Next generation PIV
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The accuracy and dynamic range of modern PIV systems has not advanced substantially over the last decade, suggesting that the current approaches have been nearly optimized. To achieve significant new advances, it is likely that a new generation of PIV designs will be needed.

The performance of a PIV system can be characterized by two quantities, the dynamic spatial range, DSR, and the dynamic velocity range, DVR (Adrian and Westerweel, 2010). The dynamic spatial resolution is defined as the field-of-view \( L_x \) divided by the spatial uncertainty of the velocity measurement. In a standard planar PIV using windowed interrogation, the spatial uncertainty is a fraction of the displacement of the particles in the plane of the light sheet, bounded by the maximum displacement \( \Delta x_{p\text{max}} = u_{\text{max}} \Delta t \), (where \( u_{\text{max}} \) is the full-scale in-plane velocity) and the light sheet thickness, \( \Delta z_0 \). In the plane, the DSR is greater than \( L_x / \Delta x_{p\text{max}} = N_x / c_{\text{max}} \), where \( c_{\text{max}} = \Delta X_{p\text{max}} / d_r \) is the maximum displacement in the pixel plane divided by the pixel spacing, \( d_r \), and \( N_x \) is the number of pixels.

The DVR is defined as the ratio of the full-scale velocity to the rms uncertainty of the velocity,

\[
\text{DVR} = u_{\text{max}} \sqrt{\left( \sigma_u^2 + \delta u^2 \right)^2},
\]

where \( \sigma_u \) is the rms uncertainty, and \( \delta u \) is the variation in the velocity caused by the temporal accelerations and/or spatial gradients in the flow. Generalizing the result to account for the latter uncertainty yields

\[
\text{DVR} = c_{\text{max}} \sqrt{c_r^2 \left( 1 + c_r^2 \right) + c_{\text{max}}^2 \frac{\delta u^2}{u_{\text{max}}^2}}.
\]

Here, \( c_r = d_e / d_r \) is the dimensionless image diameter in pixel units, and \( c_r = \sigma_{dx} / d_e \) is the rms uncertainty in measuring the image displacement as a fraction of the image diameter. In the limit of images that are small compared to the pixel size and with no velocity variation, the DVR is determined by the pixel resolution. In the limit of perfect pixel resolution and vanishing image diameter, the temporal and spatial velocity variations determine the DVR.

Currently, the maximum realistic DVR is 100-200, which implies accuracy of 0.5% of full scale, which is usable provided that the PIV is carefully adjusted to operate with the maximum velocity close to the full scale velocity. This requirement is the main reason that good PIV measurements require careful optimization, both to achieve the maximum DVR and to fill the range. PIV would be easier to use, more robust and more accurate if the DVR could be increased substantially. This paper explores methods to increase DVR and DSR to create a new generation of PIV instruments.

Increasing \( c_{\text{max}} \) will be achieved by improved camera technology that reduces the pixel size. However, it is unlikely that the pixel dimension can be reduced by more than a factor of two, from say 7 microns to 3.5 microns, because a factor of 4 decrease in the pixel area would result in a corresponding decrease in sensitivity, unless image intensifiers were used. Increasing the maximum particle image pixel displacement is feasible by using increased magnification, but that would also decrease the DSR.

The dimensionless particle diameter \( c_r \) can be decreased by optimizing the focus and using larger aperture, but only to the extent allowed by the required depth-of-field. Further, is should not go below approximately 2, in order to avoid pixel locking bias errors. Thus, current systems usually achieve the optimum value of \( c_r \) already.

Currently, the values achieved for the factor \( c_r \) are about 0.05 in real, three-dimensional flows. It depends upon the following:

- algorithm to measure the displacement, including the peak interpolator
- image noise and background noise
- image aberration
- fill-ratio of the pixels
- image overlap
- image clipping by windows

Of these effects, the fill-ratio is probably the most promising improvement, but it may be difficult to approach 100% using PIV cameras, and a new design is probably needed.

At this point, it appears that a factor of 2 can be achieved with improved cameras and fine-tuning everything else. Clearly, to reach a dramatic improvement to, say, DVR=1000:1, a significant innovation is needed.

The most obvious way to increase the DVR is to increase the maximum particle displacement. This cannot be done without losing spatial resolution in a two-pulse system. But, if one uses multiple pulses, it is possible to use the additional position samples to interpolate for particle position and velocity as a function of time. This would allow improved accuracy in assigning velocity to position. Further, increasing the number of pulses has the effect of reducing the required number of particles, so super resolution by particle tracking improves, and a number of other effects such as particle image overlap and background noise due to particles are also attenuated. The degree to which multi-pulse PIV can improve performance is explored by Monte-Carlo simulations.


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