PIV error sensitivity analysis for free turbulent flow characterization

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In the state-of-the-art of PIV, image sensors are growing in size and PIV algorithms are increasing in spatial resolution capabilities. These technological advances allow for the measurement of increasingly larger ranges of spatial scales, simultaneously. Due to the complexity of fluid flows it is a common objective to fully use this capacity and measure using the widest range of spatial scales available. For these cases, PIV setup constraints establish a coupling between the laser sheet thickness, \(d\), and the time between laser pulses, \(\Delta t\), defining an optimum value for \(d\). Due to this coupling, reducing the laser sheet thickness below the optimum value reduces the range of simultaneously measurable scales, instead of increasing it. Figure 1a depicts the constraints that define a measurement with the widest range of spatial scales available. It explains why this coupling was condition that did not apply with older technologies and becomes now one of the limiting factors.

Although the prescribed optimum value of \(d\) is required, to allow for proper \(\Delta t\) values, it superposes flow information in the direction of the imaging sensor. This spuriously introduces erroneous measurements of large fluctuations for scales smaller than \(d\). This may compromise the measurement of flow quantities like dissipation and turbulent kinetic energy \((\kappa)\), for which the contribution of the small and medium scales may be relevant. The direct consequence is that the error assessment of the small scales seems mandatory for the PIV measurements. Actually, in a typical PIV scenario where the largest flow scale, \(L\), has to be included, the smallest resolvable scale, \(l\), is in the order of \(1/120\) for modern technology (see Fig.1a). For large Reynolds numbers this is still a fractional portion of the involved spatial scales.

This work proposes the use of the classical second order structure functions of the turbulent flow to obtain the value of the characteristic velocity difference \(u_1\), at each spatial scale \(l\). This allows discriminating which components of the PIV measurement that corresponds to each scale. The second order structure function of the flow is an intuitive and easy to implement tool. The procedure proposed in this work consists of checking how if varies for measurements of the same flowfield obtained with different laser sheet thicknesses, as part of the error assessment protocol. Variation of the laser sheet width is not excessively complex to implement and can be done while running the experiment. A telescope mounting for the laser sheet formation lenses allows changing the thickness with a simple rotation.

Several tests have been performed in this sense over synthetic (DNS based) and real images. The results confirm that the laser sheet thickness spuriously increases the measured amplitude of velocity fluctuations at small scales. They also indicate that the magnitude of the error is not negligible. This is presented in Figure 1b for a real case. It represents the characteristic velocity for spatial fluctuations \(u_1\) [pixels/\(\Delta t\)] for each spatial scale \(L\) [pixels] in a jet. Two measurements with different laser sheet thicknesses are plotted for the same flow. The drop for scales below 16 pixels is not a natural decay. It is related to the moving average behavior of the PIV interrogation window (of 16 pixels size). Going from large scales towards small ones, previously to that drop, a tendency to increase the velocity amplitude for smaller scales can be appreciated for the thicker plane measurement. It can also be observed that, in the zone of discrepancy between both measurements, differences in the range of 0.1 pixels can be reached for laser sheet thicknesses in the order of 3 mm. For small scales, the thicker laser sheet case measures larger values of the characteristic velocity spatial fluctuations. This is coherent with the results obtained in synthetic images verifying that the variations across the laser sheet thickness generate spuriously large values for the velocity associated to small scales. The combined use of the proposed tools seems promising. Further work is advisable for the proper definition of these tools and possible error handling procedures.

Figure 1. a) Available range of scales that can be simultaneously measured in PIV and the boundaries that limit the measurement. b) Characteristic velocities (in pixels/\(\Delta t\)) measured for each scale in the flow with two different laser sheet thicknesses (brown upper line for \(d = 3\) mm = 47 pixels and green lower line for \(d = 1.5\) mm = 23 pixels).

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