Temporal resolution of time-resolved tomographic PIV in turbulent boundary layers

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Abstract The spectral characterization of turbulent boundary layers by time-resolved PIV poses strict requirements on the measurement temporal resolution. The present work focuses on the use of time-resolved tomographic PIV to estimate velocity power spectral density in turbulent flows. First, a discussion is given on the theoretical response of the PIV measurement technique to temporal fluctuations. The analysis includes the simple approach, based on the cross-correlation between a single pair of images and the more advanced technique based on Fluid Trajectory Correlation. For a given sampling rate, the temporal filtering is most critical for a pulsatile flow and the least for advected turbulence.

A direct numerical simulation of a turbulent boundary layer is used to simulate time-resolved tomographic PIV experiments and the spectral response of the measurements in comparison to the ground truth given by the numerical solution. The spectral response of PIV is estimated by the ratio between the measured to the exact power spectral densities. The effect of reconstruction noise is greatly reduced when moving from the single-pair analysis to the fluid trajectory correlation approach, with no reduction in temporal response. However, spatial resolution maintains its major role in determining the errors due to spatial modulation of unresolved length scales.

1. Introduction

The literature devoted to characterize the PIV measurement technique is abundant with studies related to its spatial resolution. Effects related to the imaging system, interrogation window size, weighting functions, and interrogation methods are discussed in detail in many works over the past two decades (Lavoie et al., 2007; Astarita, 2007; Schrijer and Scarano, 2008; Scarano, 2003; Westerweel, 1997; Keane and Adrian, 1992; among others). In contrast, the temporal resolution has not been given the same attention, due in part to the only recent availability of high-speed PIV hardware which enables time-resolved measurements.

1.1 Time-Resolved PIV

The time-resolved measurement regime for PIV (TR-PIV) is a condition where the PIV sampling rate enables time-domain analysis (e.g. time correlation) and description of the spectral content of the fluctuating velocity field. The condition for obtaining time-resolution is that the measurement rate is comparable to the temporal fluctuations occurring in a flow. The reference criterion for temporal resolution and accurate spectral estimates by point-wise measurements is the Nyquist-Shannon sampling theorem (Shannon, 1949). PIV measurements and in particular 3D velocity measurements such as those obtained by tomographic PIV (Elsinga et al., 2006) are based on spatio-temporal information and may be treated differently from pointwise measurements. For instance, in a previous study by Scarano and Moore (2011) it was shown that alias-free spectral estimates of advection-dominated flows can be obtained at measurement rates well below the limit dictated by Nyquist criterion. Another example is the recent fluid trajectory correlation technique (FTC; Lynch and Scarano, 2014), which estimates the velocity based on a Lagrangian tracking of fluid elements in time. Both these examples suggest that successful measurements can be carried out at frequencies below the Nyquist criterion.

Without considering time supersampling techniques (Scarano and Moore, 2011; Schneiders et al., 2014), the appropriate temporal sampling criterion for accurate spectral estimates in turbulent flows has not been extensively studied, and therefore the Nyquist criterion represents the uppermost conservative limit. For aerodynamic problems, it is often very difficult to perform PIV measurements at a rate such that all temporal fluctuations are resolved. The difficulty becomes even greater when tomographic PIV is applied, given the requirements on volume illumination and imaging depth of focus. On the other hand, such measurements are increasingly attempted in order to obtain valuable information on the fluid flow pressure (van Oudheusden, 2013) and for cross-spectra estimates of relevance in aeroacoustics (Probsting et al., 2013).
1.2 TR-PIV motion analysis

An additional difficulty in time-resolved tomographic PIV measurements is the rather small velocity and spatial dynamic range (Adrian, 1997) caused by noise due to tomographic reconstruction as well as the cross-correlation analysis. This has spurred the development of new PIV algorithms specialized for processing image sequences rather than image pairs in order to increase the range of velocities that can be measured. In general, the methods can be broken into two main categories: linear methods are based on the hypothesis of constant velocity during the measurement time interval; as a result the trajectory is approximated by a straight line. Non-linear methods adopt a high-order representation of the motion during the measurement interval. They are based on three or more exposures. Additional details are surveyed in Lynch and Scarano (2013).

