

Again, the trend of $c_{D, W}$ is reported in a separate picture (Figure 7.21). It still resembles the resistance coefficient $c_{\Delta P_D, W}$.

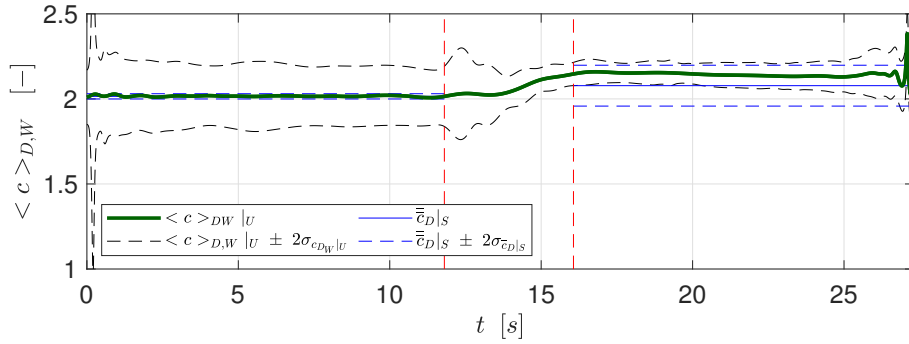


FIGURE 7.21: Time-history of the ensemble mean on 90 repeats of UF_1 (ramp-down) of $c_{D, W}$, with indication of the accuracy.

What pictured in Figure 7.18 and Figure 7.20 suggests two level of remarks: firstly, the quantities $\langle U \rangle_W$ and $\langle a \rangle_W$ appear to be characterised by a limited standard deviation, which indicates a strongly reduced dispersion of the results. Secondly, $\langle c \rangle_{\Delta P_D, W}$ and $\langle c \rangle_{D, W}$, during the phases of flow acceleration/deceleration, seem to show some irregularities, but these appear quite mitigated. It is also noted that during the ramp-up, both $\langle c \rangle_{\Delta P_D, W}$ and $\langle c \rangle_{D, W}$, at the beginning of the ramp, present a quite fashioned pattern, since the coefficient firstly drops, then gets higher and eventually turns to the steady reference. This, on one hand, appears opposite to the effect of inertial forces, which are linearly dependent on the acceleration parameter $K_{a, W}$, which is highest at the beginning of the ramp-up. In fact, this would dictate an increase of the aerodynamic drag. On the other hand, the accuracy which is there achieved is not excellent, since lower velocities are considered, for which the influence of some Pascals of tolerance might affect the estimation of the coefficient. Conversely, the results in ramp-down conditions appear characterised by a more regular trend. In this case, the flow changes its regime while a high wind speed is being tested on the model, and this might allow a higher accuracy of the results in transient conditions to be reached, if compared to the ramp-up case. Anyways, it is noted that in both cases the blue lines representing the steady references enclose the ensemble mean of the coefficients, either before and after the flow acceleration/deceleration.

In the previous graphs, the comparison between the coefficients in unsteady and steady conditions has not been investigated from a quantitative point of view. This is the object of the next two plots, specifically focusing on $c_{\Delta P_D, W}$. In particular, the first one is in Figure 7.22, which compares the set of 10 $c_{\Delta P_D, W}|_U$ (where the term $|_U$ means that the entire set of coefficients, extracted in correspondence of the 10 reference mean wind speeds $\bar{U}_k (k = 2 - 11)$ is reported) with the associated values from steady flows, which are $\bar{c}_{\Delta P_D}|_S$ (where the term $|_S$ indicates that the relevant steady flows $SF^k, k = 2 - 11$, are analysed). The abscissa represents the acceleration number $K_{a, W}$, in particular its ensemble mean, since this value is an instantaneous quantity gathered once from every time history, as is $c_{\Delta P_D, W}$. It is noteworthy to mention that this graph naturally encloses the values of both the ramp-up and the ramp-down, being the first on the positive abscissa and the second on the negative one. The ordinate along which the blue dots are placed expresses the ratio between the ensemble mean of $c_{\Delta P_D, W}|_U$ and $\bar{c}_{\Delta P_D}|_S$. There is a horizontal dashed line, in correspondence of 1, which indicates the threshold below which the coefficients are found to be lower than the steady reference; if the ratio is higher, this translates into an overshooting. The two solid lines, which link consecutive states, enclose the temporal variation of the states. This trend has to be followed, for the ramp-up, from higher $K_{a, W}$ to lower ones. This happens for the ramp-down as well, whose part has to be read from slightly negative values of $K_{a, W}$ to the left part of the graph (see also Figures 6.39C and 6.40C).

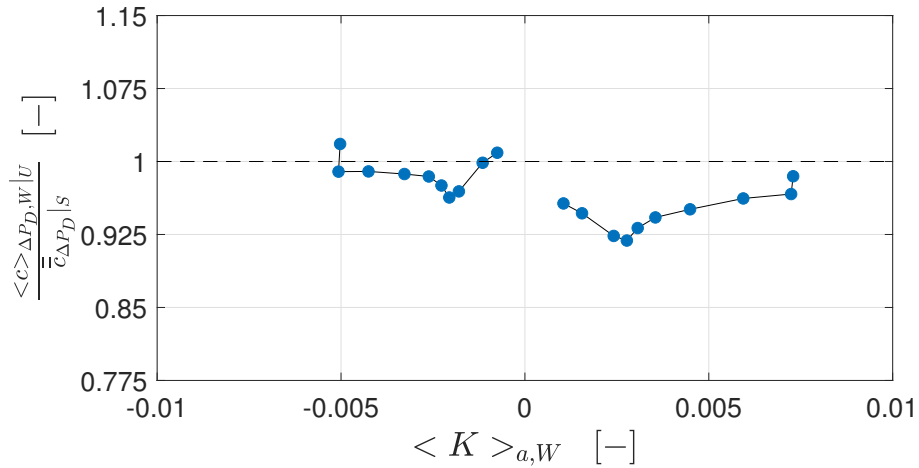


FIGURE 7.22: Comparison between the aerodynamic drag in unsteady and steady conditions against the acceleration number $K_{a, W}$.

This plot highlights a reduction of the coefficient in unsteady conditions, with a trend which does not seem driven by $K_{a, W}$. The largest drops occur for $\langle K \rangle_{a, W} = 0.0031$ for the ramp-up, and $\langle K \rangle_{a, W} = -0.0022$ for the ramp-down. These decrements are, respectively, in the order of 8 % and 4 %. Moreover, the reduction seems to follow a trend with the evolution of the ramps. In fact, both solid lines draw a function which presents a minimum for a certain $K_{a, W}$, before and after which it recovers, tending to 1. However, the graph is clearly non-symmetric, since the falls which are observed for positive $K_{a, W}$ are clearly higher than what occurs for negative $K_{a, W}$. Moreover, the first and the last points in the ramp-down show an overshooting, albeit a modest one.

Trying to justify this general reduction of the aerodynamic drag, the formulation that permits to estimate the forces induced on a body by a one-directional accelerating flow (already seen in Chapter 5) is herein recalled. Adequately replacing the general nomenclature in Chapter 5

with the one here introduced, it is possible to write:

$$F_X(t) = \frac{1}{2}\rho L b U_W^2 \bar{c}_D + \bar{c}_a \rho V a_W + \rho V a_W \quad (7.4)$$

The three terms, respectively, indicate the drag, the added mass and the Froude-Krylov forces. The wind speed is represented by U_W , while the coefficients are represented by the mean quantities evaluated in steady conditions. V is the volume of the body exposed to the fluid and is equal to $b \cdot d \cdot L$, where L is the length of the body, b is the reference cross-flow dimension and d is its depth. The added mass and the Froude-Krylov forces can be enclosed in a single term by defining the inertia coefficient $\bar{c}_m = 1 + \bar{c}_a$. Gathering the term $\frac{1}{2}\rho L b U_W^2$, Eq. 7.4 can be written as:

$$F_X(t) = \frac{1}{2}\rho L b U_W^2 \bar{c}_D \left(1 + 2 \frac{\bar{c}_m}{\bar{c}_D} \frac{A_s}{b} \frac{a_W}{U_W^2} \right) \quad (7.5)$$

where A_s is the cross-section, equal to bd . Therefore, the term relevant to the acceleration may be significant only if the body is elongated in the flow direction (d large).

The terms presented in Eq. 7.5 are now estimated for a case, the eighth one (the seventh point from right to left, whose reference steady test is SF^8). Hence, $U_W = 12.05 \left[\frac{m}{s} \right]$, $a_W = 6.71 \left[\frac{m}{s^2} \right]$, $\bar{c}_D = 2.06$ (from steady flows). $\bar{c}_a$ for a square cylinder might well be 1.51 (Blevins, 1977), hence $\bar{c}_m = 2.51$. ρ is kept equal to $1.20 \left[\frac{Kg}{m^3} \right]$. For this set of data, the second term in the brackets in Eq. 7.5 is equal to 0.0067, while the first, associated with the drag force, is by definition unitary. Therefore, the contribution of the acceleration-induced forces is estimated as the 0.7 % of the global force. Converting these values in a difference of pressures ΔP_D , the contribution of the drag is 204.3 [Pa] (from steady flow pressure tests), and the second is quantified as 1.38 [Pa]. These numbers and their magnitudes offer the opportunity to make an important remark. Firstly, it is noted that this estimation would lead to a higher aerodynamic drag, rather than to a reduced one. However, regardless of the sign, it is evident that the discrepancy between the unsteady and the steady case should be modest, in the order of 1 [Pa], which is too small and cannot be appreciated with the available instrumentation. This is not surprising, since the square cylinder is not an elongated body, which are the most likely to experience an overshooting because of acceleration effects (Chapter 5). The same finding is noted for the ramp-down as well, for which a reduction of the aerodynamic drag is expected but, again, in the order of 1 [Pa]. This means that the inertial forces should not be responsible for any variation of the aerodynamic drag, since they can hardly give a meaningful contribution, readable by the pressure transducers. Therefore, if differences are appreciated, they have to be related to the variation of the aerodynamic drag, caused by the effects of the acceleration. The fact that the acceleration-induced forces are negligible also permits to disregard the effects relevant to c_a and c_m , whose exact values are actually not known. The whole of these facts seems to remove the influence of K_a on the results. Therefore, not finding a remarkable trend in Figure 7.22 is hardly surprising. Conversely, when plotting the data as a function of the acceleration a_W , an interesting tendency is found, and the same data exhibit a substantial trend, as shown in Figure 7.23. The same plot is enriched with the measurements accuracy (two times the standard deviation of the distribution associated with each reference mean wind speed).

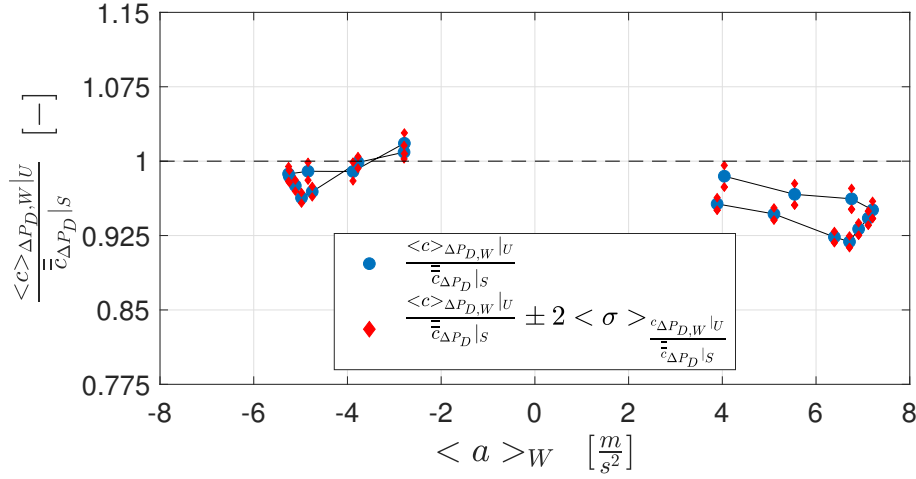


FIGURE 7.23: Comparison between the aerodynamic drag in unsteady (UF_1) and steady conditions against the acceleration a_W .

The trend indicates a stronger fall of the aerodynamic drag with the increase of the acceleration (or of the deceleration). Concerning the ramp-down, the two points which suggest a potential overshooting are moved on a similar abscissa, since the beginning and the end of the ramps share a similar magnitude of deceleration. Again, a non-symmetric reduction between ramp-up and ramp-down is apparent. The presence of the lines linking all the dots draw a sort of bow, which is well pronounced in the case of the ramp-up, depicting a clear dependence of the acceleration and its history. In the ramp-down, the bow is not clear as in the ramp-up, but it is still quite visible. Since this graph seems to successfully capture the dependence of the phenomenon, its structure is kept and replicated in the following. The last plot provides another piece of information about the different effect induced by a positive or negative acceleration. In fact, for the ramp-up, the maximum acceleration is followed by the most remarkable drop of the aerodynamic drag. In the ramp-down, the trend is opposite: the largest drop of the aerodynamic drag anticipates the strongest deceleration, which is achieved only in a following state, when the aerodynamic drag seems already to recover. Indeed, the effect of the temporal derivative of a_W on the results may be derived from Figure 7.24, where the blue dots are associated with a positive quantity of its ensemble mean (identifying the first part of the ramp-up and the second part of the ramp-down), and the red dots are relevant to a negative derivative (the second part of the ramp-up and the first part of the ramp-down).

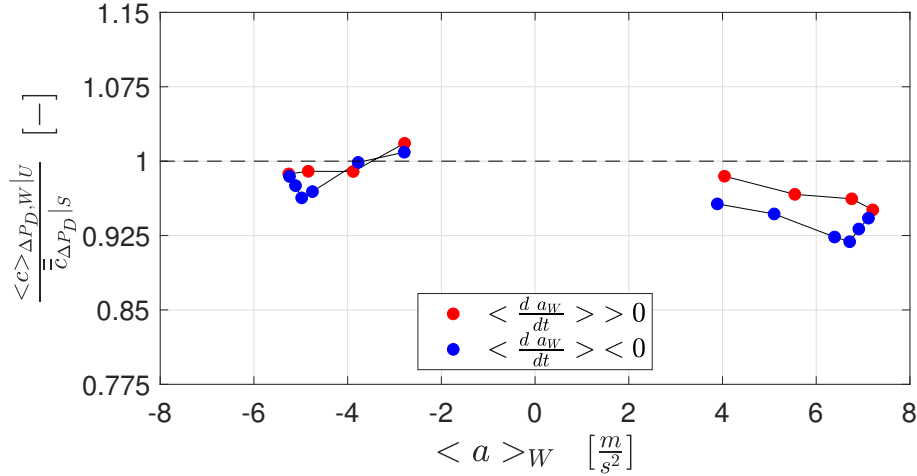


FIGURE 7.24: Influence of the temporal derivative of a_W on the reduction of the aerodynamic drag.

A more comprehensive graph concerning the role played by the derivative of the acceleration is shown in Figure 7.25, which reports $\langle \frac{d a_W}{dt} \rangle$ in abscissa. The red dots are here referred to the ramp-up, while the blue ones concern the ramp-down.

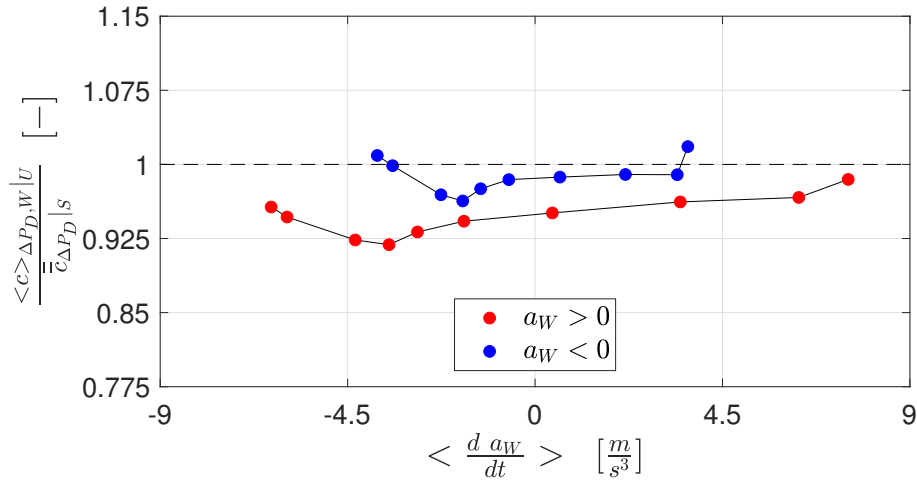


FIGURE 7.25: Comparison between the aerodynamic drag in unsteady (UF_1) and steady conditions against the temporal derivative of a_W , $\frac{d a_W}{dt}$.

During the ramp-up, it appears that the second part of the increase in velocity $\left(\frac{d a_W}{dt}\right) < 0$ is characterised by the most important reduction of the drag, while in the first part this mitigation is lowered. The ramp-down shows its, albeit modest, largest fall for a negative derivative of the acceleration as well. Commenting the two points which express an overshooting, they have different colours in Figure 7.24 and, in fact, are the first and last point of the blue branch in Figure 7.25. Amongst the two, the one associated with the end of the ramp-down (in red in Figure 7.24, and presenting a positive abscissa in Figure 7.25), is higher. However, this leads to an overshooting of 2 %, which might well be also associated with the accuracy of the instrumentation, which is reduced for low wind speeds.

Test UF_{13}

The procedure to define the ensemble mean of the tests characterised by a T_b lower than 30 [s] is not different from what illustrated for the cases with a higher T_b . Indeed, taking UF_{13} (Figure 6.42) as case of interest, Figure 7.26 follows the same scheme of Figure 7.18 or 7.20, showing the ensemble mean (on 30 repeats) of U_W (Figure 7.26A), a_W (Figure 7.26B) and $c_{\Delta P_D, W}$ (Figure 7.26C). In this case, the body undergoes both effects of ramp-up and ramp-down, which are separated by the most limited amount of time T_b amongst the ones present in the test matrix (Table 6.5).

