IMAGE PROCESSING IN PIV

Milan Pěta, Jan Novotný
Czech Technical University in Prague, Fakulty of Mechanical Engineering,
Division of Fluid Dynamics and Thermodynamics,
Technická 4, 166 07 Prague 6, Czech Republic
Corresponding author: J. Novotný – markvart@seznam.cz

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Abstract

In PIV measurements we don’t measure velocity of the particles themselves but we measure only displacement of tracing particles. This displacement is computed from a pair of images captured with time delay $\Delta t$, therefore the image processing plays an important role in measurement by PIV method. Displacement of seeding particles is determined by using cross-correlation technique. Accuracy of PIV measurement is given by efficiency of finding and location of true peak in cross-correlation plane. The aim of this article is to present the influence of dimension interrogation area, number of particles and displacement of particles at time “$\Delta t$” on pattern of cross-correlation area.

Our basic task was to find out the influence of the image quality on the shape of cross-correlation area. This known dependency allows us to determine the optimal density of particles and optimal choice of image processing (correct application of linear filter). Furthermore we observed the relationship between the particle displacement and the size of interrogation area. Next parameter we investigated was the bit depth influence of the picture.

For determining of the influence of the source data quality on the resulting cross-correlation area we created our own algorithm in the MATLAB environment. Data for the analysis were acquired by software “Generator of Images” and two PIV systems. First of these systems was a commercial system PIV from the DANTEC company. This system consists of a couple of mini Nd:YAG lasers and CCD cameras with bit depth of 12 bit and 1024x1280 pixels shape. Second one was obtained from internal Czech Technical University grant. It is a low cost system with a continual laser with 60W output and a CCD camera with 1280 x 1024 pixels (bit depth 8-10 bits) and a 15 Hz frequency. With lowering the resolution to 640 x 512 pixels we obtained 60 Hz frequency.

Fig. 1. The figure shows the shape of correlation area computed from exact data. Size of particle - 10 pixels in diameter. Dimension of interrogation area 32x32 pixels. Number of particles per Interrogation Area (IA) 10. There was no noise and lost of pair inside IA.

By using software “Generator of Images” we were able to generate images with accurate displacement of pattern of seeding particles and with further optional parameters and therefore we were able to investigate dependence of this parameters on the shape of cross-correlation area and accuracy of PIV measurements. The influence of these parameters is presented in charts. We designed the optimal linear filter for image processing.
We further proposed another – more precise – way of locating the peak position and compared it to the three-point sub-pixel interpolation. When processing images of the tracers we used partly data obtained directly from the ‘Generator of Images’ software system and partly data we tried to smooth out using linear signal-smoothing filters. We finished our work by optimizing the form of the mask with the aim of improving both the RMS uncertainty and the absolute error in the determined position of the peak.

**Generator of Images:**

Images of the tracers can be described using the Airy function [1]. When describing an image of a tracer, one most often uses the Gauss curve, which ensures the best agreement with the measured image of the particles.

The Gauss curve describing the tracer signal is defined by the relation:

\[ I(x, y) = I_0 \exp \left[ -\left(\frac{(x-x_0)^2 + (y-y_0)^2}{(1/8) \cdot d_t^2}\right) \right] \quad [1] \]

where:
- \(x_0\) and \(y_0\) define the position of the center of the particle
- \(d_t\) is the diameter of the image of the particle in pixels
- \(I_0\) is the value of the maximum in grey scale.

The GP software is capable of automatically generating an exact pair of images or a set of images while the basic parameters can be adjusted arbitrarily: particle density, particle image size, their relative displacement, noise level, etc. To verify that the particle image generator works correctly, we checked the effect of the RMS uncertainty in the peak position and its dependence on the bit depth of the images, size of the investigated area, and for displacements from 0 to 0.8 pixels. We then compared the resulting graph with values available in the literature. The result was satisfactory and we were thus able to work with the data obtained in this manner.