The multi-frame technique proposed by Hain and Kahler (2007) is a linear method, which optimizes the velocity dynamic range by an adaptive selection of the time separation between the exposures $\Delta T$. At each location in the measurement domain a pair of images is selected within the sequence such that the particle image displacement is kept roughly uniform. As a result, the relative measurement error is decreased in regions of small displacement.

The sliding average correlation (SAC; Scarano et al., 2010) is a linear method, which locally applies the principle of ensemble correlation (Meinhart et al., 2000) and uses an instantaneous predictor to apply image deformation for the short time interval where correlation maps are averaged (typically 3 to 5). The SAC method was extended with pyramid correlation (Sciacchitano et al., 2012), which applies a combinatorial approach to the correlation signal from all images within a time interval. The resulting correlation planes are rescaled (homothetic transformation) to represent a consistent displacement, and applied as a correction to the linear trajectory.

In both SAC and pyramid correlation, the local fluid trajectory passing through the measurement point is approximated as a straight-line with constant velocity. This is the main limiting factor for extending the total time interval $\Delta T$ over which a fluid element can be tracked. For linearized trajectories, an extension of $\Delta T$ leads to growing truncation errors due to the effect of fluid parcel acceleration (see i.e., Boillot and Prasad, 1996). Therefore careful attention is required in order to optimize the local extension of the measurement interval, leading to adaptive methods (see for instance Hain and Kahler, 2007; Sciacchitano et al., 2012).

The fluid trajectory correlation (FTC; Lynch and Scarano, 2013) is an image sequence correlation-based technique, which tracks the particle pattern corresponding to a chosen fluid element along a nonlinear trajectory. A polynomial model is applied to fit the motion of the parcel within the measurement interval and the properties of the trajectory are obtained. The theoretical background has been described in Lynch and Scarano (2013) and a recent application to the case of a 4-pulse tomographic PIV system for the study of flows in the high-speed regime has been reported (Lynch and Scarano, 2014). An interesting development of the FTC concept, has been the fluid trajectory evaluation by ensemble averaging (FTEE) recently proposed by Jeon et al. (2013). The FTEE approach combines the FTC principle with the correlation averaging from pyramid correlation.

The aforementioned techniques are based on spatial cross-correlation analysis. Other approaches exist based on particle tracking (i.e., Novara and Scarano, 2013; Schanz et al., 2013). However, these techniques are mostly applied to flows in water tunnels where precise control over seeding conditions and high-quality imaging is possible. Because of the current interest in aerodynamic applications in wind tunnels, this article focuses on correlation-based TR-PIV analysis.

The main motivations for this work are to examine the temporal resolution of PIV, clarify the temporal modulation effects that occur applying time-resolved tomographic PIV for the study of wall-bounded turbulence, and determine the effect of advanced analysis algorithms on the temporal response. The first is treated using a simple analytical test case of a convecting sine wave. For the latter two, a direct numerical simulation (DNS) of an incompressible turbulent boundary layer (Probsting et al., 2013) is taken as reference to reproduce a synthetic PIV experiment and compare the spectral estimates with the ground truth.

2. Temporal Response of PIV

An analysis of the temporal response is introduced via a simplified flow model of a travelling sine wave field
within a convecting field. The use of a sine wave is inspired by the widespread use of the spatial sine wave test for determining the spatial response of PIV (see e.g., Scarano and Riethmuller, 2000; Astarita, 2007; Schrijer and Scarano, 2008). Here a travelling sine wave test is considered to account for the unsteady effect caused by convection. Two cases are considered, without and with convection, respectively. The velocity field for the first case (without convection) is described by,

\[ u = 0 \]  
\[ v(t) = v_0 \sin(\omega t) \]

Where the oscillations about a fixed point are described by the angular frequency \( \omega = 2\pi/\tau_{flow} \). The time \( \tau_{flow} \) is the period for one full oscillation of the wave, and \( \Delta T \) is the interval over which the measurement is made. This allows a time ratio \( t^* \) to be established, \( t^* = \Delta T/\tau_{flow} \). Figure 1 gives a schematic description of these quantities. In this case, there is no convection velocity direction around a fixed point. This case may be imagined as produced by a vibrating membrane or a piston or in a resonator cavity (figure 3, left).