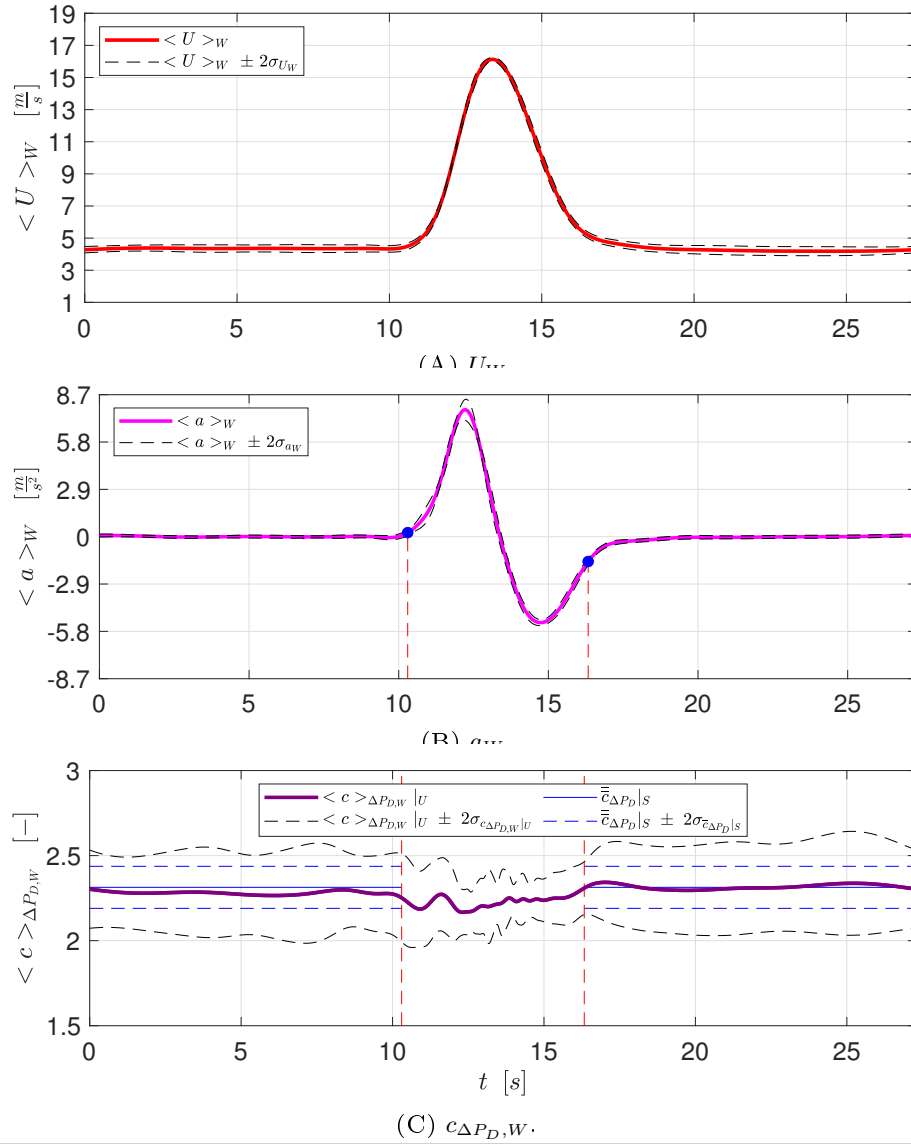


FIGURE 7.26: Ensemble mean on 30 repeats of UF_{13} of different quantities, with indication of the accuracy.

The relative variation of $c_{D, W}$ is provided in Figure 7.27.

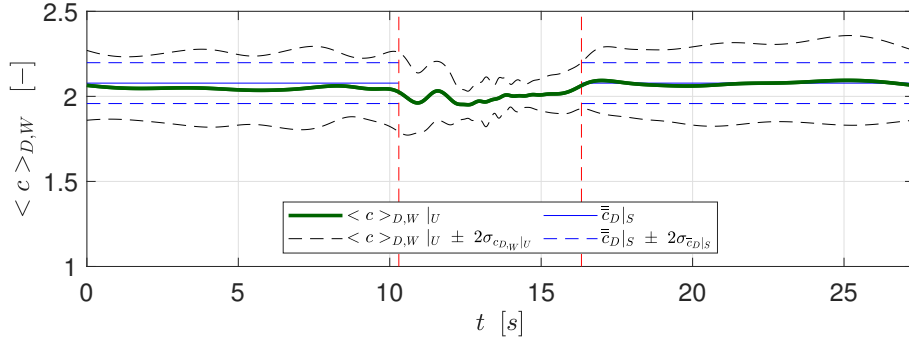


FIGURE 7.27: Ensemble mean on 30 repeats of UF_{13} (ramp-down) of $c_{D,W}$, with indication of the accuracy.

In principle, the results concerning $c_{\Delta P_{D,W}}$ and $c_{D,W}$ in the ramp-up should be consistent with the ones recorded for UF_1 , whereas the results in the ramp-down conditions might be affected by the presence of a lower T_b , which may prevent the full development of the wake before the flow deceleration. The comparison between coefficients in unsteady and steady conditions (analogously to Figure 7.23) is not shown here, but it is commented in the section concerning the effect of T_b .

Influence of U_{low}

The effect of the choice of U_{low} is herein investigated, by comparing in the same graph data from tests which differ for the choice of this parameter only. The first graph is shown in Figure 7.28 and explores the results of UF_1 , UF_2 , UF_3 and UF_4 (Figure 6.30). It is noted that each test reports a different number of dots, since tests which are characterised by a higher U_{low} present a lower number of points (the up-crossed and down-crossed reference mean velocities are less).

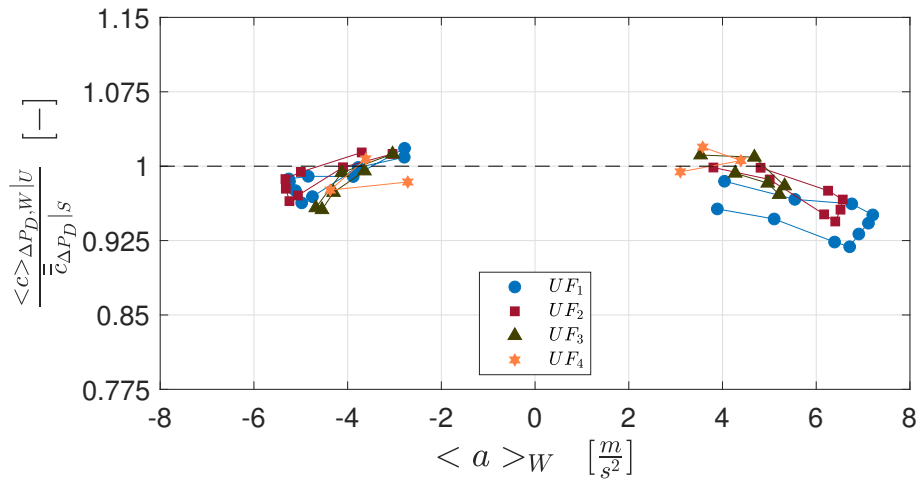
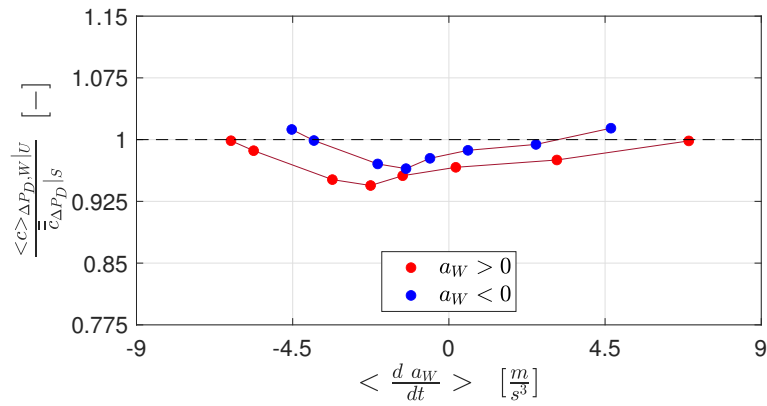
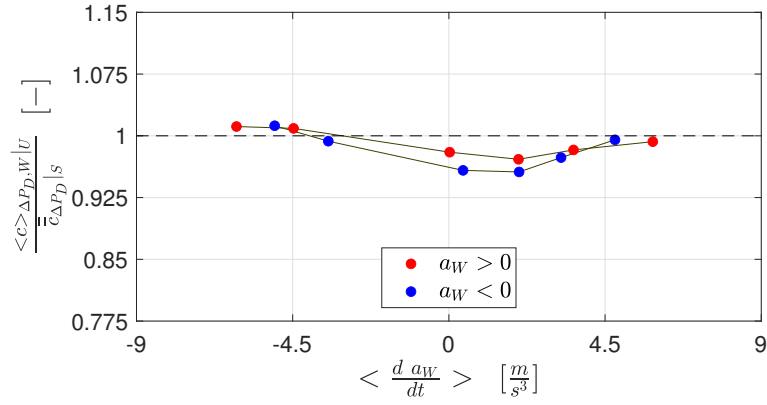


FIGURE 7.28: Comparison between the aerodynamic drag in unsteady and steady conditions against the acceleration a_W (UF_1 , UF_2 , UF_3 and UF_4).

The overlapping of the four different tests seems coherent, depicting a consistent agreement with the acceleration a_W . In particular, it is noted that tests whose U_{low} is higher, undergo reductions of the aerodynamic drag which are lower if compared to UF_1 . In fact, UF_2 exhibits a maximum reduction of 6 % and 4 % for ramp-up and ramp-down, while the data of UF_3

and UF_4 , respectively, show the highest drop to be equal to 3 % and 4 %, and 1 % and 2 %. If, on one hand, this might lead to consider U_{low} as a crucial parameter, on the other it is fair to note that lower levels of acceleration are reached if U_{low} is higher (see Section 6.7.3). Moreover, an increase of U_{low} also seems to have an impact as regards the symmetric behaviour between positive and negative accelerations, as highlighted by Figure 7.28 and by the numbers reported concerning the maximum drop of the aerodynamic drag. As a matter of fact, an increase of U_{low} makes the drop of the aerodynamic drag less sensitive to the sign of the acceleration. Furthermore, it is possible to appreciate that tests with a higher U_{low} might show some states in the ramp-up which are close to 1, indicating values which are similar to the steady references, as for ramp-down conditions.

Recalling the finding concerning the temporal derivative of the acceleration, the next three plots (Figures 7.29A, 7.29B and 7.29C) show the results concerning the aerodynamic drag against $\langle \frac{d a_W}{dt} \rangle$, as in Figure 7.25.

(A) UF_2 .(B) UF_3 .

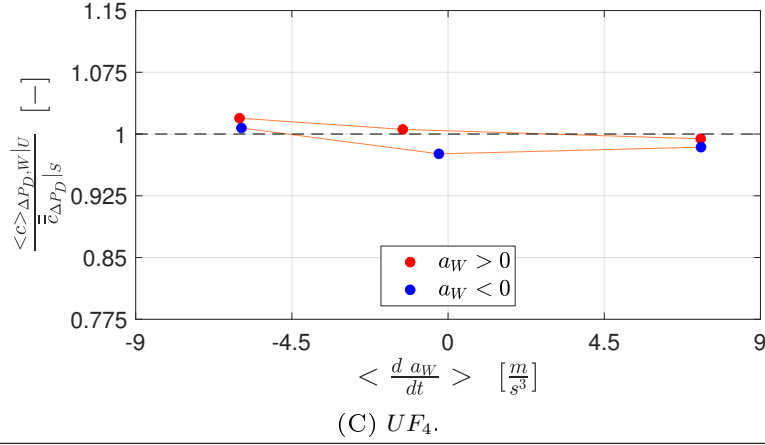


FIGURE 7.29: Comparison between the aerodynamic drag in unsteady (UF_2 , UF_3 and UF_4) and steady conditions against the temporal derivative of a_W , $\frac{d a_W}{dt}$.

Concerning UF_2 (Figure 7.29A), the largest drops still occur for a negative value of $\frac{d a_W}{dt}$. This is no longer true for UF_3 (Figure 7.29B), which shows its highest loss of aerodynamic drag for a positive abscissa. The magnitudes of the two lines are more comparable now. Actually, the two lines are swapped, if compared with UF_1 and UF_2 . The values linked to UF_4 are close to 1. This set of plots allows a different consideration to be made. If U_{low} increases, the delay between the maximum acceleration ($\langle \frac{d a_W}{dt} \rangle = 0$) and the maximum drop of aerodynamic drag appears smaller, regardless of the sign of acceleration. Another interesting result concerning the influence of U_{low} is presented in Figure 7.30, which shows the same ordinate as before, on a different abscissa, now made non-dimensional. This is the quantity $\langle \frac{\bar{a}_{W,x} t_x}{U_W |U|} \rangle$, where t_x is the time interval that passes between the beginning of the ramp-up (identified as the time instant for which $a_W = 0.25 [\frac{m}{s^2}]$), and $\bar{a}_{W,x}$ is the mean acceleration in the time interval t_x .

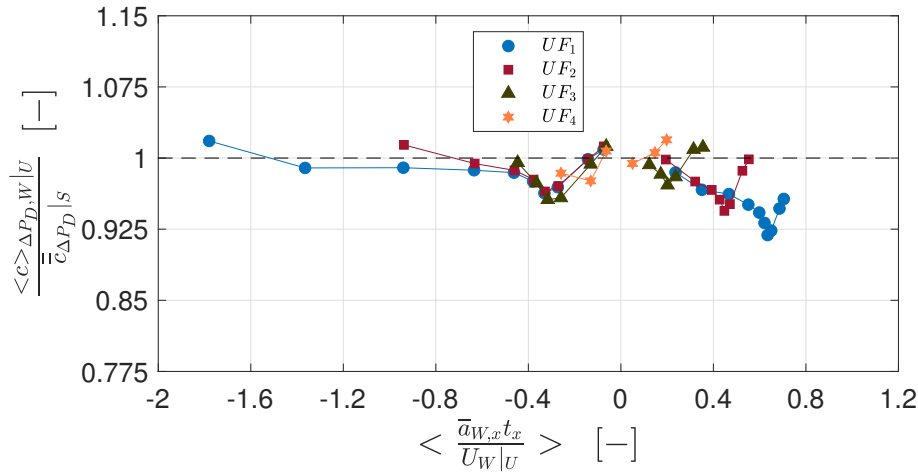


FIGURE 7.30: Comparison between the aerodynamic drag in unsteady and steady conditions against the parameter $\langle \frac{\bar{a}_{W,x} t_x}{U_W |U|} \rangle$ (UF_1 , UF_2 , UF_3 and UF_4).

The graph still does not present a monotonic trend with the abscissa. In fact, focusing on the ramp-up, all the tests exhibit a fall which increases with the abscissa, followed by a recover of the aerodynamic drag. However, the graph clarifies, perhaps better than Figure

7.28, that different tests show results which depend on their history. As a matter of fact, the regrowth of the aerodynamic drag appears to occur at different values of the non-dimensional abscissa for each test. Conversely, the results on the negative abscissa are more similar, but the effect of U_{low} is expected to be limited in the ramp-down.

Influence of U_{high}

Focusing on U_{high} , the results of UF_2 and UF_5 (Figure 6.31) are analysed in Figure 7.31. The trend is still coherent with what described before and, again, highlights the effect of the acceleration. UF_5 is characterised by limited values of acceleration, hence its variation of the coefficient are small. Interesting remarks can be addressed concerning the ramp-down as well, which seems to be interested by slightly higher coefficients.

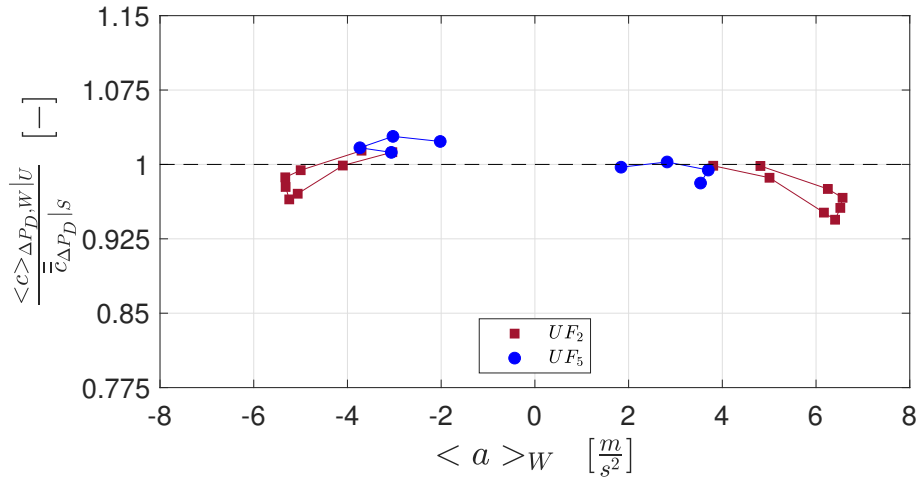


FIGURE 7.31: Comparison between the aerodynamic drag in unsteady and steady conditions against the acceleration a_W (UF_2 and UF_5).

Influence of $\Delta\tau$

This section examines the effect of the acceleration on tests which differ because of the choice of $\Delta\tau$, keeping all the other quantities as the same. As already discussed in Section 6.6.3, there are three possible comparisons to be made. The first is between UF_1 and UF_6 (Figure 6.32A), the second is between UF_2 and UF_7 (Figure 6.32B), and, finally, it is possible to compare UF_3 , UF_8 and UF_9 (Figure 6.32C). Focusing on the first case, Figure 7.32 reports the comparison.

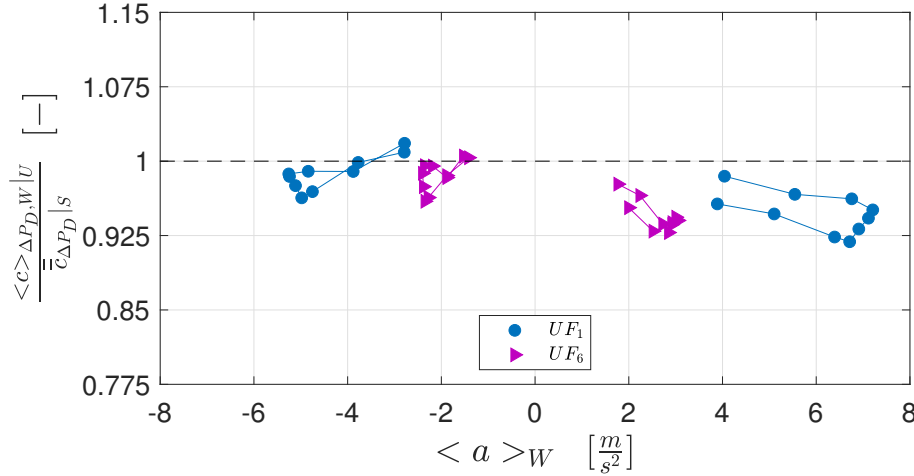


FIGURE 7.32: Comparison between the aerodynamic drag in unsteady and steady conditions against the acceleration a_W (UF_1 and UF_6).

The individual analysis of each of the two sets of results indicates a decrease of the load with the increase of the absolute value of the acceleration, as already commented for UF_1 . However, the comparison between UF_1 and UF_6 shows values which are not different, in spite of the different magnitudes of the acceleration. Moreover, the non-symmetric character of the trends between positive and negative accelerations is still present in UF_6 . The comparison between the results of UF_1 and UF_6 is again presented in Figure 7.33, this time by reporting the derivative of the acceleration in the abscissa axis. The continuous lines represent the data of the ramp-up, whereas the dot dashed lines concern the ramp-down. Obviously, the data relative to UF_6 are collected in a reduced portion of the graph if compared to the UF_1 data, being the acceleration and its derivative much more limited in absolute value. This graph permits to point out that UF_6 exhibits more remarkable drops of the resistance for the first part of the ramp-up (when the derivative of the acceleration is still positive, but is decreasing). On the other hand, the trends of the ramp-downs appear more similar.

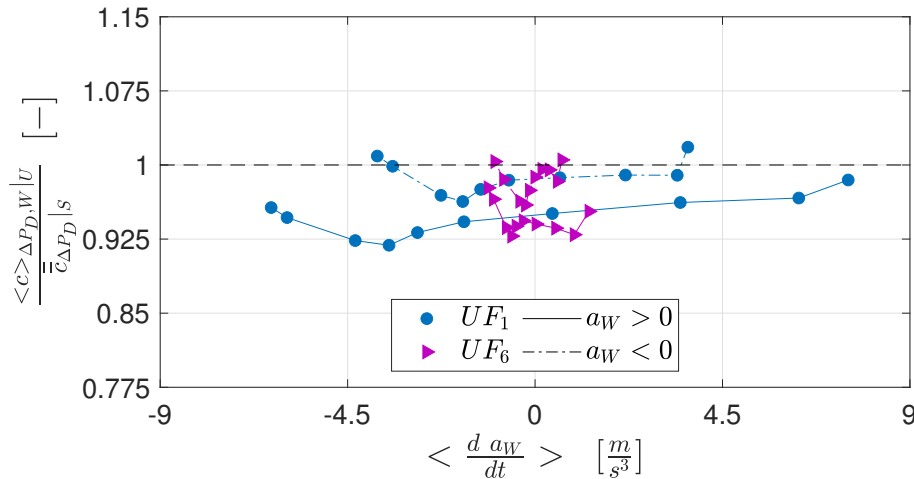


FIGURE 7.33: Comparison between the aerodynamic drag in unsteady (UF_1 and UF_6) and steady conditions against the temporal derivative of a_W , $\frac{da_W}{dt}$.

