Third-order double-frame digital particle image velocimetry

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This article derives a method for correcting first-order or second-order shift-vector fields to achieve third-order accuracy. The main idea is to identify the most likely streamline with constant curvature from the first-order shift vector and its gradient. The work establishes a theoretical framework including the systematic errors of the first-order and second-order shift vector's absolute value and angle. Synthetic images of a stationary vortex are used to validate the proposed method. The approach is very general and can be applied to any first-order vector field achieved from window-correlation PIV, single-pixel ensemble-correlation PIV, particle tracking velocimetry or optical flow methods. It also works for all 3D extensions of the techniques, such as 3D-PTV or tomographic PIV.

The evaluation of double-pulse double-frame DPIV images approximates the path of motion by a straight line. Starting from the first-order shift vector field, which connects the start point and the end point of this line segments, a third-order shift vector field is constructed in this section. The straight line is the shortest possible path, thus, for complex flows, it is likely that the actual path is longer. Hence, the absolute value of the estimated shift vector is generally underestimated. Assuming an actual path with constant curvature, as shown in Fig. 1, this bias error depends on the radius of the curvature R and on the arc's angle ξ.

In order to compensate for first and second order bias errors the parameters ξ and R must be extracted from the shift-vector field. Neighboring shift vectors that connect two points on the same streamline can be used to estimate the flow path's curvature, as illustrated in Fig. 3. The aim is to find a vector δ1 on a small radius r → 0 that fulfills the following condition:

$$\beta_1 + \varphi = \beta_2 - \varphi$$

Under this condition, all four points (start point and end point of shift vector and neighboring vector) fall on the same circle which represents a constant-curvature approximation of the path of motion.

The developed method was validated by analyzing synthetic DPIV images of a stationary Lamb-Oseen vortex (Fig. 2). The estimated third-order vector fields demonstrated the benefit for standard window-correlation (instantaneous and ensemble-averaged) as well as for single-pixel ensemble-correlation. Due to the third-order correction, the bias error of the shift vector's absolute value and angle is significantly reduced. This result is of great importance for the accurate estimation of velocity fields from DPIV data acquired at low optical magnification, as required for high dynamic spatial range.

Fig. 1 Third-order reconstruction by using neighboring vectors that follow the same path.

Fig. 2 Averaged third order shift vector field of a simulated Lamb-Oseen vortex using single-pixel ensemble-correlation. The first- (blue) second- (green) and third-order (black) shift vectors are shown for a cross section.

References