The velocity field for the second case (with convection) includes a spatial wave which is convected, and is described by,

\[ u = u_c \]
\[ v(x, t) = v_0 \sin(kx - \omega t) \]

where \( u_c \) is the convection velocity and the wave propagation speed \( u_w \) is specified by the angular frequency \( \omega \). Note that the convection speed does not need to coincide with the speed of the propagating wave; the relation between the convection and wave velocities is given by the velocity ratio \( u^* = u_c/u_w \).

The wavenumber is the inverse of the wavelength \( k = 2\pi/\lambda_x \). The angular frequency is identical to the first case, \( \omega = 2\pi/\tau_{flow} \). The challenge is defining a suitable \( \tau_{flow} \). For this case, \( \tau_{flow} \) is defined as the time required for a wave of speed \( u_w \) to travel a distance \( \lambda_x \), i.e., \( \tau_{flow} = \lambda_x/u_w \).

This scenario physically corresponds to a fluctuation convected at speed \( u_c \), which is also subject to its own motion \( u_w \). For a velocity ratio \( u^* \approx 1 \), this represents purely advected turbulence where the pattern of eddies is transported as ‘frozen’ with very small variations along their transport. This is observed for example, in developed grid turbulence as well as in the low-shear regions of boundary layers and wakes (see figure 3, right).

In the intermediate case (0 < \( u^* < 1 \)) the convection velocity differs from the wave speed, which occurs in highly sheared turbulent flows and in separated shear layers. In the outer part of the turbulent boundary layer (shown in figure 3, center), the wave speed and the convection velocity are nearly identical. In contrast, near the wall, the large velocity gradient results in the interaction of coherent structures transported at different velocities, in turn giving different values for the local wave speed and particle convection velocity.
The two parameters governing the temporal response are the normalized time \( t^* \) and the velocity ratio \( u^* \). Note, for the first case of oscillatory flow, the convection velocity \( u_c = 0 \) and therefore \( u^* = 0 \). For brevity, the normalized spatial wavelength \( l^* = WS/\lambda_x \) is set to the fixed value of 0.25 that makes spatial modulation effects negligible (Schrijer and Scarano, 2008). A sequence of 9 synthetic images is generated for each value of \( l^* \) and \( u^* \) covering the range from 0 to 2. The synthetic images are 1000 x 200 pixels with a particle density of 0.1 ppp and particle diameter of 2 px. The particle motion is estimated in time via a fourth-order ODE solver applied to the analytical velocity field specified by equations 1 and 2. The interrogation is made using single-pair cross-correlation analysis on the outermost images of the sequence (e.g., images 1 and 9). FTC is used to analyse the entire sequence \( N = 9 \) and the polynomial order is varied from 1 to 6.

An example velocity profile for \( t^* = 1.25 \) and \( u^* = 0.5 \) is shown in figure 4. A clear modulation in the measured velocity is produced with the single-pair analysis. A similar result is obtained with FTC at low polynomial order \( P < 3 \). When the polynomial order is increased to 3 most of the modulation effects are eliminated, to disappear completely in this case for \( P > 4 \). The identical behaviour noted for FTC \( P = 1, 2 \) and 3,4 and 5,6 has already been noted in Lynch and Scarano (2013) and confirmed by Jeon et al. (2013). It is caused by the symmetry of the method in time. The full analysis explores the range of \( t^* \) and \( u^* \) and focuses on the amplitude modulation. This is calculated following Schrijer and Scarano (2008) by using a ratio of the integrals of the measured velocity field and the exact velocity field,

\[
\frac{v}{v_0}(t^*) = \frac{\int |v_{\text{meas}}(x)| dx}{\int |v_{\text{exact}}(x)| dx}
\]  

(5)

where the integrals are evaluated over the measurement time \( \Delta T \) and numerically performed using the trapezoidal method. This analysis is shown in figure 5.
Figure 5: Amplitude modulation as a function of the normalized time $t^*$. Plots represent three different velocity ratios; left, $u^* = 0$ (piston-driven/oscillating); center, $u^* = 0.5$ (mixed convection/wave speed); right, $u^* = 1.0$ (purely advected turbulence).