Referring to UF_1 , the trends were visually described by the presence of two bows. These are apparently still present for UF_6 , covering almost the same range on the ordinate, but

less extended along the acceleration axis. A second aspect which is worth to be mentioned concerns the non-simultaneous occurring of the maximum fall with the maximum acceleration/deceleration, as in UF_1 . This seems to be highlighted by UF_6 as well, albeit the corresponding bows are not so neat as the ones relative to UF_1 .

Figure 7.34 and Figure 7.35, respectively, report the comparison between UF_2 and UF_7 , and between UF_3 , UF_8 and UF_9 .

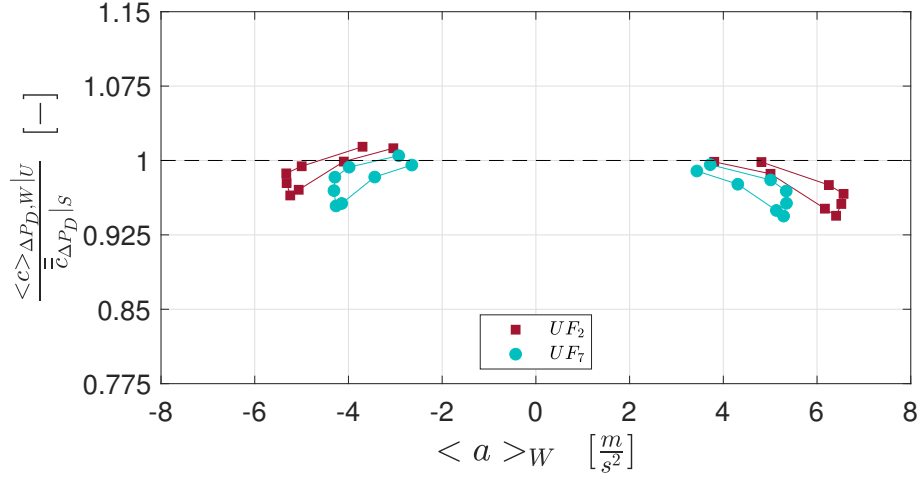


FIGURE 7.34: Comparison between the aerodynamic drag in unsteady and steady conditions against the acceleration a_W (UF_2 and UF_7).

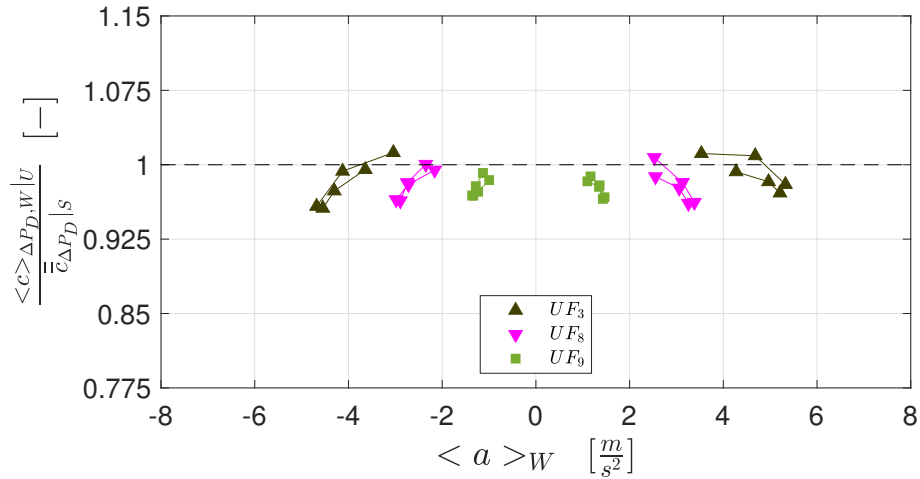


FIGURE 7.35: Comparison between the aerodynamic drag in unsteady and steady conditions against the acceleration a_W (UF_3 , UF_8 and UF_9).

The last two graphs seem to confirm what seen in Figure 7.32: regardless of the flow acceleration, the highest reduction of the aerodynamic drag occurs in the middle of the ramp, and this value does not appear to be too sensitive to the magnitude of the acceleration. Conversely, it seems more dependent on the values U_{low} and U_{high} . At the beginning and at the end of the ramps, the values are similar to the steady references, being their ordinate close to 1.

Figures 7.32, 7.34 and 7.35, in their ensemble, confirm the remark already made in the section

devoted to the influence of U_{low} . In fact, by scrolling down from the first to the last plot, an evident recover of the symmetric behaviour between positive and negative accelerations may be observed. Moreover, the whole of the gathered data allows another remarkable result to be pointed out. The minimum drop of the resistance that is observed appears not to be a function of the acceleration, or of its history. In fact, the tests carried out between the same U_{low} and the same U_{high} undergo approximately the same loss of aerodynamic drag, regardless of the level of the acceleration. Furthermore, studying the minimum ratio between the aerodynamic drag in unsteady and steady conditions, it is possible to observe a clear dependence of this quantity on the difference between U_{low} and U_{high} . This, named as ΔU_W , is placed in abscissa in Figure 7.36, whose ordinate is the minimum of the ratio between the aerodynamic drag (then, only a single point is considered from each test). A negative abscissa means that the data are relevant to the ramp-down, while a positive value indicates a ramp-up. Figure 7.36 is also enriched with a colour bar, which reports the magnitudes of the absolute value of the acceleration associated with the minimum of the ratio. This graph offers a striking view of the importance of ΔU_W , which seems to rule the maximum drop of the aerodynamic drag, almost independently of the achieved acceleration.

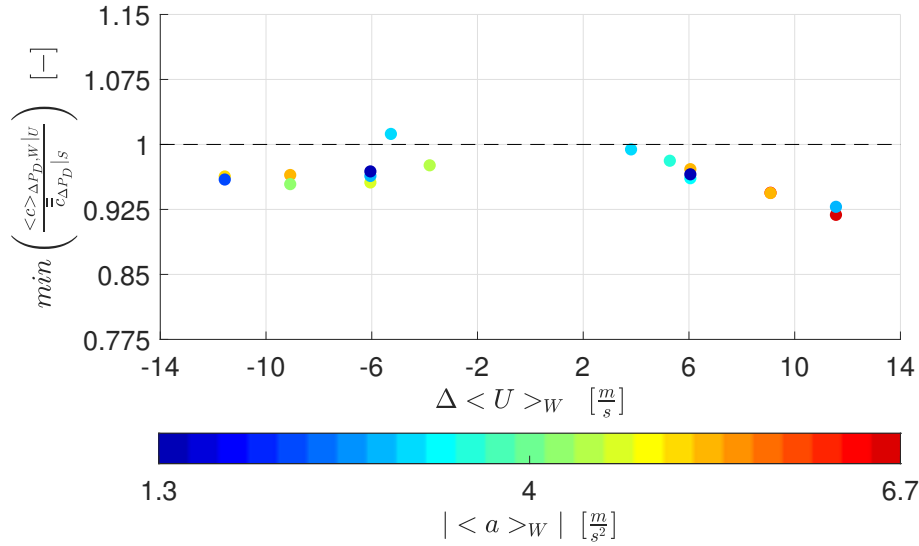


FIGURE 7.36: Variation of the maximum drop of the aerodynamic drag with the difference between U_{high} and U_{low} .

Influence of T_b

This section focuses on the influence of T_b on the results. To consider the whole set of data in a single plot would lead to an overlapping of 50 points (10 dots for 5 tests) in a single semi-axis of the abscissa, making the graph unreadable. To avoid this, the tests are distinguished between long (UF_1, UF_{10}) and short ($UF_{11}, UF_{12}, UF_{13}$) values of T_b . Concerning the former family, Figure 7.37 shows the comparison between the two tests.

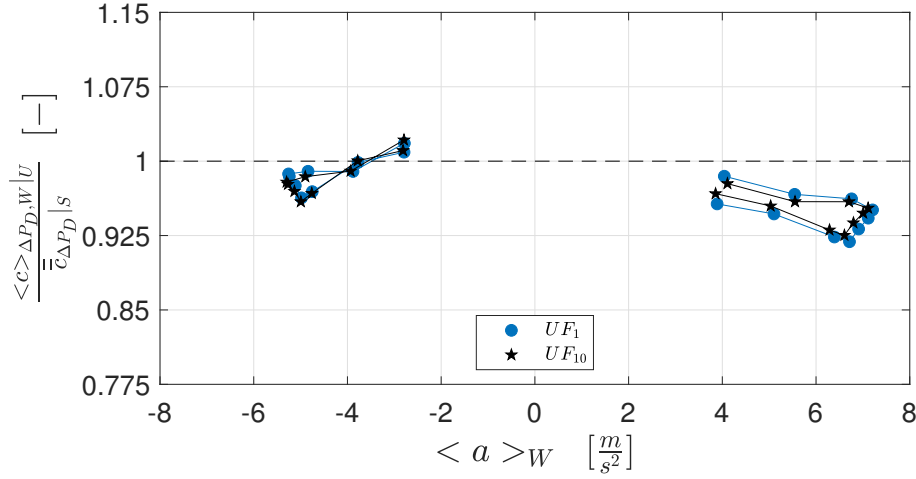


FIGURE 7.37: Comparison between the aerodynamic drag in unsteady and steady conditions against the acceleration a_W (UF_1 , UF_{10}).

The trends seem similar indeed, and the small discrepancies might well be associated with the accuracy of the instrumentation.

Moving to tests with short T_b , Figure 7.38 reports the data concerning UF_{11} and UF_{12} .

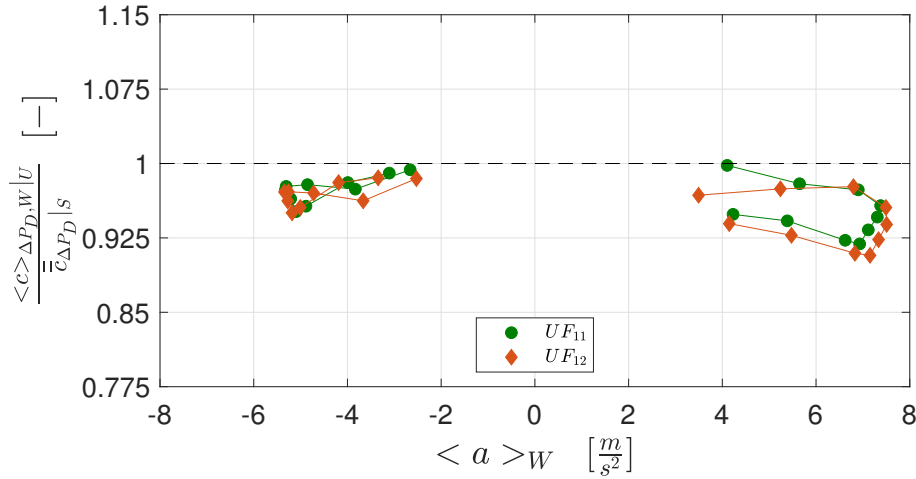


FIGURE 7.38: Comparison between the aerodynamic drag in unsteady and steady conditions against the acceleration a_W (UF_{11} , UF_{12}).

In this case, the two initial points of the ramp-up are slightly different between UF_{11} and UF_{12} . Actually, their trends of the first part of the flow acceleration are moderately dissimilar from the ones of UF_1 and UF_{10} , drawing a slightly larger bow. Moreover, moving to the ramp-down, the presence of points exhibiting an overshooting is no longer shown by the graph. Concerning this aspect, UF_1 and UF_{10} start with a value which is modestly higher than 1 (respectively relevant to a $\langle \Delta P \rangle_{D, W} |U_{W=\bar{U}_{11}}|$ equal to 304.6 and 305.1 [Pa], to be compared to the steady reference from SF^{11} , which is 301.9 [Pa]. For UF_{11} and UF_{12} , instead, this quantity is respectively equal to 299.9 [Pa] and 297.5 [Pa]. A similar finding is seen for the end of the ramp-down as well, for which UF_{12} registers the highest drop. As a matter of fact, UF_{12} displays a bow that appears slightly lowered than UF_{11} . A last graph is proposed, focused on UF_{13} only (Figure 7.39).

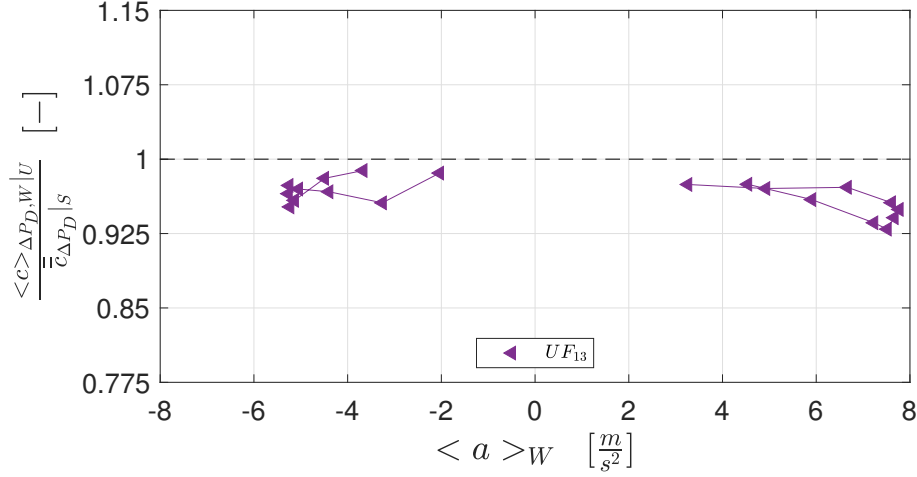


FIGURE 7.39: Comparison between the aerodynamic drag in unsteady and steady conditions against the acceleration a_W (UF_{13}).

By looking at this last plot, the bow of the ramp-up appears more elongated and stretched than before. As a matter of fact, the results at the end of the ramp-up are close to the ones registered at its beginning. The ramp-down, instead, presents a wider bow than UF_{11} and UF_{12} , linked to a further drop of the aerodynamic drag at the end of the ramp-down. This seems the most remarkable finding for this set of tests, for which the effect of T_b appears to be mainly reflected on the ending part of the ramp-down. This exhibits a higher fall of the aerodynamic drag for low values of T_b , while tests characterised by higher magnitudes of T_b , in the same phase, quickly recover the steady condition. This may also be noted from Figure 7.40, which reports the time-history of the ensemble mean of $c_{\Delta P_{L,W}}$ for the ramp-downs of the different tests. They have been aligned by imposing the same time instants at the down-crossing of $\overline{U}_{11}$. This picture seems to further confirm what described before. UF_1 and UF_{10} seem to follow a similar pattern, while UF_8 and UF_{12} and UF_{13} appear characterised by a lower aerodynamic drag, in particular at the beginning and at the end of the ramp-down. The region concerning the highest deceleration seem to lead to similar results, regardless of T_b .

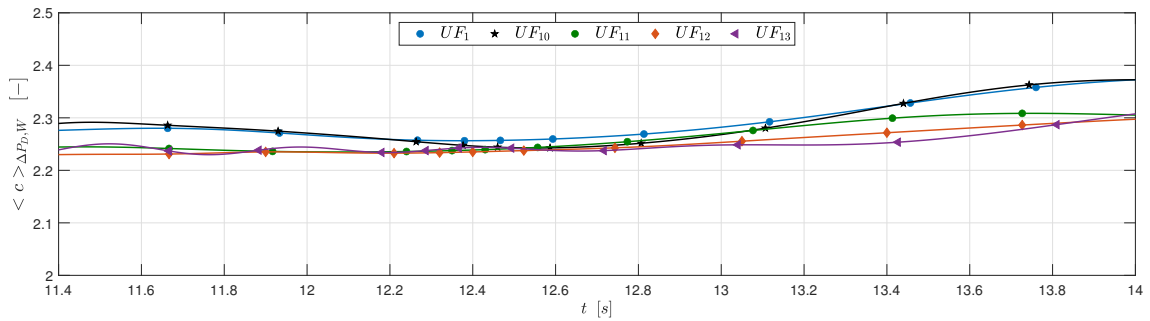


FIGURE 7.40: Ensemble means of the resistance coefficient for the ramp-down conditions of tests characterised by different values of T_b .

Finally, it is stressed that the differences associated with the influence of T_b are, all in all, limited.

7.3.2 Selected mean pressure coefficients

After having focused the attention on the effects of the acceleration on the aerodynamic drag, some comments are now made concerning the pressure coefficients. It has already been noted that, at variance with the quantities relevant to the aerodynamic drag, the pressure coefficients are dependent on the choice of the static pressure. The latter has been defined in Chapter 6 as the mean between the ones acquired by $P2$ and $P3$. The pressure taps which are deeply investigated now are 4 out of the 6 highlighted in Figure 7.41. These latter six play a significant role: $C06$ and $C29$, as seen before, are strictly related to the aerodynamic drag. The other four ($C18$, $C40$, $C23$ and $C35$) are of great interest for the vortex-shedding. Amongst the latter ones, $C18$ and $C23$ are now maintained for further analyses, disregarding $C40$ and $C35$ for sake of brevity, since their outcomes are supposed to be similar to $C18$ and $C23$. The original pressure signals and the static pressure are treated with the $L2$ continuous wavelet technique illustrated in Chapter 6. Hence, it is possible to find the j^{th} mean pressure coefficient in unsteady conditions as:

$$c_{P,j,W} = \frac{P_{j,W} - P_{s,W}}{P_{dyn,W}} \quad (7.6)$$

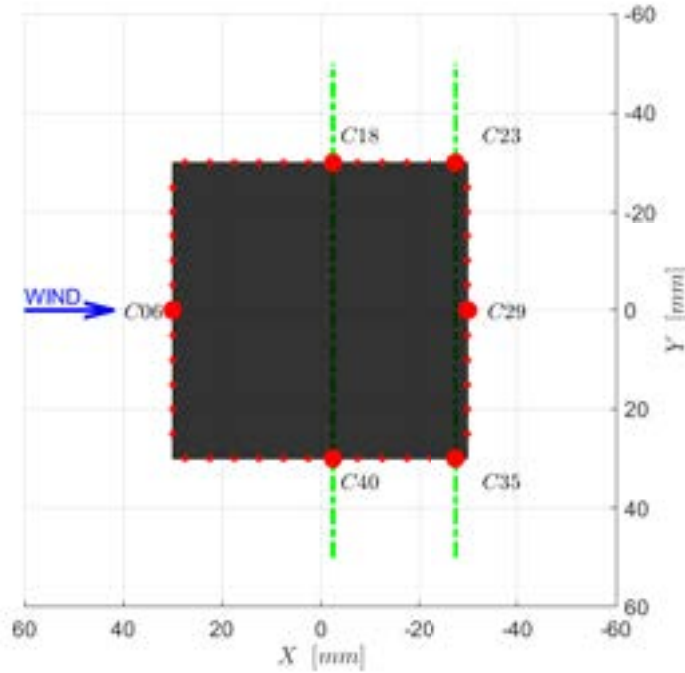


FIGURE 7.41: Mid-span section of the model with identification of six pressure taps of special interest.

