A super-resolution approach for uncertainty estimation of PIV measurements

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A super-resolution approach is proposed for the a posteriori uncertainty estimation of PIV measurements. The measured velocity field is employed to determine the displacement of individual particle images. A disparity set is built from the residual distance between paired particle images of successive recordings. Within each interrogation window, the disparity set is treated with a statistical analysis to infer the measurement uncertainty.

The performance of the estimator is first assessed via Monte Carlo simulation on a uniform flow field with varying out-of-plane displacement. The uncertainty is accurately estimated in optimal imaging conditions, while it is underestimated in sub-optimal imaging conditions.

The experimental assessment is conducted on a water jet experiment. The capability of the super-resolution technique to quantify the uncertainty within 0.1 px accuracy is proven.

Working principle of the estimator

The present approach makes use of the super-resolution concept to evaluate the measurement uncertainty of the displacement vector (viz. velocity) obtained from cross-correlation. The individual contributions of the particles are then extracted and form the basis to evaluate the dispersion of the error. The procedure followed for the uncertainty estimation can be split into four parts.

Image deformation. The two recordings I₁ and I₂ of a pair, defined at time t₁ and t₂ = t₁ + Δt respectively, are symmetrically deformed to the intermediate time instant t = t₁ + Δt/2 through the velocity field V, according to Scarano (2002); the deformed images I₁ and I₂ are thus generated.

Particle images detection. To detect the particle images, the intensity product image Π = I₁I₂ is considered; the peaks of Π correspond to particle images correctly paired, which have the largest contribution in building the correlation peak. These particle images are detected in I₁ and I₂ in a neighborhood of search radius r (typically 2 pixels), centered in each relative maximum of Π.

Disparity set computation. The particle images position is computed with subpixel accuracy via conventional 3-point Gaussian fitting (Westerweel, 1997) of the intensity peak, centered in the locations corresponding to the relative maxima of I₁ and I₂. The Gaussian fitting provides two particle position sets X₁={x₁ ¹, x₂ ¹, ..., xₙ₁ ¹} and X₂={x₁ ², x₂ ², ..., xₙ₂ ²}, where the superscript indexes the deformed image and N is the number of particle pairs in an interrogation window. The disparity set D is computed as the difference between X and X': D = |d₁, d₂, ..., dₙ| = X' − X.

Statistical analysis. In each interrogation window, the disparity set is treated in a statistical manner to infer the measurement uncertainty; the mean μ and the standard deviation σ are calculated. The combined uncertainty δ is finally computed as:

\[ δ = \{δ₁, δ₂\} = \sqrt{μ² + (σ/\sqrt{N})²} \]

The entire procedure for the quantification of the measurement uncertainty is sketched in figure 1.

Fig. 1 Scheme of the super-resolution estimator for uncertainty estimation.

Assessment and results

The performance of the estimator is assessed via Monte Carlo simulation in presence of out-of-plane motion and considering different imaging conditions and interrogation window sizes. In optimal imaging conditions and up to large out-of-plane displacement, the discrepancy between quantified and actual uncertainty is below 0.05 pixel units, while it rises up to 0.1 px when the imaging conditions are suboptimal because the particle images position itself is subject to peak-locking (see figure 2).

Fig. 2 Actual and estimated uncertainty for varying out of plane displacement wᵢ: left: optimal imaging conditions (dᵢ = 2 px); right: suboptimal imaging conditions (dᵢ = 0.5 px).

The estimator is also assessed on a water jet experiment where the capability to quantify the uncertainty within 0.1 px accuracy has been proven in a wide gamut of flow conditions.

References