For $u^* = 0$, the flow is oscillatory about a fixed position in space. The single-pair and low-order FTC methods behave as a top-hat moving average filter in time and match the response of the corresponding sinc function. Notably the FTC method implemented with higher-order polynomial offers better-than-sinc behavior with reduced modulation. If a -3 dB (power) attenuation is taken as a cutoff, the range of frequencies resolved by the methods is up to $t^* = 0.5$ for single-pair and FTC $P=1, 2$ (identical to the Nyquist criterion), $t^* = 1.2$ for FTC $P = 3, 4$, and $t^* = 1.8$ for FTC $P = 5, 6$.

In the other extreme ($u^* = 1$) the fluctuation wave speed is identical to the convection speed (such as encountered in frozen turbulence) and the methods show no sign of modulation. This behavior is due to the linearity of the particle trajectories in the interval $\Delta T$; when the wave speed matches the convection speed, the particle trajectories become nearly linear within $\Delta T$. This paradoxical result may change when a more complete model for the fluctuations is chosen, such as two-dimensional vortices, where both velocity components are nonzero.

The above result suggests that the Lagrangian nature of PIV measurements, even using single-pair analysis, allows for resolution of frequencies in excess of the Nyquist criterion. Also, using FTC with polynomial orders greater than 3 reduces amplitude modulation even in the worst-case scenario of $u^* = 0$. These findings represent an optimistic estimate of the temporal response of time-resolved PIV, considering the highly simplified model of convecting turbulence. Moreover, the above discussion does not account for the spatial modulation effects, which become increasingly important for two or three dimensional fluctuations as discussed in Schrijer and Scarano (2008). Therefore, the assessment by means of a turbulent flow case produced by numerical simulations is proposed hereafter.

3. Temporal Response in Turbulent Boundary Layers

3.1 Description

The present study follows the recent focus on the capability of tomographic PIV to investigate turbulent boundary layers (Atkinson et al., 2011). Ghaemi et al., (2012) and later Probsting et al. (2013) highlighted the difficulty of obtaining reliable spectral estimates for pressure fluctuations in the turbulent boundary layer. Here we focus on the spectra of velocity fluctuations, where for the ‘inner-flow’ region matching the local wavenumbers is critical from the spatial as well as temporal point of view.

A DNS simulation of a turbulent boundary layer is used for generating synthetic tomographic PIV data. Details regarding the simulation are given in Pirozzoli (2010), Bernardini and Pirozzoli (2011), and Probsting et al., (2013). The synthetic velocity field spans $(x, y, z) = (1.5L, 1.0L, 1.0L)$ along the streamwise, wall-normal, and spanwise components, respectively, where $L$ is the characteristic length scale equal to $\delta_g$.

A visualization of the DNS velocity field is given in figure 6. The spectrum is estimated by an average of the individual spectra from a number of points in the streamwise and spanwise directions as shown by the red spheres at height $y = 0.2L$ in figure 6. The spectrum for each point is estimated using the Welch method by dividing the signal into 12 sections with 75% overlap and averaging the points at a specific height.

The spectra exhibit a range of over 4 decades in power, and a frequency range from approximately 35 Hz to the Nyquist frequency of 9.15 kHz. Due to the limited number of samples, low-frequency portions of
the spectra are not estimated to full convergence, and the following discussions focus on the high frequency portion of the spectrum approximately 1000 Hz and above.

![Image](image_url)

Figure 6: Example of DNS volume (left) with isosurfaces of Q criterion indicated. Red spheres indicate spectral sampling points at y = 0.2L. The PSD of streamwise and wall-normal velocity fluctuations (right).