As in the section of the aerodynamic drag, firstly the results for UF_1 are illustrated, and secondly the entire set of tests is explored, following the same path of analysis applied in the previous Section.

Test UF_1

The variation of the pressure coefficients which are evaluated in unsteady conditions are compared with their steady references by means of adequate ratios, as already done in the

previous section. Now, the quantity in the ordinate is $\frac{\langle c \rangle_{P_{CX,W}} |u|}{\bar{c}_{P_{CX,W}} |s|}$, where CX is the tap object of the investigation. If the investigated tap undergoes a reduction of suction (so, its pressure coefficient increases), this ratio is lower than 1. By the same token, its pressure coefficient decreases if a higher suction is acquired by the tap and, consequently, the ratio is higher than 1.

Each of the 4 sub-plots present in Figure 7.42 shows this quantity against the ensemble mean acceleration $\langle a \rangle_W$. $C06$ is displayed in Figure 7.42A, while the two taps $C18$ and $C23$ of the lateral face are in Figure 7.42B and Figure 7.42C. The tap in the leeward face $C29$ is presented in Figure 7.42D.

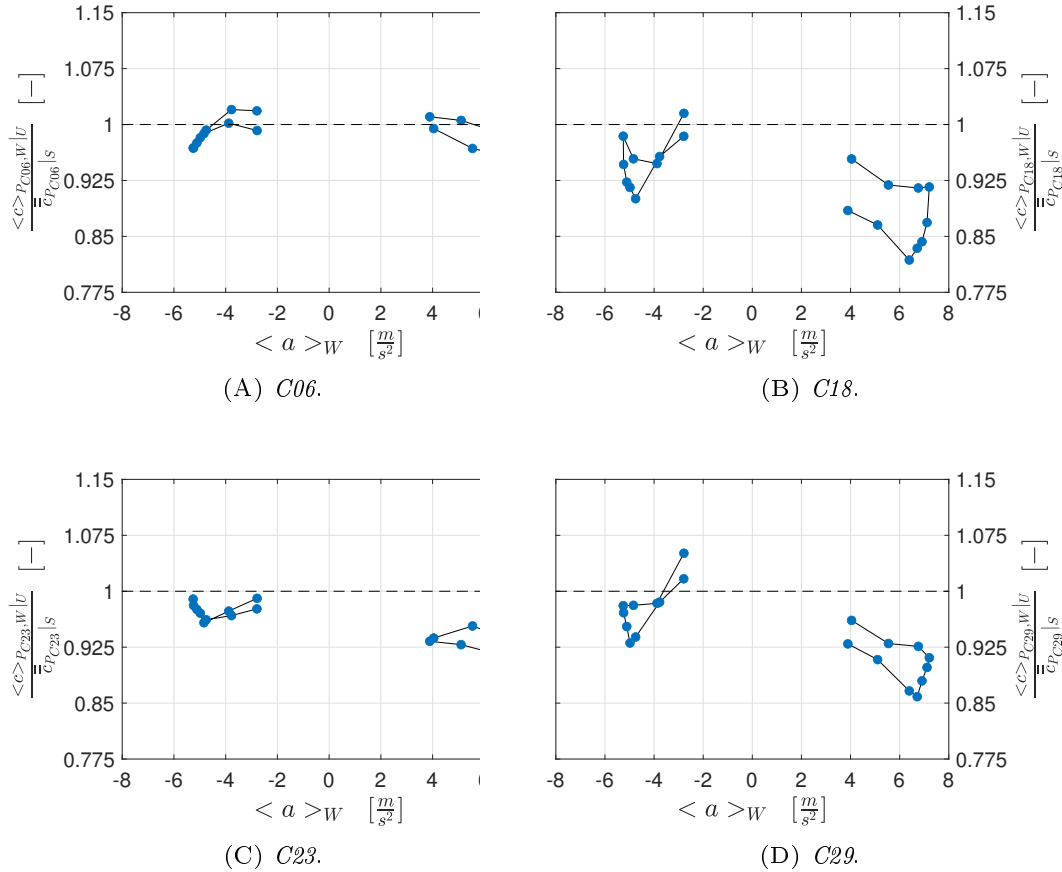


FIGURE 7.42: Comparison between the selected mean pressure coefficients in unsteady and steady conditions against the acceleration a_W (UF_1).

The set of data in Figure 7.42 seems to confirm what already seen for the aerodynamic drag, so a general diminution of the ratio between coefficients is found in different conditions. This seems enhanced with the increase of the acceleration. In particular, analysing $C06$ (Figure 7.42A), this mitigation appears limited. This is not surprising, since the reference dynamic pressure is strictly linked to this tap and this coefficient should be close to 1, since it coincides with the stagnation point. As a matter of fact, this value is never lower than 0.96. The behaviour of $C29$ (Figure 7.42D) resembles what seen concerning the aerodynamic drag (Figure 7.23), with a clear fall for positive accelerations (up to 14 %) of the ratio between the mean pressure coefficients in the two conditions, followed by a smaller reduction for the ramp-down as well (up to 7 %). The presence of two cases for which the coefficient is slightly lower than the steady reference is noted again, but with mitigated values (2 % at the beginning of the flow deceleration and 5 % at its end). It is also important to point out that the

maximum increase of the coefficient is almost double than the corresponding reduction of the aerodynamic drag, and this is plausible. The taps placed on the lateral face again show a general growth of the mean pressure coefficient, more pronounced for *C18*, which undergoes a jump up to 19 % in ramp-up conditions, and up to 10 % for the ramp-down case. The rise experienced by *C23* is instead mitigated, and its mean coefficient achieves a maximum increase of 8 %. Furthermore, it seems that its results are less dependent on the acceleration, since all different states experience quite similar growths, contrary to what occurs for the other taps. This is reflected also by the shape of the bow which links all the states, which appears more squeezed than what happens, for instance, for *C18*. The difference between the two taps which are on the same face might be explained taking vortex-shedding into account, which does not manifest itself in the same way along the same face. In fact, while in the region of *C18* the interference with the edge and the downstream wake is limited, that is not the case for *C23*. Indeed, close to the edge, the measurements might well be affected by the interference with the wake and vortices of different dimensions. Hence, the effects of the acceleration appear much more pronounced for *C18*, than for *C23*. The three different plots (*C18*, *C23* and *C29*), in their whole, again exhibit a non-symmetric pattern, since the ratios associated with the ramp-up are clearly lower than what occurs for negative accelerations.

Influence of U_{low}

Figure 7.43 shows the variation of the selected mean pressure coefficients against $\langle a \rangle_W$ for the tests UF_1 , UF_2 , UF_3 and UF_4 , which differ for the choice of U_{low} only.

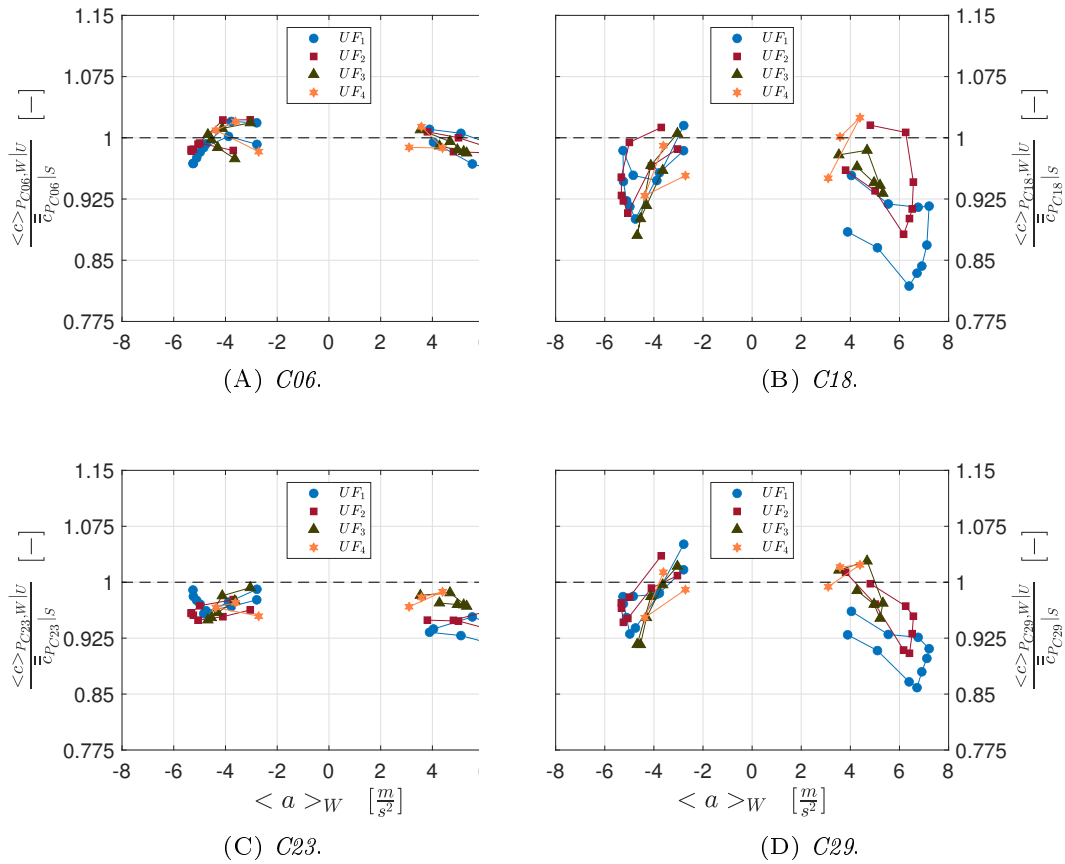


FIGURE 7.43: Comparison between the selected mean pressure coefficients in unsteady and steady conditions against the acceleration a_W (UF_1 , UF_2 , UF_3 and UF_4).

The scheme is the same as in the previous paragraph, presenting *C06* (Figure 7.43A), *C18* (Figure 7.43B), *C23* (Figure 7.43C) and *C29* (Figure 7.43D). As it was the case for the aerodynamic drag, the ratios of the mean pressure coefficients seem to be evidently dependent on the acceleration, showing their largest drops in correspondence of the highest accelerations. *C18* still appears as the tap which is mostly affected by the acceleration. Then, again, *C23* seems to experience a growth of the pressure in all conditions, with values which appear less spread than the other taps. *C29* displays a few conditions in which the coefficient is lower than in steady cases, for limited values of acceleration or deceleration, confirming the outcome concerning the aerodynamic drag (Figure 7.28). However, when the acceleration or the deceleration increases, the coefficient is higher than the steady reference. Tests which start from higher U_{low} show many results whose ordinate is close to 1.

Influence of U_{high}

Figure 7.44 compares the results of the selected mean pressure coefficients for the tests UF_2 and UF_5 , which differ because of U_{high} . *C06* is pictured in Figure 7.44A, *C18* in Figure 7.44B, *C23* in Figure 7.44C and *C29* in Figure 7.44D.

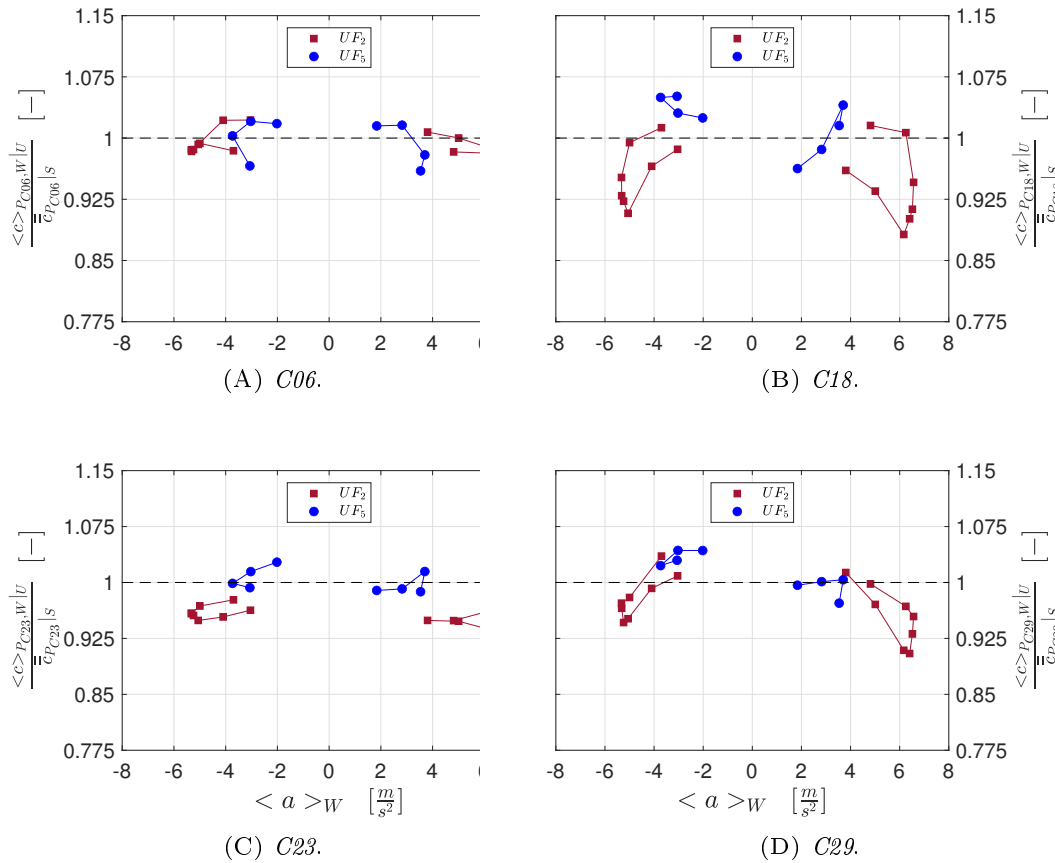


FIGURE 7.44: Comparison between the selected mean pressure coefficients in unsteady and steady conditions against the acceleration a_W (UF_2 and UF_5).

As already appreciable from Figure 7.31, the results seem coherent with the acceleration. The points relevant to UF_2 , which reaches a higher U_{high} , are always lower than the ones of UF_5 , which is characterised by limited magnitudes of acceleration and, consequently, by points close to 1. The maximum rise of the coefficient is observed for *C18*, which experiences a maximum growth of about 12 %.

Influence of $\Delta\tau$

Moving to tests which differ because of $\Delta\tau$, the next pictures again report the comparison between the mean pressure coefficients. In particular, Figure 7.45 shows the comparison between UF_1 and UF_6 , Figure 7.46 focuses on UF_2 and UF_7 , Figure 7.47 displays the data of UF_3 , UF_8 and UF_9 . For these cases, the plots reporting the variation of the aerodynamic drag are, respectively, Figure 7.32, 7.34 and 7.35. The coefficients are reported in the usual order, being $C06$ on top left, $C18$ on top right, $C23$ on bottom left and $C29$ on bottom right.

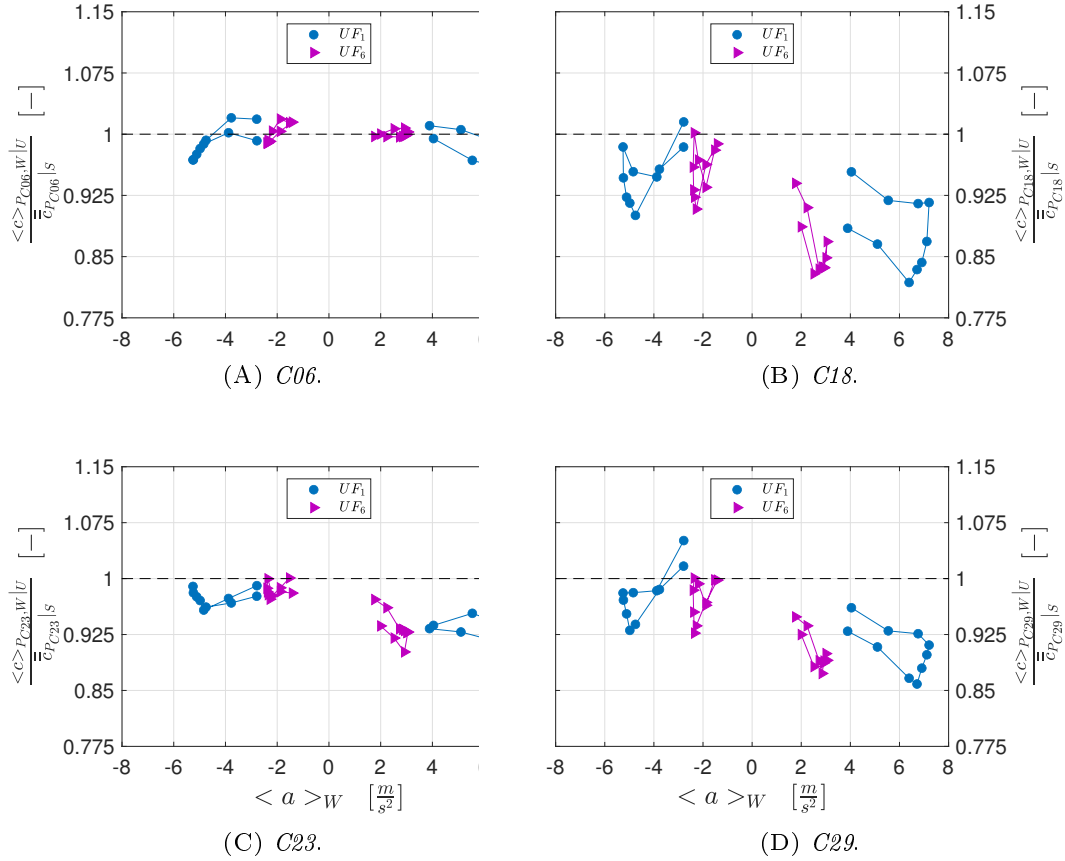


FIGURE 7.45: Comparison between the selected mean pressure coefficients in unsteady and steady conditions against the acceleration a_W (UF_1 and UF_6).

Coherently with what found for the mean resistance coefficients, the variation of the mean pressure coefficients (excluding $C06$, which is placed at the stagnation point) seems not to be totally dependent on the acceleration. In fact, UF_1 and UF_6 seem to lead to similar increases of the pressure coefficient for $C18$, $C23$ and $C29$, similarly to what occurs for the corresponding drop of the aerodynamic drag. In fact, for both tests the growth reaches numbers up to 19/18 ($C18$) and 14/13 % ($C29$). Then, again, it is noted that the increase of the coefficients experienced in the ramp-down appears lower than what occurs in the ramp-up. Going forward, the other comparisons are presented in Figures 7.46 and 7.47.

