Advances in Applied Mathematics and Mechanics
Adv. Appl. Math. Mech., Vol. **11**, No. 3, pp. 675-685

DOI: 10.4208/aamm.2018.s11
June 2019

On the Double-Step PIV Algorithm of Wall-Bounded Flows

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Received 17 August 2018; Accepted (in revised version) 6 December 2018

Abstract. Double-step interrogation schemes with decreasing window size are investigated. Particle image pairs are created by Monte Carlo methods based on a simulated hypersonic transitional boundary layer flow. Two types of initial-step interpolation, with and without non-slip conditions at the wall (so-called CSIN and CSI), are respectively investigated. It can be concluded that the non-slip condition is very important to the multi-grid interrogation scheme. CSIN has a good agreement with the preset results but CSI does not. The error level of CSI near the wall is nearly 5 times that of CSIN.

AMS subject classifications: 76Kxx

Key words: PIV, hypersonic boundary layer, window-correlation algorithm.

1 Introduction

In the past years, the knowledge of wall-bounded flow dynamics has been greatly advanced by the combination of experimental and numerical work [1, 2]. Investigations based on multi-methods to validate each other were a commonly-used strategy for unknown complex problems [4–6]. Improvements in experimental techniques might revolutionarily promote the experiments' power that unexpectedly discovered a new physics [7–20]. Particularly, particle-Image-Velocimetry (PIV) measurements very near the wall are still a great challenge. One important issue is a proper algorithm to evaluate the particle image displacement with high shear near the wall, which has not been systematically solved up till now.

Westerweel [21] were the first to propose the iterative multi-step cross-correlation scheme. The displacement predictions were obtained by a standard cross-correlation analysis and used to shift the next-step interrogation windows. Scarano and Riethmuller [22] then suggested a decreasing window size with the step to obtain a high

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spatial resolution, which was so-called multi-grid scheme. Scarano [23] then embedded the window-deformation algorithm into the multi-grid scheme to enhance the correlation signal when the velocity gradient was considerable. The next-step window was deformed according to the velocity's first- or second-order derivatives calculated by the predictions. The scheme can achieved an error level less than 10^{-2} pixel, so that accepted as a standard procedure in the on-market commercial softwares.

If the fluid-solid interface immerges in a Cartesian gird, interrogation windows inevitably overlap the interface. Theunissen et al. [24] pointed out that the interface interference reduced the signal-to-noise ratio of window-correlation. To eliminate its negative effect, one way was to apply adaptive grids that parallel to the interface, which was first suggested by Theunissen et al. [24] and further applied by Joen and Sung [25]. The other way was to add artificial particles in the wall region, as suggested by Zhu et al. [26], to balance the intensity truncation over the interface. Jia et al. [27] combined the two way together and applied them to a moving boundary.

Lin and Perlin [28] pointed out that a reliable initial prediction was very important in the iterative scheme. Zhu et al. [26] found that although artificial particles caused a little bias at the wall, they helped iterative steps correctly converged due to velocities were forced zero in the solid region. Therefore, it was believed that an accurate non-slip condition at the wall might ultimately solve the problem.

For many actual cases, the PIV parameters cannot satisfy all these criteria. The first estimate of the displacement by the window-correlation method is always unreliable. Huang [30] discussed a process by which bad data is corrected by moving average smoothing. However, they pointed out that the method failed at the boundary because there were no data beyond the boundary. The present method is a modification to their method that adds some stationary particles on the wall side of the interface. The procedure not only compensates for the particle distribution across the interface, but also introduces a no-slip condition at the interface. Therefore, the data can be validated by a smoothing process at the interface.

For the stationary interfaces, the PKU group developed the image parity exchange (IPX) technique by adding the optimal synthetic particles (OSP) in the solid region to get a better velocity prediction near the interface [26]. The improved image-preprocessing method expands the traditional window deformation iterative multigrid scheme to PIV images with very large displacement commonly encountered in measurements in hypersonic boundary layers. Before the interrogation, stationary artificial particles of uniform size are added homogeneously in the wall region. The initial estimation near the wall is then smoothed by data from both sides of the shear layer to reduce the large random uncertainties. Interrogations in the following iterative steps then converge to the correct results to provide accurate predictions for particle tracking velocimetries. The algorithm successfully extracted the small flow structures of the second-mode wave in the hypersonic boundary layer [5,6] from PIV images with low signal-noise-ratios when the traditional method was not successful.

The OSP method has been successfully applied in the experimental investigations