Synthetic tomographic PIV data are generated at two spatial resolutions: 25 vox/mm and 50 vox/mm. The first corresponds closely to the experiment of Probsting et al. (2013). The DNS velocity field is sampled at 18.3 kHz, or $\Delta t_0 = 5.5 \mu\text{sec}$. PIV images are generated at twice this sampling rate ($F_{SS} = 2$), $\Delta t_1 = 2.5 \mu\text{sec}$, to allow for a time-centered evaluation for both single-pair and FTC schemes. A diagram of this timing configuration is shown in figure 7. Note that all processing is done centered on a DNS time stamp; therefore, the sampling frequency of the velocity from the PIV evaluation is also 18.3 kHz, instead of 36.6 kHz. For the 50 vox/mm case, $F_{SS} = 4$ to keep the identical particle displacement in voxels for the same $\Delta t_1$.

Particle image generation is similar to that used by the sine-wave test, but adapted to 3-D and to create projection images for tomographic reconstruction (similar to Worth et al., 2010 and de Silva et al., 2012). A particle field is generated at random locations and propagated through the DNS velocity fields using a fourth-order Runge-Kutta ODE solver. Particle recycling boundary conditions are placed on all sides of the volume, such that a particle exiting a face of the volume is introduced at the opposite face but in a randomized location.

Reference volumes are created using 3-D integration of Gaussian particles (adapted from Lecordier and Westerweel, 2005). Particle images are created by projecting the 3-D particle positions onto 2-D sensors via a pinhole camera model (Tsai, 1986) and performing a standard 2-D Gaussian integration. Four cameras are simulated with viewing directions of 30 degrees from the normal along both directions (cross configuration), corresponding to a system aperture of 60 degrees along horizontal and vertical direction, an optimal configuration for tomographic reconstruction (Scarano, 2013).

To generate volumes of varied spatial resolution without modifying the reconstruction or correlation performance (for example, the particle density in the projection images) the volume thickness is varied accordingly. The parameters are given in table 1. In total, a set of 2000 tomographic reference volumes and projection images for each spatial resolution is generated.
Table 1. Synthetic volume parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Resolution [vox/mm]</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Freestream velocity, U [m/s]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Particle Image Supersampling Factor, FSS</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Particle concentration, C [part/mm3]</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Camera Working Distance, Tn [m]</td>
<td>0.315</td>
<td>0.21</td>
</tr>
<tr>
<td>Magnification, M [-]</td>
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<td>1.0</td>
</tr>
<tr>
<td>Volume Size (Illuminated) [mm3]</td>
<td>12 x 6 x 12 (9.6)</td>
<td>12 x 6 x 6 (4.8)</td>
</tr>
<tr>
<td>Volume Size [vox]</td>
<td>450 x 150 x 300</td>
<td>900 x 300 x 300</td>
</tr>
<tr>
<td>Projection Size [px]</td>
<td>350 x 226</td>
<td>525 x 276</td>
</tr>
<tr>
<td>Particles per voxel, ppv [-]</td>
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</tr>
<tr>
<td>Particles per pixel, ppp [-]</td>
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<td>0.077</td>
</tr>
<tr>
<td>Source density, Ns [-]</td>
<td>0.24</td>
<td>0.24</td>
</tr>
</tbody>
</table>

For all reconstructions, an in-house volume reconstruction code based on the MART algorithm (Elsinga et al., 2006) is used. The weighting function is calculated using cylinder-sphere intersection where the cylinder radius is set to equal the area of one pixel, and the sphere radius is set to equal the volume of one voxel. The reconstructed volumes are initialized with uniform value of 1.0. Five iterations are performed using a relaxation parameter of 1.0 and a 3x3x3 Gaussian smoothing of the volume after each iteration, excluding the final iteration.

For all correlation analysis, identical correlation settings are used. An in-house multi-pass, multi-grid volume deformation algorithm (Fluere) performs 3D cross-correlation by symmetric block direct correlation and Gaussian window weighting. Three iterations at a final window size of 24 x 24 x 24 voxels at 75% overlap are used, with a second order regression filter (Schrijer and Scarano, 2008) used after each iteration, excluding the final iteration. The number of particles within the interrogation window is kept constant in all cases, Nt ≈ 8.