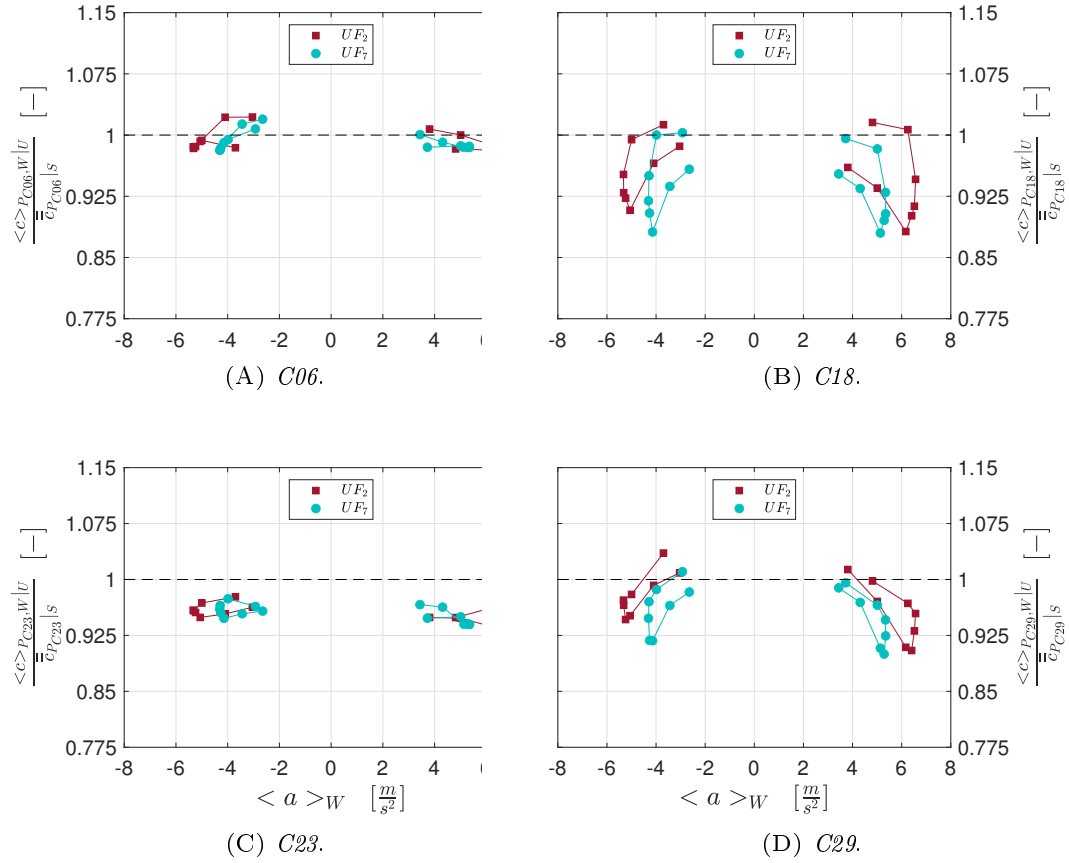
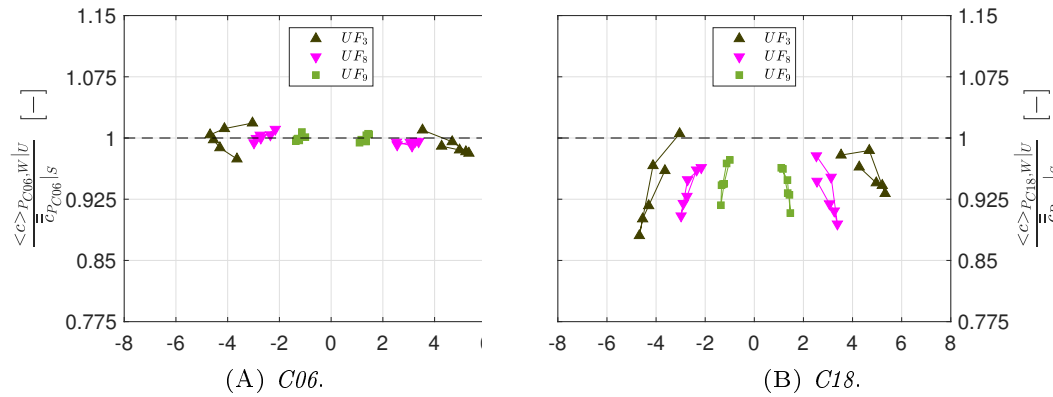


FIGURE 7.46: Comparison between the selected mean pressure coefficients in unsteady and steady conditions against the acceleration a_W (UF_2 and UF_7).

The remarks expressed for UF_1 and UF_6 might be extended to the comparison between UF_2 and UF_7 , even though in the latter case there is a small difference in terms of flow acceleration. The results seem again quite similar, exhibiting almost equal trends. Actually, these appear almost simply translated on the acceleration axis, especially for C_{18} , C_{23} and C_{29} .



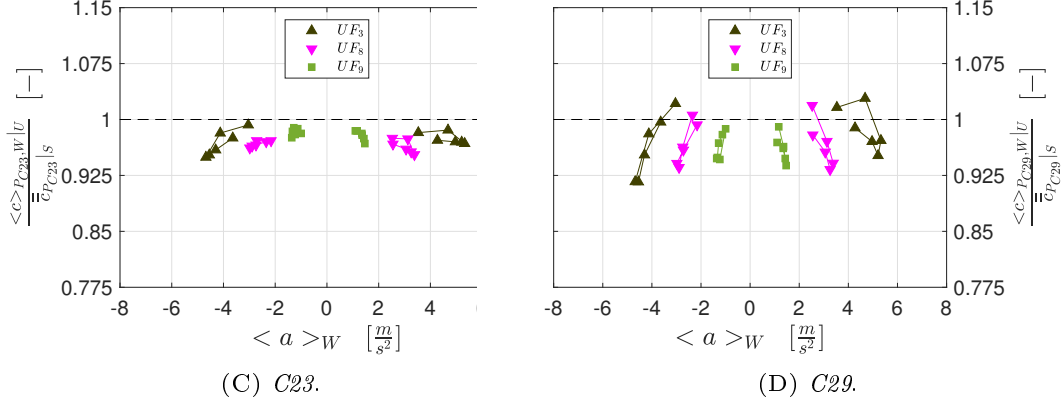


FIGURE 7.47: Comparison between the selected mean pressure coefficients in unsteady and steady conditions against the acceleration a_W (UF_3 , UF_8 and UF_9).

Observing Figure 7.47, the trend of the coefficients of UF_3 is again similar to the one of the other tests, but in a much shorter range of acceleration. Moreover, it is pointed out that this set of tests presents a U_{low} which is quite high ($\bar{U}_5 = 9.81 \frac{m}{s}$), so the accuracy is higher than the other two cases, whose U_{low} is lower. $C18$ is the coefficient which undergoes the highest jump in the mean pressure coefficient, quantified as the 7 % in ramp-up, while in the ramp-down that is about the 12 % (so, a higher growth than what experienced under ramp-up conditions). A quite similar result is found for $C29$ as well, while $C23$ is subjected to reduced effects (less than 5 %).

Futhermore, it is remarked that, moving from low U_{low} to higher ones, the symmetric pattern of the graphs is recovered, as it has been observed for the aerodynamic drag. This enhances what appreciated before, so that a low value of U_{low} makes the results sensitive to the sign of the acceleration, whereas this effect is mitigated for higher values of this quantity. Finally, the results concerning the mean pressure coefficient confirm the important result already highlighted for the aerodynamic drag, namely that the maximum discrepancy between the unsteady cases and the steady ones appears not to be a function of the achieved acceleration but rather of the difference between U_{low} and U_{high} .

Influence of T_b

Finally, results are compared from tests which differ because of the choice of T_b . In the section concerning the aerodynamic drag, a distinction has been made between tests with high values of T_b (UF_1 , UF_{10}) and those with short ones (UF_{11} , UF_{12} , UF_{13}). Now, only UF_1 and UF_{13} are maintained to perform a comparison in terms of mean pressure coefficients, which is reported in Figure 7.48. The scheme is the one consolidated in the previous sections, reporting $C06$ on top left, and, following in a clockwise sense, $C18$, $C29$ and $C23$.

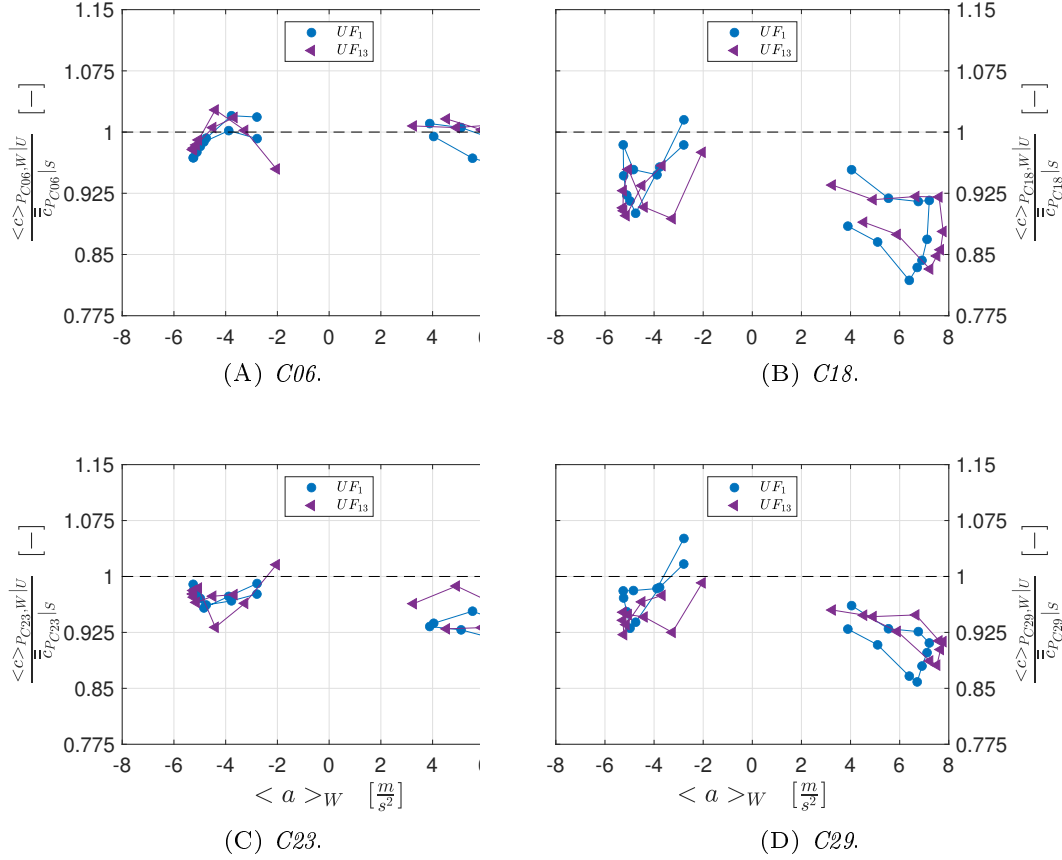


FIGURE 7.48: Comparison between the selected mean pressure coefficients in unsteady and steady conditions against the acceleration a_W (UF_1 , UF_{10} , UF_{11} , UF_{12} and UF_{13}).

The results seem to follow what seen for the aerodynamic drag. In particular, differences between the two tests are found for $C29$ and $C18$, for the ramp-down. In fact, the reduction of the pressure seems to be much quicker for the case UF_1 , rather than for UF_{13} . As a matter of fact, taking the whole set of data associated with tests with different T_b into account, the mean pressure coefficient of $C29$ in unsteady conditions at the end of the ramp-down $\langle c \rangle_{P_{C29,W}}|_{U_W(t)=\bar{U}_2}$, is -1.28 , -1.27 , -1.25 , -1.23 and -1.23 , respectively for the tests UF_1 , UF_{10} , UF_{11} , UF_{12} and UF_{13} . Therefore, an increasing trend is observed for decreasing T_b . This seems to clarify the influence of T_b on the aerodynamic drag and on the base pressure in the ramp-down. Moreover, the coefficients $C29$ and $C18$ evaluated in UF_{13} are never lower than their steady counterparts.

However, as happened for the aerodynamic drag, also the numbers expressed by these pressure coefficients are quite similar, letting transpire a modest influence of T_b on the results.

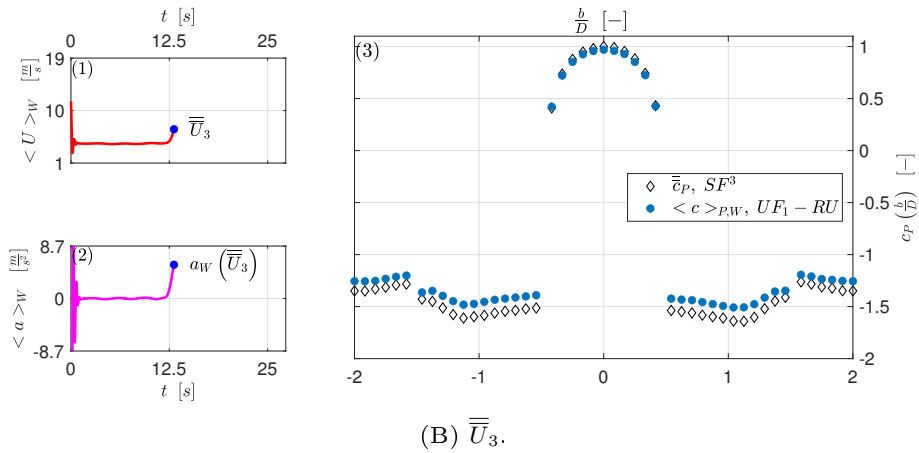
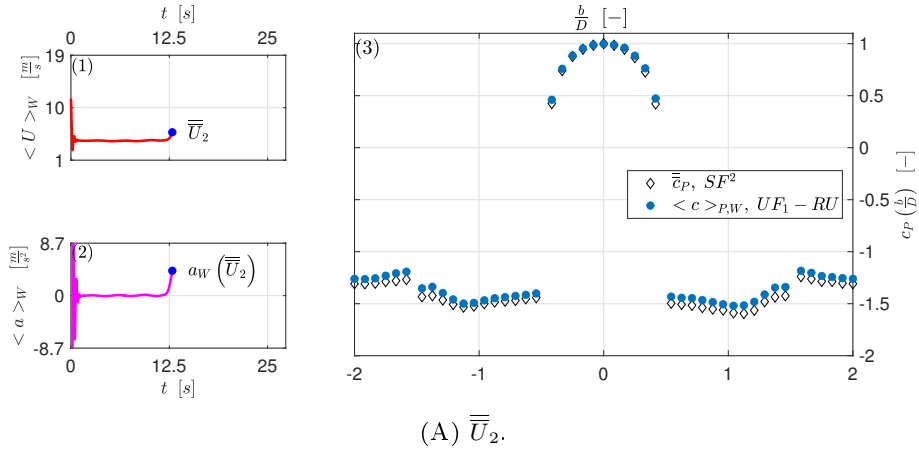
7.3.3 Mean pressure coefficient distribution

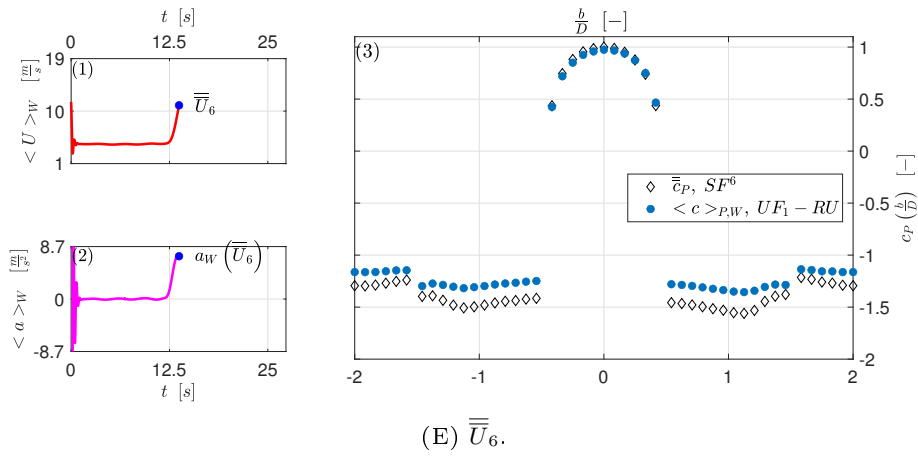
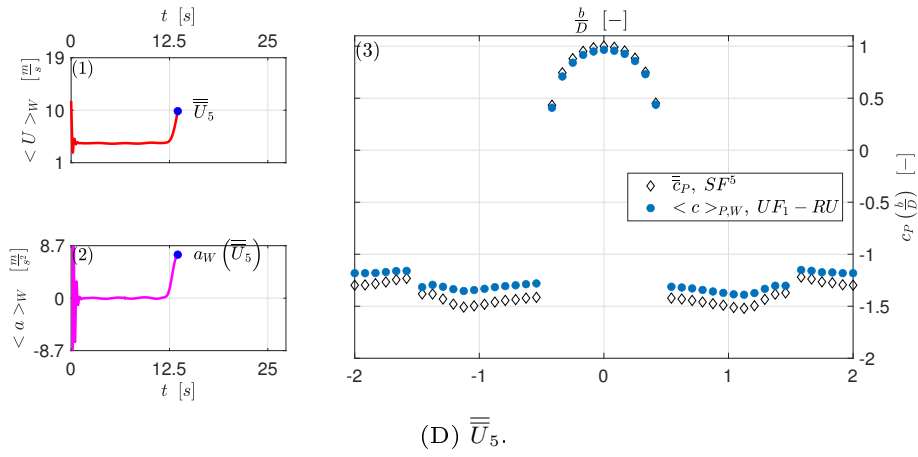
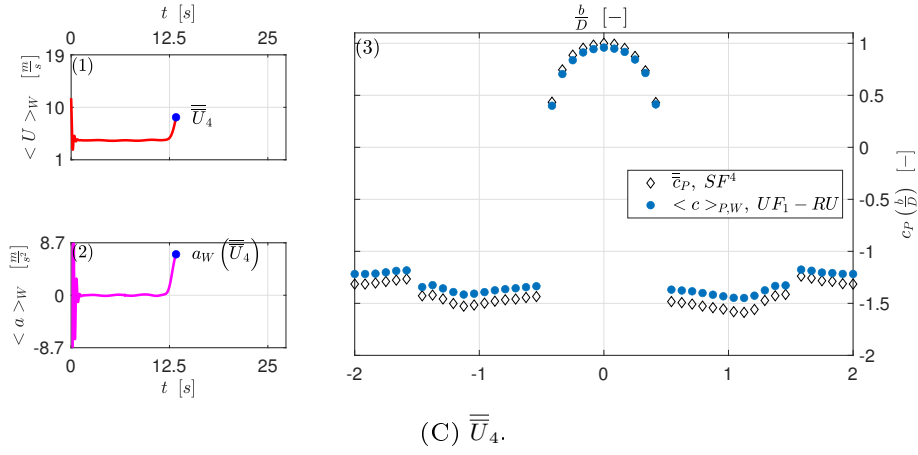
If, in the previous section, only the results of four (representative of six) mean pressure coefficients have been displayed, the entire group of taps of the mid-span section is herein investigated. At variance with the previous section, the graphs that are shown do not directly enclose the effect of the acceleration, but show mean pressure distributions evaluated as an ensemble mean of instantaneous states in unsteady conditions, which are then compared with the ones obtained during the steady conditions (Section 7.1.2). The appropriate steady condition depends on the selected reference mean wind velocity.

