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

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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 (PSD) 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 (FTC). 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 FTC 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.

Evaluation of Temporal Response

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. The convecting sine wave is described by,

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

where various values of \( u_c \) and the angular frequency allow the effect of convection, wave motion, or both to be considered. Three cases are investigated: first, no convection (piston driven flow/vibrating membrane); second, wave speed less than convection (shear flows); third, wave speed equal to convection (purely advected turbulence). PIV modulates the velocity as a linear filter for oscillatory flow (see figure 1), but the modulation effect is reduced as convection increases. Fluid trajectory correlation exhibits reduced modulation for all cases compared to single-pair interrogation.

Temporal Response in Turbulent Boundary Layers

The analysis is extended to the more realistic case of wall-bounded turbulence, following the recent focus on tomographic PIV for investigating turbulent boundary layers. A DNS simulation of a turbulent boundary layer is used for generating synthetic time-resolved tomographic PIV data.

The temporal response of single-pair PIV interrogation is examined by direct comparison to the PSD of the DNS as shown in figure 2 (top). A comparison is made to simple linear filters applied in space and time to show the dominant sources of spectral filtering. The spatial filtering of PIV is shown to be more severe in some cases than the temporal filtering.

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Fig. 2 Normalized PSDs of velocity fluctuation for linear filters (top) and FTC analysis (bottom)

Analysis using FTC is also presented (figure 2, bottom); it is shown that for even much larger measurement kernels, no modulation in the spectra occurs. A final analysis, not shown here in the abstract, evaluates the effect of tomographic reconstruction on the spectra. The reconstruction introduces noise which sets an upper limit to the frequencies measured.

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Fig. 1 Modulation vs normalized time \( t \) for three velocity ratios; left, \( u=0 \); center, \( u=0.5 \); right, \( u=1.0 \).