### 3.2 Single-Pair and Linear Filter Analysis

Spatial and temporal modulation effects produced by PIV are scrutinized with the application of linear filters to the DNS data and compared with the simplest PIV analysis based on single-pair cross correlation on the reference volumes (without reconstruction artifacts), which provides the reference level of spatio-temporal modulation of the velocity introduced by the PIV analysis. A 3x3x3 moving spatial average filter is applied to the DNS field prior to the time sampling to evaluate the spatial modulation effect on the time signal. A temporal sliding average with a kernel equivalent to Δt = 0.025 is applied to the time signal of the DNS, yielding the temporal filtering effect. A sample time trace of these analyses applied to the 25 vox/mm case is shown in figure 8. The large scale fluctuations are unaffected by this level of filtering, whereas differences in the order of 1% can be observed for the peak values, with the spatial averaging effects being more pronounced.

![Figure 8. Time history of wall normal velocity component from DNS. Single-pair analysis, spatial and temporal filtering. Probe position y/L = 0.2.](image-url)
The effect of such filters in the frequency domain is shown by the power spectral density (PSD) of the signals in figure 9. The comparison of measured data PSD with respect to the reference DNS data (left) shows a roll off of the power starting approximately from 1 kHz for the streamwise component and 2 kHz for the wall-normal component. The effect of such a low-pass filter is consistent with previous findings by e.g., Probsting et al. (2013) and Ghaemi et al. (2012) which reported an attenuation of velocity fluctuation amplitude in the high frequency range (typically beyond 3kHz). Note that since the 3D particle distribution is considered here, the effect of tomographic reconstruction noise (i.e. ghost particles, Elsinga et al., 2010) is not considered yet. Normalizing the PSD of the measured velocity with that of the DNS data (figure 9, right), a power modulation can be presented, similar in nature to the sine-wave modulation graphs discussed earlier (figure 5).

![Figure 9. PSD (left) and normalized PSD (right) of streamwise (top row) and wall-normal (bottom row) velocity fluctuations at probe position y/L = 0.2. Case with 25 vox/mm spatial resolution. Note difference in logarithmic and linear scaling between plots.](image)

Considering first the effect of the moving average filter in time, the behavior reproduces closely (figure 9) a low-pass filter with frequency response is well-described by a sinc function of the form,

\[
MTF_f(f) = \text{sinc} \left( \frac{2\pi f}{f_0} \right)
\]

where \(f_0\) is the sampling frequency of the velocity \(f_0 = 1/\Delta t_0\). The spatial filtering has a more dramatic effect, as it attenuates the fluctuations to a greater degree compared to the time filter. The spatial filtering also behaves similar to a sinc function or raised to second power, as discussed by Schrijer and Scarano (2008) for 2-D fluctuations, and possibly to the third power for 3-D fluctuations (Novara et al., 2013).

The result from the single-pair analysis matches well with the spatially-filtered data, and is well below that of the temporally-filtered data. In other words, at this spatial resolution the frequency response of the PIV measurement is spatially limited. A study devoted to the effects of PIV spatial resolution on the turbulent spectrum estimates is given by Foucaut et al (2004). Sampling at a higher rate will not lead to a
resolution of higher frequencies. Second, a flattening of the PSD occurs for frequencies exceeding 4 kHz (figure 9 top-right), and therefore the PIV measurement becomes also noise limited in this frequency range.

The spatial modulation is reduced when considering the volumes with a greater spatial resolution of 50 vox/mm, shown in figure 10. Here the spatial filter is well above that of the temporal filter, indicating that this measurement is temporally limited. The single-pair analysis exhibits a frequency response between these two filters, indicating a frequency response slightly better than described by the time filter. This is particularly noticeable in the case of wall-normal fluctuations (figure 10, bottom-right), which is closely analogous to the convecting sine wave tests performed in the previous section.

Figure 10. PSD (left) and normalized PSD (right) of streamwise (top row) and wall-normal (bottom row) velocity fluctuations at probe position y/L = 0.2. Case with 50 vox/mm spatial resolution. Note difference in logarithmic and linear scaling between plots.