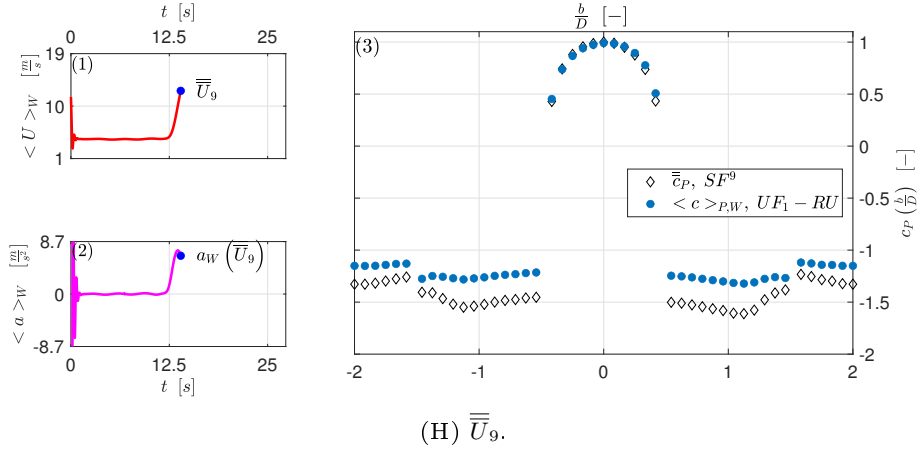
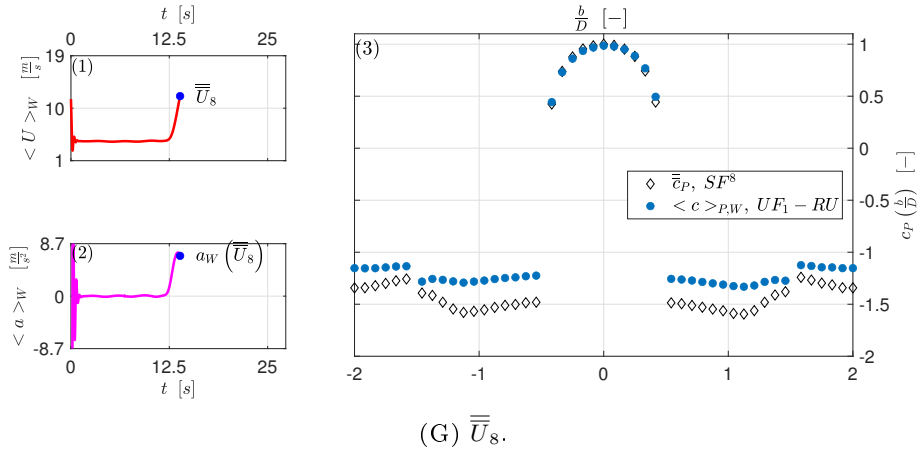
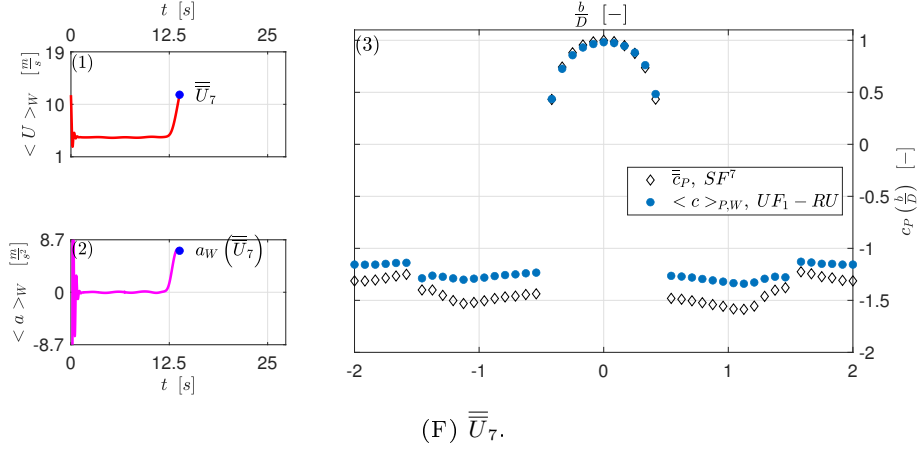
The section is structured as follows: firstly the results of UF_1 for each of the ten velocities up- (or down-) crossed during the ramp are reported, and secondly selected comparisons for the other tests are shown.

Test UF_1

Starting with UF_1 , Figure 7.49 and Figure 7.50, show the comparison between the pressure distributions, respectively for the ramp-up and the ramp-down conditions. Each figure contains 10 different sub-plots, since the comparison can be made for each reference wind speed which is up- (or down-) crossed in the ramp. Each of the ten sub-plots is structured as follows: (1) reports the time history of the ensemble mean of U ; (2) displays the ensemble mean of the acceleration a_W . In both (1) and (2), a blue dot stops the time history and indicates that the point of interest is reached ($\langle U \rangle_W = \bar{U}_k$, for $k = 2 - 11$, and the corresponding value of $\langle a \rangle_W$). The information contained in (1) and (2) serves to support what reported in (3), which endows the steady references with black open diamonds, overlapped by solid blue dots which, instead, indicate the ensemble mean of the distributions in unsteady conditions. Focusing on Figure 7.49, reading from top to bottom allows the evolution of the pressure distribution under the effect of an increasing velocity to be followed. The acceleration increases in the first 4 sub-plots (Figure 7.49A, 7.49B, 7.49C and 7.49D), while it descends for the other plots (Figure 7.49E, 7.49F, 7.49G, 7.49H, 7.49I and 7.49J).







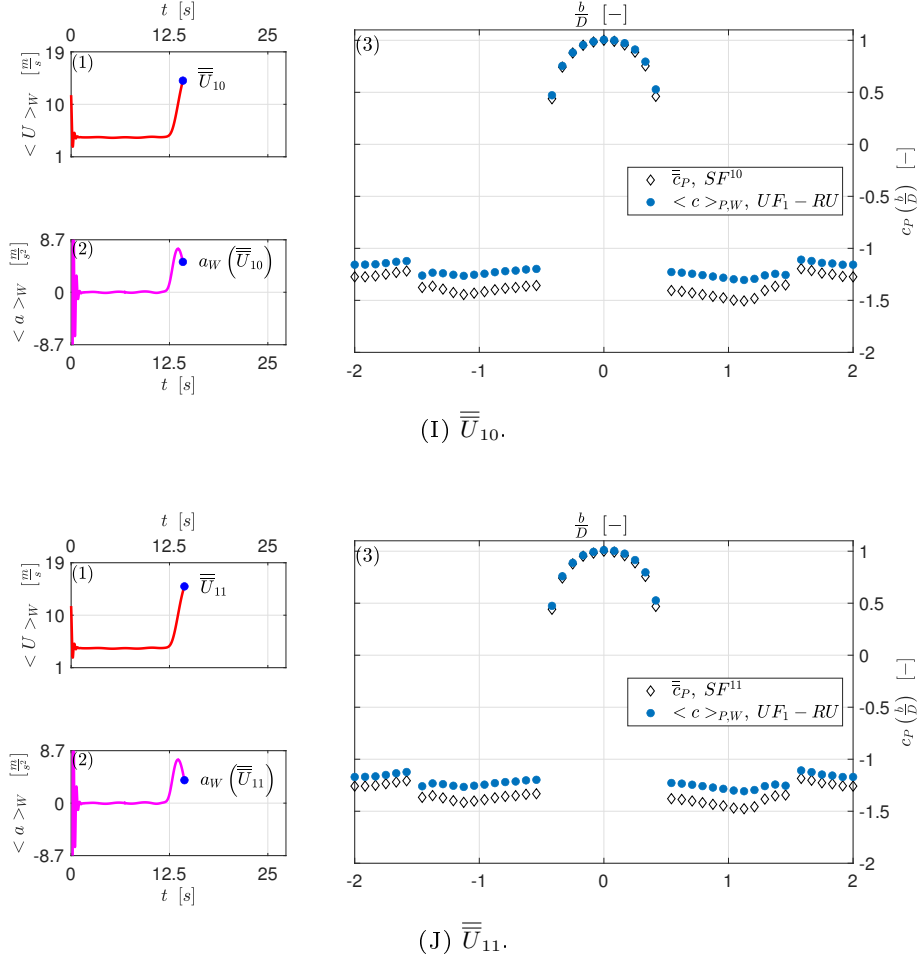
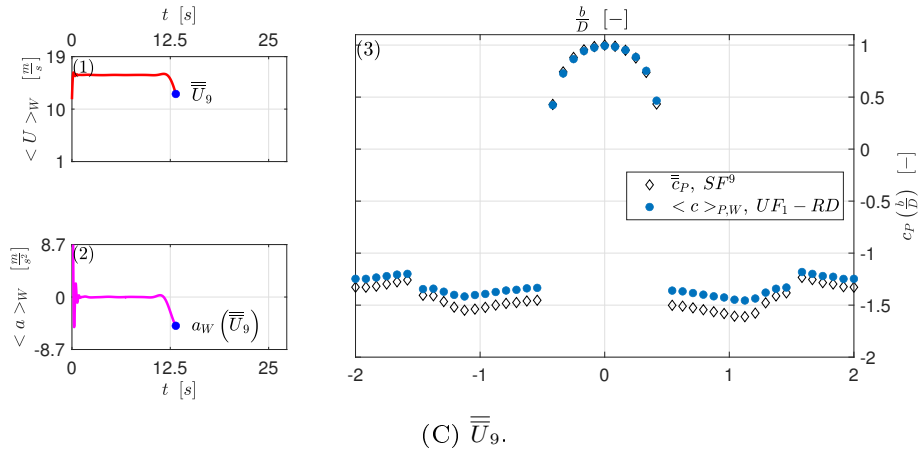
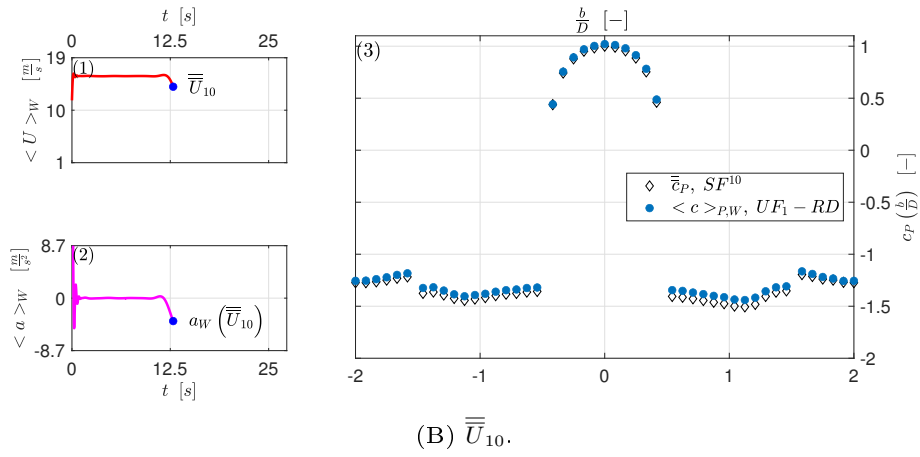
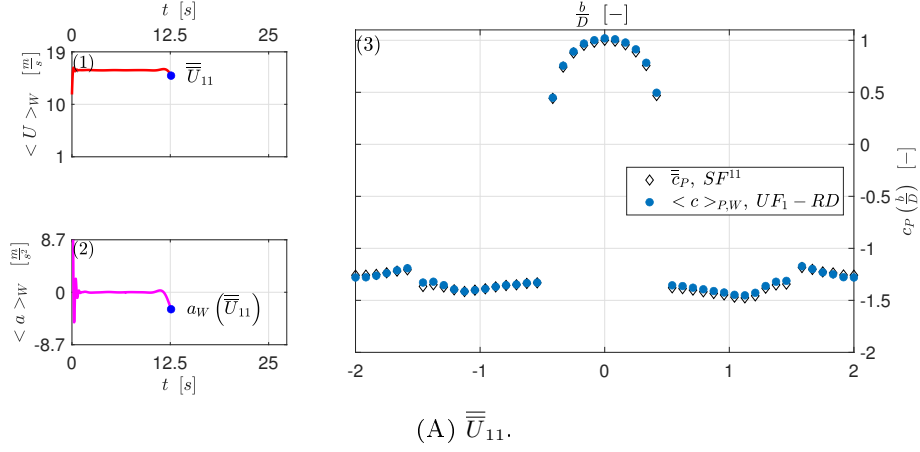
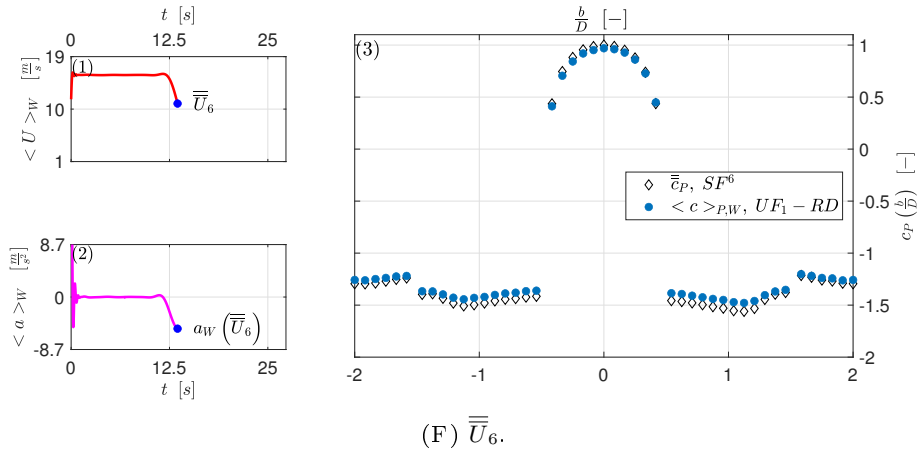
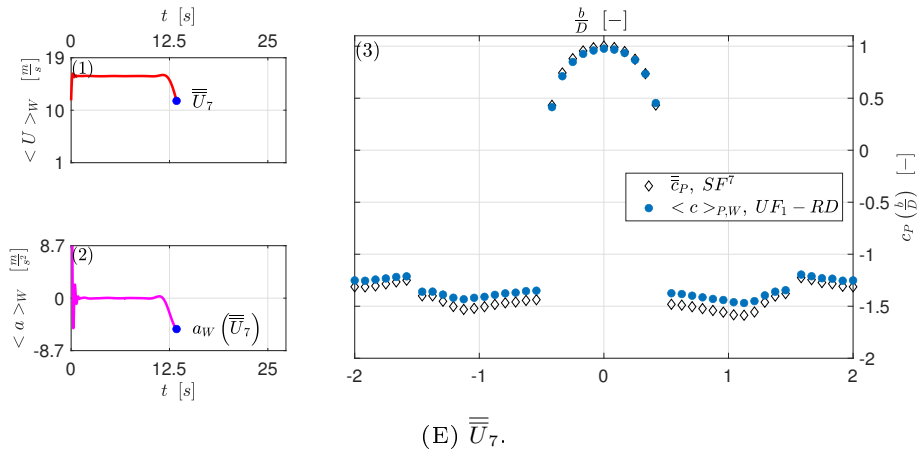
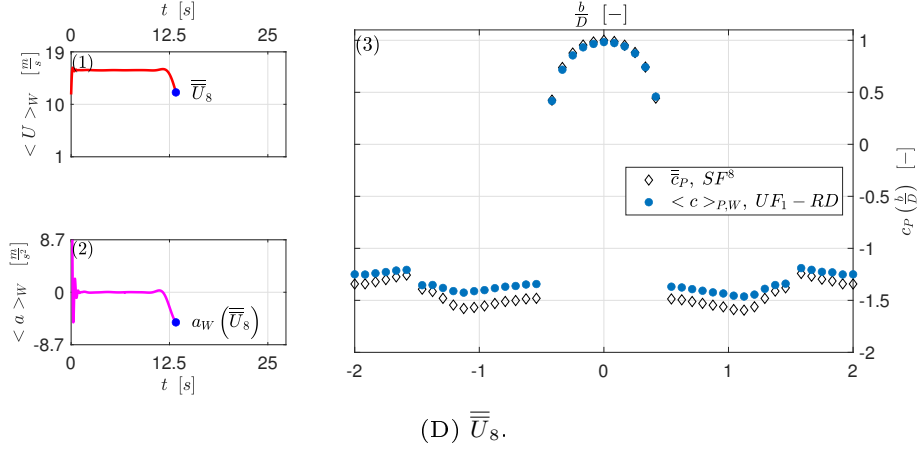
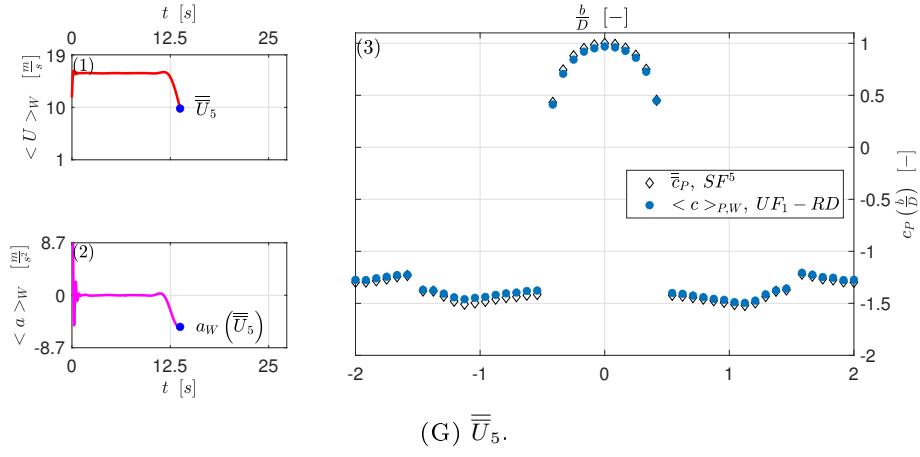
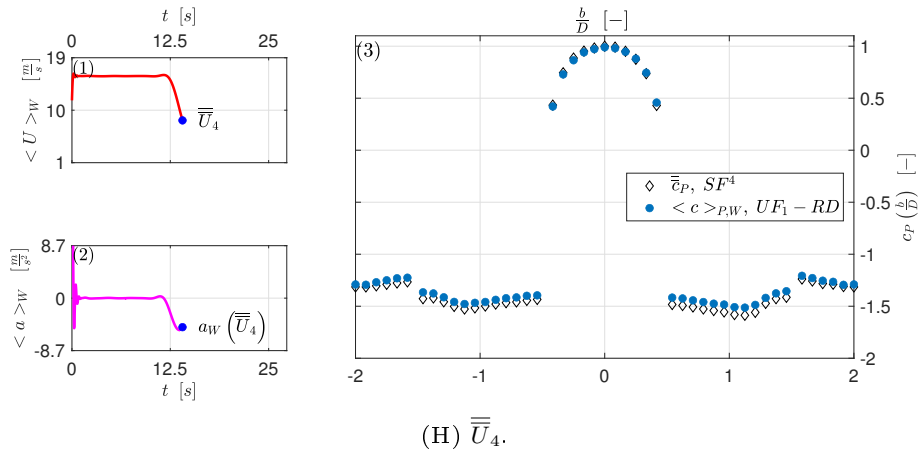
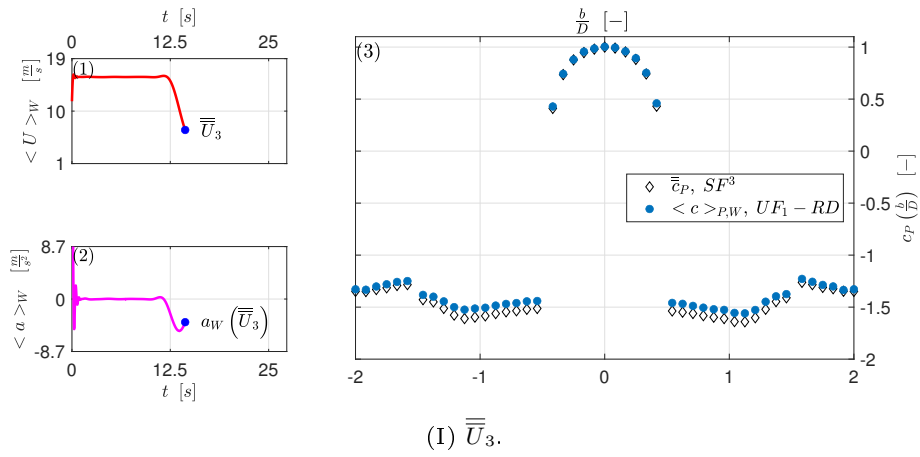


FIGURE 7.49: Comparison between the mean pressure coefficient distributions in unsteady (ramp-up) and steady conditions for UF_1 ; (1) $\langle U \rangle_w$, (2) $\langle a \rangle_w$, (3) c_p .