3.3 Single-Pair and FTC Analysis

The analysis is extended to cover the effect of advanced TR-PIV processing algorithms with various measurement time intervals ΔT on measurement of the TBL. For brevity, only single-pair and FTC processing with N = 7 and 11, F = 2 and 3 are considered. Linear techniques such as SAC and pyramid correlation are estimated to exhibit similar behavior as the single-pair case and nonlinear techniques such as FTEE are estimated to exhibit similar behavior as FTC.

Figure 11 shows the normalized PSD for both the streamwise and wall-normal velocity components. Recalling that the results obtained here do not contain any noisy artifact due to real imaging and tomographic reconstruction, little difference between the noise floor of single-pair and FTC evaluation is not surprising. Instead, it is worth noting that although the FTC algorithm encompasses a longer time for the measurement (3 or 5 times larger than single pair), no sign of earlier temporal modulation is observed. This is also due to the higher-order polynomial description adopted for the particle motion.
3.4 Effects of Tomographic Reconstruction

Some effects of the noise level encountered in a real experiment are accounted for when simulating the tomographic reconstruction from the recorded images. The ghost particles created during the reconstruction process lead to a modulation in velocity gradients and an increased cross-correlation noise level (Elsinga et al., 2010). The previous single-pair analysis was repeated for the 25 vox/mm reconstructed volume case, and the PSD is shown in figure 12.

At high frequency, a clear noise floor is established due to the artifact of tomographic reconstruction appearing as an additional noise term in the cross-correlation analysis. The latter results in a greater PSD level compared to the DNS data. This behavior is similar to that reported by Atkinson et al. (2011) and Worth et al. (2010), and establishes an effective cutoff frequency for the measurement (Foucaut et al. 2004). For low frequencies (up to 2 kHz), a significant modulation is observed. The behavior of the simulated measurements is partly due to the relatively high seeding density, introducing in turn a low-quality reconstruction. The average reconstruction quality of 0.6 is well below the 0.75 guideline established in Elsinga et al. (2006). It is expected, however, the fundamental trends in the spectra will remain unaltered even with the low-quality reconstruction.

FTC is also applied to the reconstructed volumes as shown in figure 13. At high frequencies, the cases using a polynomial of order 2 give the greatest reduction in the level of the noise floor, along with a larger number of images used in the sequence. At low frequencies, an identical behavior is observed as in figure 11, where no sign of earlier temporal modulation is observed compared to the single-pair evaluation. However, the modulation of turbulent fluctuations also at such low frequency is beyond what would be expected by linear filters, which requires further scrutiny of the simulated experiment.
Figure 13. PSD (left) and normalized PSD (right) of streamwise velocity fluctuations at probe position y/L = 0.2 at spatial resolution 25 vox/mm for single-pair and FTC processing schemes applied to the reconstructed volumes.

Conclusions

The temporal response of PIV was investigated using a simplified model of a convecting sine wave representing a turbulent fluctuation. An analysis showed that the temporal modulation follows the Nyquist criterion for oscillatory flow without convection, but exhibits little or no modulation when the convection is close to the wave speed. Additionally, the FTC technique when used with a polynomial order greater than 2 showed an improvement in the temporal response even in the worst-case scenario of no convection.

The analysis was extended to a more realistic scenario of convecting wall-bounded turbulence by simulating a PIV experiment of a turbulent boundary layer given by DNS. Single-pair analysis was compared to the results from linear filters in space and in time to show that the predominant modulation in the signal is due to spatial filtering. A second case at higher spatial resolution showed that for streamwise fluctuations, temporal filtering plays the predominant role. However, for wall-normal fluctuations the single-pair analysis exceeded the temporal filter estimate, as suggested by the simplified sine wave model. FTC analysis showed no additional modulation in the spectra, despite using a kernel 5 times longer than the single-pair analysis.

Tomographic reconstructions were performed to evaluate the effect of a realistic noise source on the spectra. The measurement noise due to tomographic reconstruction was particularly high, due to the high particle density, which introduced a clear noise floor in the high frequency portion of the spectrum, introducing in turn a maximum measurable frequency. The FTC analysis appears to reduce the height of the noise floor by nearly an order of magnitude while showing no additional temporal modulation in the low frequency range.

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