Following this path, it is clear that, after an initial state in which the two cases are similar (Figure 7.49A), a growing difference arises, in particular for the leeward and the lateral faces. Indeed, all these parts seem to be subjected to a reduced suction with respect the corresponding steady references. Conversely, the windward face seems well replicated. As already noted for the aerodynamic drag, when the acceleration stops to increase (in correspondence of $\overline{U}_5$, Figure 7.49D), the difference between the distributions keeps increasing, up to the reaching of $\overline{U}_8$. Eventually, in the last part of the ramps, the differences are lowered (Figure 7.49J). Analogously, Figure 7.50 shows the comparisons between the mean pressure coefficient distributions evaluated in steady conditions with the ones extracted during the ramp-down. Also in this case, it is possible to follow the evolution of the flow deceleration from top to bottom, browsing from the first reference (SF^{11} , Figure 7.50A) to the last one (SF^2 , Figure 7.50J).





(G) $\bar{U}_5$.(H) $\bar{U}_4$.(I) $\bar{U}_3$.

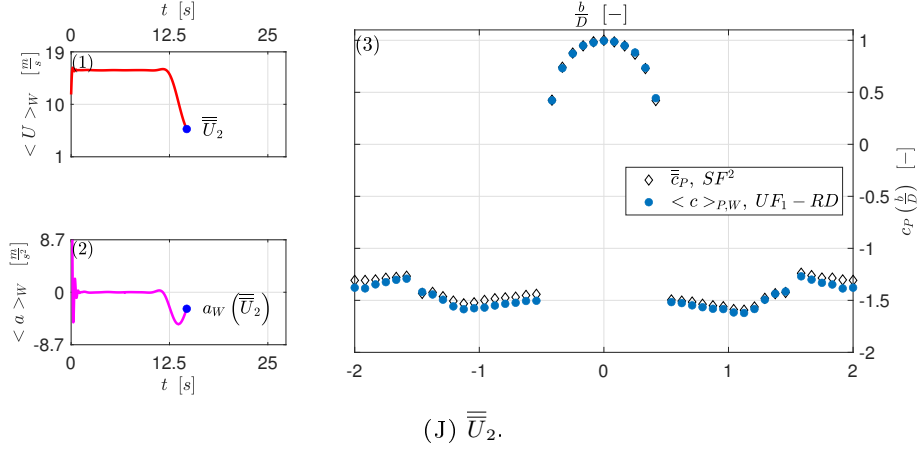


FIGURE 7.50: Comparison between the mean pressure coefficient distributions in unsteady (ramp-down) and steady conditions for UF_1 ; (1) $\langle U \rangle_W$, (2) $\langle a \rangle_W$, (3) c_P .

Also in this case, the first plot (Figure Figure 7.50A) represents two similar distributions. Nonetheless, as soon as the deceleration grows (Figure 7.50B, 7.50C, 7.50D, 7.50E), discrepancies arise and all the taps in the leeward and in the lateral faces become subjected to a lower suction. The distribution which undergoes the highest discrepancy with the steady case is in Figure 7.50D, which anticipates the highest deceleration. From that state on, the base pressure is recovered, reaching $\bar{U}_2$ with a limited decrease with respect the steady flow. This again seems coherent with what found concerning the aerodynamic drag. Figures 7.49 and 7.50, in their whole, offer the opportunity to make some considerations. Firstly, the highest discrepancies between distributions in unsteady and steady conditions are found in correspondence of high level of acceleration or deceleration. Actually, during the ramp-up, the maximum acceleration anticipates the largest discrepancy, whereas in the ramp-down the opposite behaviour is observed. Differences seem to become negligible for low values of the accelerations. Furthermore, higher discrepancies are found in the ramp-up, highlighting a non-symmetric behaviour between positive and negative accelerations. Both these findings are in agreement with what expressed in Section 7.3.1 for the aerodynamic drag, and in Section 7.3.2 for $C18$, $C23$ and $C29$. Therefore, it seems now possible to claim that the effect of the acceleration is of great interest for the measurements of the entire set of taps on the leeward and on the lateral faces.

Influence of U_{low}

Concerning the influence of U_{low} , Figure 7.51 shows the comparison between four different pressure distribution gathered analysing UF_1 , UF_2 , UF_3 and UF_4 and its steady counterpart. The first four are all selected by imposing $U_W = \bar{U}_8$, while the last quantity comes from SF^8 .

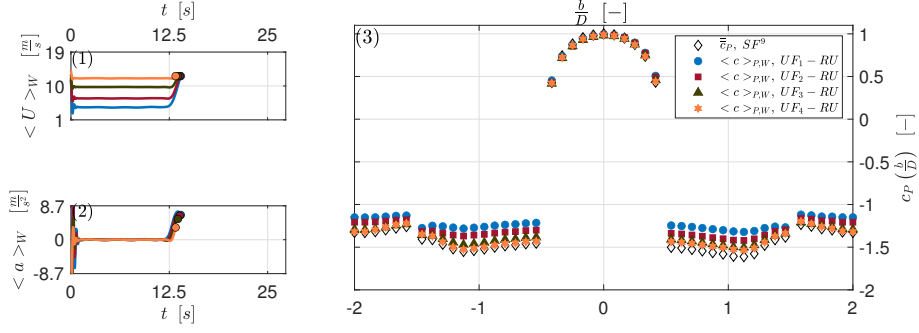


FIGURE 7.51: Comparison between the mean pressure coefficient distributions in unsteady (ramp-up, UF_1 , UF_2 , UF_3 and UF_4) and steady conditions (SF^9); (1) $\langle U \rangle_W$, (2) $\langle a \rangle_W$, (3) c_P .

Each of the different unsteady tests, as explained in Section 7.3.1, reaches the reference wind velocity $\overline{U}_9$ with a different acceleration (as reflected by the sub-plot (2)). In particular, $\langle a \rangle_W (\overline{U}_9)$ is equal to 6.39, 6.16, 5.33 and 3.10 $[\frac{m}{s^2}]$, respectively for UF_1 , UF_2 , UF_3 and UF_4 . The trend is an increasing rise of the base pressure for tests which start from lower U_{low} and, consequently, higher accelerations. The case of UF_4 seems close to the steady reference. This is in agreement with what illustrated before (Section 7.3.1).

Influence of U_{high}

To show the effects associated with U_{high} on the pressure distribution, Figure 7.52 proposes a comparison between the pressure distribution of UF_2 and UF_5 , in correspondence of $\overline{U}_7$, down-crossed during the flow deceleration. While for UF_5 that velocity represents almost the beginning of the ramp-down, UF_2 down-crosses $\overline{U}_7$ with an already quite remarkable deceleration.

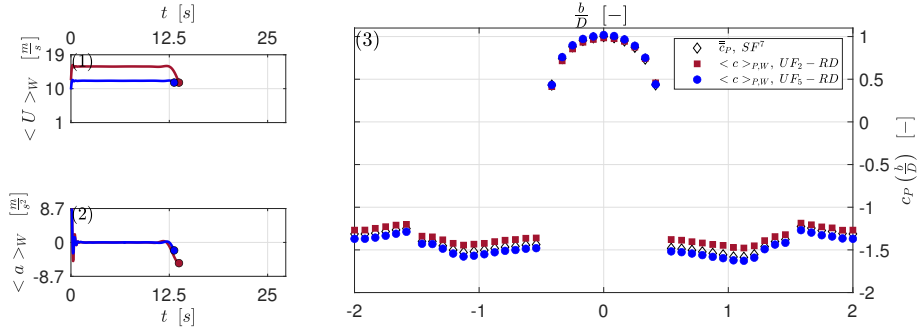


FIGURE 7.52: Comparison between the mean pressure coefficient distributions in unsteady (ramp-down, UF_2 and UF_5) and steady conditions (SF^7); (1) $\langle U \rangle_W$, (2) $\langle a \rangle_W$, (3) c_P .

It appears that the case of UF_5 presents a higher suction throughout its perimeter in the afterbody, which is in close agreement with the steady reference. On the other hand, UF_2 presents a drop of the suction in the leeward and lateral faces, as noted for UF_1 . This result seems again in agreement with what presented in Section (Section 7.3.1).

Influence of $\Delta\tau$

According to Section 7.3.1, the choice of $\Delta\tau$ has been revealed as not crucial for the aerodynamic drag, since the results of tests which differ for the adoption of $\Delta\tau$ only appear similar. Focusing on one of the three examples shown there, this Section shows a comparison (Figure 7.53) between pressure distributions of UF_1 and UF_6 , for a selected reference mean wind speed, $\bar{U}_9$. In the same plot, the steady reference from SF^9 is indicated in black.

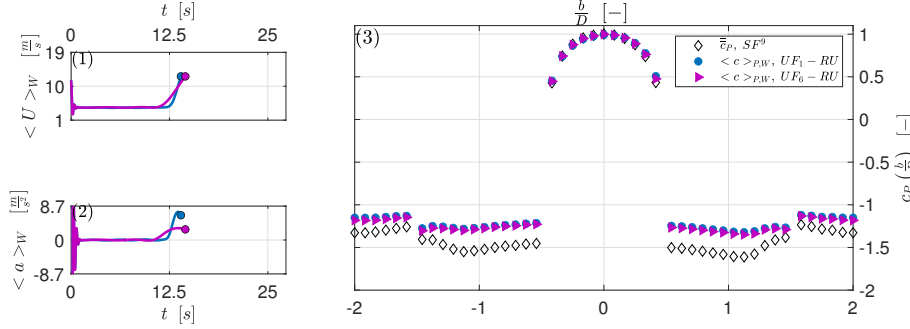
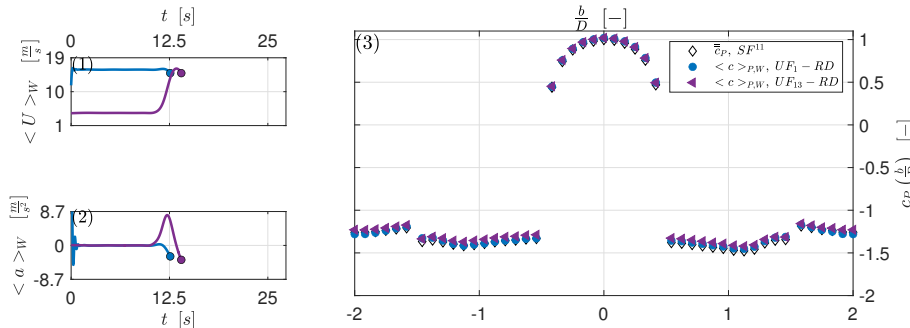


FIGURE 7.53: Comparison between the mean pressure coefficient distributions in unsteady (ramp-up, UF_1 and UF_6) and steady conditions (SF^9); (1) $\langle U \rangle_w$, (2) $\langle a \rangle_w$, (3) c_p .

The result enclosed in the plot confirms the finding concerning the aerodynamic drag. In fact, it seems almost impossible to distinguish between the two sets of data, since they basically present the same increase of pressure with respect the steady reference. This variance compared to the steady case appears then more related to the difference between U_{low} and U_{high} , rather than being related to the associated acceleration.

Influence of T_b

Finally, focusing on the parameter T_b , Figure 7.54 shows the comparison between selected pressure distributions of UF_1 and UF_{13} and the corresponding steady references. In particular, Figure 7.54A shows this in correspondence of $\bar{U}_{11}$, while Figure 7.54B extracts data for $\bar{U}_2$. They respectively represent the first and the last available references in the ramp-down. According to Figures 7.37 and 7.39, the base pressure of UF_{13} is expected to be higher than what occurs for UF_1 .



(A) Comparison in correspondence of $\bar{U}_{11}$ (steady reference is SF^{11}).

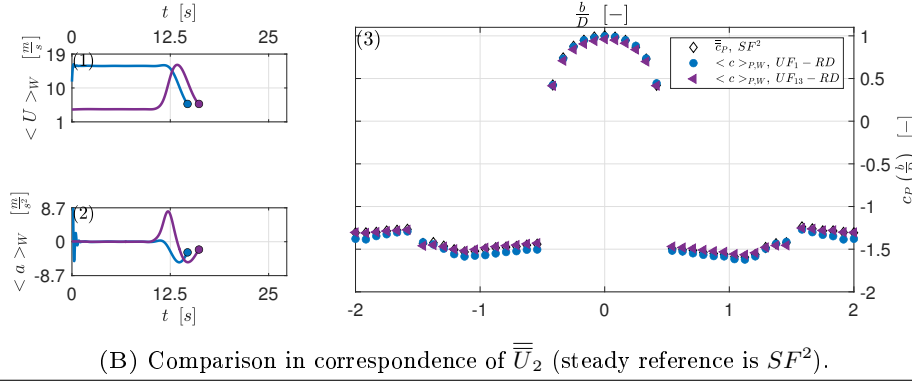


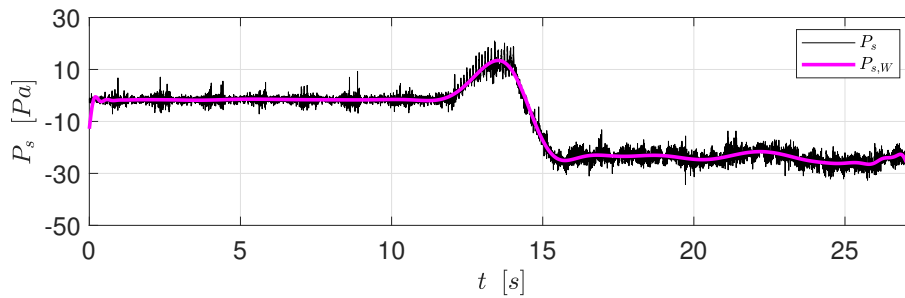
FIGURE 7.54: Comparison between the mean pressure coefficient distributions in unsteady (ramp-down) and steady conditions (UF_1 and UF_{13}); (1) $\langle U \rangle_W$, (2) $\langle a \rangle_W$, (3) c_P .

The pictures, in particular Figure 7.54B, seem to confirm this remark. Nevertheless, the discrepancies are not much pronounced.

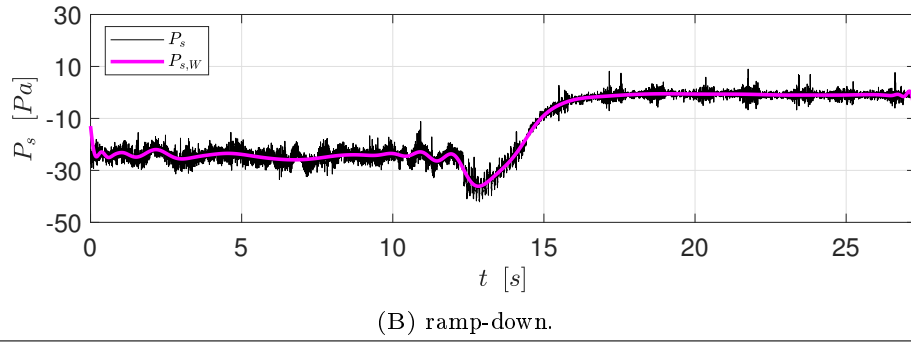
7.3.4 Static pressure

This section deals with a peculiar aspect that has been observed during the performing of the unsteady flows, namely the variation of the static pressure induced by the acceleration or the deceleration. This quantity (P_s) has been observed to decrease in steady flows with the velocity (Table 6.3). On the other hand, during unsteady tests, evident jumps have been noted from its recordings, clearly traceable to the acceleration or the deceleration. This Section is devoted to show two examples selected from the test UF_1 , particularly from one of its repeats. Subsequently, a quantification of the discrepancies between the estimated static pressure in steady and unsteady conditions for all the reference wind velocities is reported. What is observed concerning the static pressure is finally employed to investigate other signals, particularly the pressures acquired by selected taps, the same of Section 7.3.2, without removing their static component.

Figure 7.55 shows the variation of the static pressure P_s and its slowly-varying mobile mean $P_{s,W}$ for one repeat of UF_1 . The ramp-up is shown in Figure 7.55A, while the ramp-down is in Figure 7.55B). It both cases, it is possible to appreciate an abrupt change of the time-history, clearly induced by the acceleration or deceleration.



(A) ramp-up.

FIGURE 7.55: Variation of the static pressure from one repeat of UF_1 .

To shed lights on this subject, a clearer plot is proposed in Figure 7.56, which indicates in black the static pressure $\overline{P}_s$ for the whole set of mean wind speed. It basically converts the numbers of Table 6.3, averaging between $P2$ and $P3$, in a plot. Moreover, the blue and red lines, respectively, draw the corresponding values measured during the ramp-up and the ramp-down. On one hand, it is important to remark that these absolute quantities cannot be considered as suitable references, since they are dependent on the condition of the room where the reference pressure is measured, at variance with the evaluation of the dynamic pressure (i.e. ΔP_D). On the other hand, these values are found when unsteady flows are simulated immediately following the steady ones, so for the same conditions of the adjacent room. These differences appear quite large. For instance, the value in correspondence of $\overline{U}_3$ is $-2.86 [Pa]$ in steady conditions. During the ramp-up, the ensemble mean of P_s evaluated for $U_W = \overline{U}_3$ is $11.3 [Pa]$, whereas for the ramp-down it drops to $-17.0 [Pa]$.

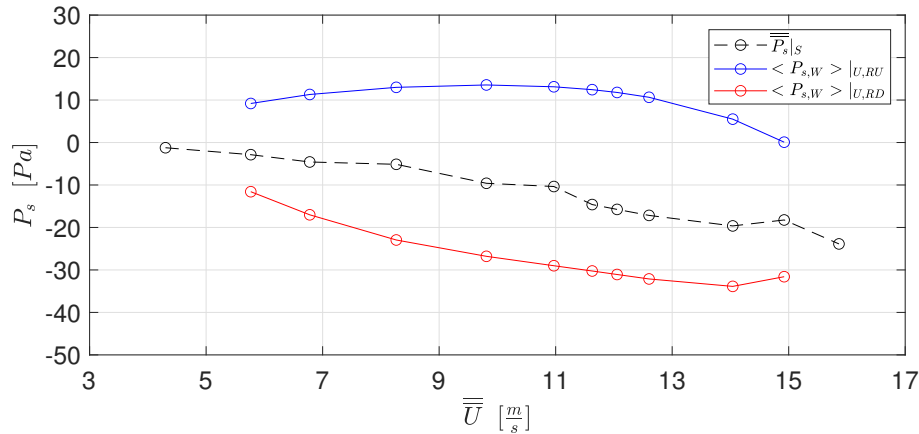


FIGURE 7.56: Static pressure in steady and unsteady conditions.

A similar finding is obtained also when analysing the pressures read by the same selected taps listed in Section 7.3.2, which exhibit large differences between the two conditions. It seems possible now to describe the ratio between the quantities in unsteady and steady conditions following what illustrated for the aerodynamic drag or the mean pressure coefficients, hence with a ratio between the two cases. In doing so, the abscissa is replaced by indicating the acceleration number $K_{a,W}$. The results (Figure 7.57) seem to show a good trend, which reveals an almost linear dependence of the ratios on $K_{a,W}$. Figure 7.57A, 7.57B, 7.57C, 7.57D, 7.57E respectively show the trends for $C06$, $C18$, $C23$, $C29$ and P_s .

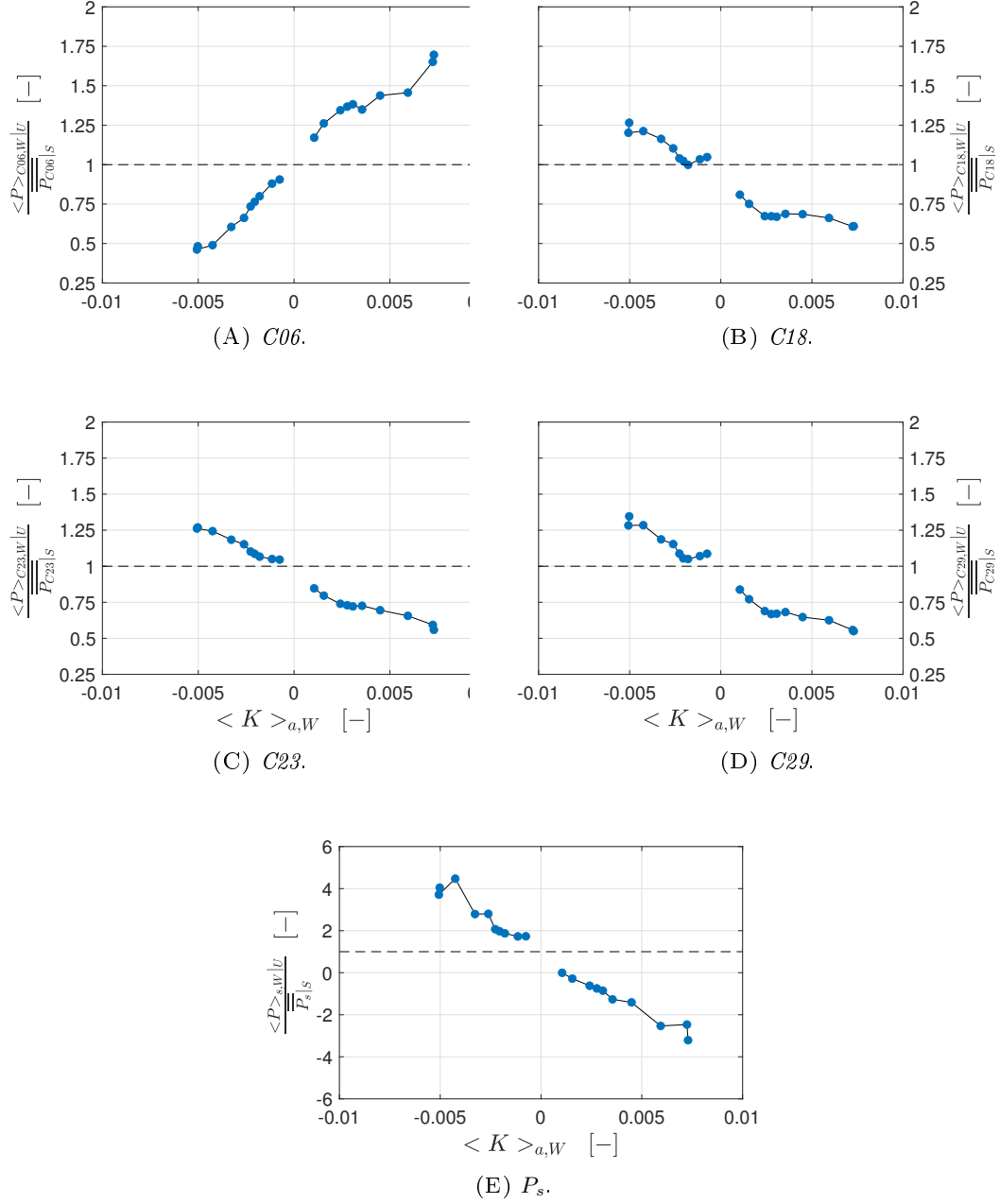


FIGURE 7.57: Comparison between the selected pressures in unsteady and steady conditions against the acceleration number $K_{a,W}$ (UF_1).

Other comparisons, taking the variation of the parameters U_{low} , U_{high} , $\Delta\tau$, T_b into account (following the scheme traced in Chapter 6), are presented in Appendix G, Section G.1. All the results presented there seem to confirm a linear dependence of the quantities on $K_{a,W}$. The behaviour here observed for the static pressure does not constitute an exception in the literature concerning accelerating flows. Indeed, it has been recently reported by (Koliyabandara and M. S. Mason, 2019), analysing the data acquired in the suction wind tunnel of the University of Queensland. Moreover, also (Shirato et al., 2009) showed the variation of the static pressure induced by the acceleration generated by a opening shutter. Both these cases depict a reduction of the static pressure, while an increase is observed in the MFWT-TKU (which is a blower wind tunnel). The reason of this discrepancy may be found in the different nature of the experimental facilities.

7.4 Discussion on the adopted methodology

This Section aims to cross-check some of the results which have been obtained in the previous part of the Chapter, with particular concern with the aerodynamic drag. This is firstly pursued by comparing the estimation of $c_{D,W}$ obtained in Section 7.3.1 and what can be obtained from integrating the mean pressure coefficients $\langle c \rangle_{P,W}$. This is herein presented for UF_1 . So, Figure 7.58 shows the comparison, reporting in abscissa the reference mean wind speed $\bar{U}$ of interest. The blue line is the mean drag coefficient that is obtained following the procedure described in Section 7.4, while the red line reports the integration of the mean pressure coefficients (in the legend, the text $f = \langle c \rangle_{P,W}$ means function of $\langle c \rangle_{P,W}$). The black dashed line links the values associated with the steady flows. The ramp-up is studied in Figure 7.58A, while the ramp-down is investigated in Figure 7.58B.

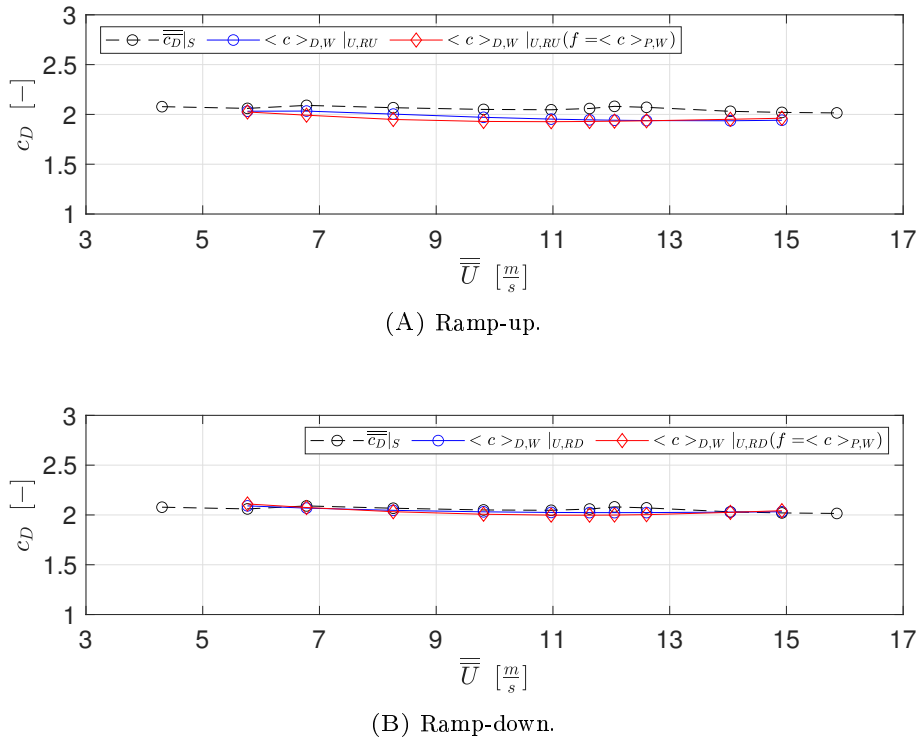
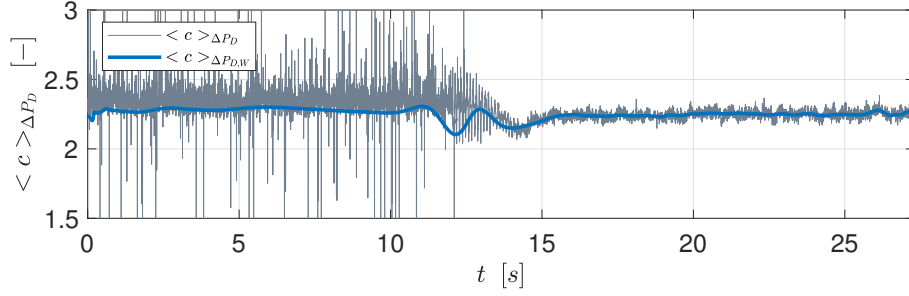


FIGURE 7.58: Comparison between the mean drag coefficient in transient conditions $\bar{c}_{D,W}$ obtained by employing different methods (UF_1).

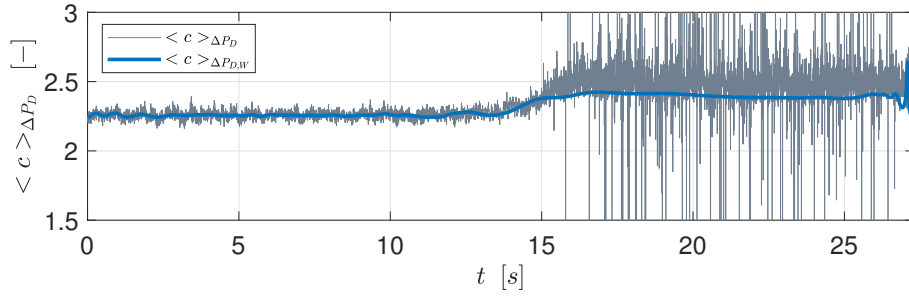
Commenting the ramp-up, by inspecting Figure 7.58A it seems that the two trends are quite similar. In particular, the estimation through the mean pressure coefficients seems to lead to a slightly higher reduction of the aerodynamic drag, especially for the first part of the ramp. The results become almost coincident for the last part of the flow acceleration, where the accuracy of the instrumentation is higher. Moving to the ramp-down, Figure 7.58 shows two similar lines, which differ for limited values. Therefore, it seems possible to claim that the two methods lead to close results, which are indeed coherent. The cases of UF_2 , UF_3 , UF_4 and UF_6 are reported in Appendix G, Section G.2, and highlight an improvement of the matching between the two methods for higher magnitudes of U_{low} .

Another possible comparison which can be made is here presented. In Chapter 6, it has been mentioned that the ensemble mean of the resistance coefficient $c_{\Delta P_D}$ is hardly usable for understanding the effects of acceleration, since the influence of turbulence seems to prevent the formation of a regular trend. However, this quantity may still be used for a comparison with the trend of the ensemble mean which comes out from the filtering through CWT ,

$\langle c \rangle_{\Delta P_D, W}$. This is accomplished in Figure 7.59, where $\langle c \rangle_{\Delta P_D}$ is drawn in grey and $\langle c \rangle_{\Delta P_D, W}$ is in blue.



(A) Ramp-up.



(B) Ramp-down.

FIGURE 7.59: Comparison of the ensemble mean of the resistance coefficient $c_{\Delta P_D}$ and of its filtering through *CWT* $c_{\Delta P_D, W}$ (UF_1).

Both graphs show a good agreement when the wind speed is high, so in the second part of the graph for Figure 7.59A, and in the first for Figure 7.59B. Conversely, the estimation through the *CWT* filtering seems to slightly underestimate the coefficients for the low wind speed. As for the previous analyses, the situation easily improves when U_{low} is higher (see Appendix G, Section G.2).

7.5 Conclusions

This chapter has presented the first batch of results of the wind tunnel test campaign, which mainly concerns the aerodynamic drag and the mean pressure coefficient distribution. The evaluation of these quantities for steady flows is straightforward, being directly found through temporal mean of an adequate number of repeats. This allows the steady references to be defined, in terms of reference wind speed, mean resistance and drag coefficients, and mean pressure coefficients. Conversely, to estimate these quantities in unsteady conditions, it is not possible to proceed with classic temporal means of time histories, but it is necessary to analyse ensemble means of an adequate number of repeats. On top of that, because of the turbulence present in the wind tunnel, it has been necessary to firstly carry out a filtering of the signals. This tailored technique has allowed suitable signals to be defined, for the reference dynamic pressure, the static pressure and the loads (a general term to indicate the whole set of pressures), which can be easily inspected. In particular, the signal of the reference wind velocity is explored, seeking the indexes which identify when it crosses certain reference values, defined under steady flows conditions. These time instants are employed to find the corresponding loads, which are selected and compared to the steady reference values. Summarising these outcomes, the main result is a reduction of the aerodynamic drag, both for the ramp-up and

ramp-down conditions. This would never have been predicted by studying Eq. 7.4 or Eq. 7.5, introduced in Chapter 5, which permit to evaluate the force in the alongwind direction acting on a body subjected to a one-directional accelerating flow. In fact, from these relations a reduction is expected for the ramp-down only, whereas for the ramp-up the opposite result is foretold. Moreover, when filling these equations with the numbers relevant to one of the unsteady flow pressure tests (UF_1), it turns out that the effects induced by acceleration should be negligible and not appreciable from the available instrumentation. Conversely, the same test UF_1 exhibits remarkable reductions of the aerodynamic drag, up to 8 % and 4 %, for the ramp-up and the ramp-down, respectively. These variations are associated with a loss in terms of pressure difference between front and rear surfaces of the model in the order of 10 - 15 [Pa] (working on ΔP_D), for which the tolerance of the pressure transducers cannot be responsible. Therefore, the discrepancies here observed have to be related to a variation of the aerodynamic drag, induced by the effects of the acceleration. In fact, when plotting the reduction of the aerodynamic drag against the acceleration (Section 7.3.1), a trend is clearly evident. This implies a consistent reduction of the aerodynamic drag for higher acceleration or deceleration. This loss might perhaps be related to vortex-shedding. In fact, it is well-known in the literature that the aerodynamic drag is a function of this phenomenon. Under steady flow conditions, a fully-developed wake has the time to be originated and formed, being constituted of vortices with a certain intensity and configuration. This allows the resistance mechanism to be activated, defining the corresponding aerodynamic drag. When instantaneously up-crossing or down-crossing the same velocity, the wake has no time to assume the same configuration. The (instantaneous) configuration of the vortices is probably different, as is their intensity, and this might well prevent the same aerodynamic drag of the steady conditions to be achieved.

It has also been observed that the trend is evidently non-symmetric. Indeed, the drop of the aerodynamic drag is much enhanced for positive accelerations, up to 8 %, while a reduction of 4 % is achieved during the flow deceleration. Another interesting outcome offered by the analysis of UF_1 concerns the non-simultaneous occurrences of the maximum drop of the aerodynamic drag with the maximum acceleration or deceleration. In particular, in the ramp-up, the peak of the acceleration anticipates the highest reduction of drag force, whereas in the ramp-down the opposite happens. In both cases, the most remarkable drop of the aerodynamic drag occurs for a negative derivative of the acceleration. The whole of these facts highlights the presence of fluid-memory effects characterising the phenomenon, which becomes dependent on previous states. The entire memory of the fluid is concentrated in its vorticity field, which, in unsteady conditions, is linked to many different states. Therefore, these may disturb the actual state, whose aerodynamic drag is affected by previous cases. The present results seem to confirm that the acceleration is indeed connected with the fluid memory effects.

The next step has been to study selected mean pressure coefficients (in particular, C_{18} , C_{23} and C_{29} , Section 7.3.2), whose trend is found to be qualitatively coherent to the one of the aerodynamic drag. The mean pressure coefficients seem to quantitatively undergo the effects of the acceleration in different ways, depending on their position. C_{29} , strictly representative of the base pressure, experiences an increase up to 15 %. C_{18} and C_{23} , located on the upper lateral face, show growths up to 19 % and 8 %, respectively, and this different behaviour might well be associated with the different level of interference with the edge and the wake downstream. Additionally, this trend has also been noted by analysing the entire set of taps of the mid-span section (Section 7.3.3); indeed, the highest discrepancies compared to the steady references are found for high levels of acceleration or deceleration, which appear to erode the suctions experienced by the whole afterbody, suggesting again a weakening of the vortex shedding and a reduction of the aerodynamic drag. The same graphs indicate a modest decrease of the base pressure in correspondence of the end of the ramp-down, which might

justify an increase of the aerodynamic drag. This phase is associated with the most negative values of the acceleration parameter, which might support this small overshooting. Also the distribution relevant to the first reference wind velocity down-crossed in the ramp-down exhibits a slight decrease of the base pressure, probably still associated with the wind field of U_{high} and not still influenced by a (still) small value of the acceleration.

Starting from these results, concerning the test UF_1 , the dependence on the parameters introduced in Chapter 6 is deepened, firstly concerning the aerodynamic drag and, secondly, with regard to the pressure coefficients. The effect of a different U_{low} , higher compared to UF_1 , induces profound effects on the results in the ramp-up, since the reductions are strongly mitigated. Furthermore, an increase of U_{low} seems to be reflected also into a recovering of a symmetric trend between ramp-up and ramp-down. The presence of fluid-memory effects seems to be evidently pointed out by Figure 7.30, which reports a non-dimensional mean acceleration in the abscissa axis. This perhaps better clarifies that the evolution of the aerodynamic drag of the body is a function of previous states, and is different from test to test.

Concerning the effects of U_{high} , the comparison between UF_2 and UF_5 again shows results which well compare on the acceleration axis. In particular, UF_5 exhibits mitigated effects.

As for the influence of the variation of $\Delta\tau$, the trends of the single tests appear to be coherent with the acceleration, as noted for UF_1 . However, when comparing UF_1 with UF_6 , UF_2 with UF_7 , UF_3 with UF_8 and UF_9 , the maximum reductions of coefficient are similar, in spite of the difference of acceleration. In particular, it has been observed that the ruling parameter concerning the maximum reductions of the aerodynamic drag is the difference between U_{high} and U_{low} . In fact, by plotting the maximum reductions against it, the graph exhibits a regular pattern, which appears not to be a function of the acceleration. Finally, focusing on T_b , its effects appear to be modest, but present. Indeed, a smaller value of T_b (UF_{11} , UF_{12} and UF_{13}) seems to affect the aerodynamic drag of states of the ramp-down, particularly the ones at the beginning of the ramp-down and the ones approaching its end. Some differences are found in the ramp-up as well, but a trend is not clear.

The analyses of the data coming from the pressure coefficients show trends which are in agreement with the aerodynamic drag, leading to similar findings. In the same way, the associated distributions of the mean pressure coefficients still appear to reflect the trend of the drag and resistance coefficients.

On the whole, the results seem coherent with the paper by Yang and Mason (Yang and Matthew S. Mason, 2019), who mention a reduction of the drag coefficient of about 10 %, and indicate the possibility of overshooting the steady loads (for ramp-up only) as unlikely. The magnitudes of the acceleration number are comparable to the ones reported here, while the accelerations are in general higher (up to $15 \left[\frac{m}{s^2}\right]$).