![Dependence of RMS Uncertainty on Particle Image Shift and Bits Depth of the Image](image)

**Fig. 2.** Dependence of accuracy of standard three points sub-pixel interpolation on particle image shift and bits depth, filling factor 25 %
New methods of sub-pixel interpolation and linear filter optimization.

When measuring average flow-field parameters, the classical three-point sub-pixel interpolation is quite sufficient. However, if we need to interpret quantities such as shear stresses in liquid based on the instantaneous maps of velocity vectors, this is inadequate. Therefore, we developed a new method of determining the position of the maximum in the correlation plane. We then refined this method opening thus two options of determining the position of the peak in the correlation plane with a higher precision. The first method, SI1, is less time-consuming, yet the increase in the precision is not so impressive. The second method, SI2, is approx. three times more precise than the standard sub-pixel interpolation but computer time required to perform the calculation is more than ten times longer. During the tests we tried to improve the quality of the input data using a linear filter $F$, but this approach did not turn out to be suitable as can be seen in the following graph.

Linear Filter:

\[
K = \frac{1}{9} \begin{bmatrix}
 1 & 1 & 1 \\
 1 & 1 & 1 \\
 1 & 1 & 1 \\
\end{bmatrix}
\]

Since this mask turned out to be unsuitable, we wrote an optimization algorithm intended to determine what type of linear filter it is suitable to use if we want to increase measurement precision using the PIV method. We wrote an optimization program for the SI1 algorithm in order to save computing time. The resulting linear filter $K_{Optimized}$ turned out to be highly suitable and the increase in precision was significant.

We optimized a pair of images with a generated image of particles with a diameter of 2.5 pixels and displacement of 0.5 pixels in both directions.

After applying the above-mentioned linear filter, we obtained an average value of the measured displacement (in total, in each optimization step, we calculated 100 CC areas and based on these, we determined the average value and RMS)

\[
K_{Optimized} = 0.15 \cdot \begin{bmatrix}
-1.11 & -0.9 & -1.02 \\
-1 & -1.32 & -0.97 \\
-1.2 & -1.308 & -1.06 \\
\end{bmatrix}
\]

Mean displacement:

$Dx = 0.49$ pixel, $Dy = 0.49$ pixel

RMS of displacements:

$RMS_x = 0.01$ pixel, $RMS_y = 0.012$ pixel

![Subpixel- Interpolation 2](image)

Fig.3. The dependency of RMS uncertainty and mean error on Particle image shift. The size of particles: 2.5 pixels in diameter, IA 32x32, filling factor 25 %.
Fig. 4. The dependency of RMS uncertainty and mean error on Particle image shift. The size of particles: 2.5 pixels in diameter, IA 32x32, filling factor 25%.

Fig. 5. The dependency of RMS Uncertainty and Pitch of the Peak on Level of the noise. The size of particles: 2.5 pixels in diameter, IA 32x32, filling factor 25%.
Detection of the effects of noise on the form of the cross-correlation area:

Since the images taken by the measuring systems are mostly burdened by noise such as reflections, imperfect shielding of the ambient lighting, etc, we decided to prepare an analysis of the impact of noise on the form of the CC area. We gradually increased the noise level until it reached the signal level. In the following graphs, we can clearly see the impact of the noise both on the measurement precision and on the maximum value of the peak in the correlation plane. For the purpose of these tests, the correlation plane was normalized according to [1]. We can see that also the size of the CC plane normalized in this way can be used as a qualitative parameter when determining the correct setup. We again tried using the linear filter K here but we failed once more. The source data we tried to filter in this way and reduce thus its noise level, was finally of a higher quality than the filtered data.

Conclusion:

The goal of our work was to become familiar with the method of interpreting displacements in particle images in PIV measurements. We successfully verified that we can use the Particle Generator program to create images with precisely specified parameters, which then form the input data for further analyses. The influence of the bit depth turned out to be negligible and the impact of particle displacement was determined to be the same as in other papers dealing with the same issues. We succeeded in writing a successful optimization program based on linear filtration of the images and we used it to increase the precision of displacement measurements. The displacement of particle images was 0.5 pixels in both X and Y directions. Average values of the displacement calculated using the optimized linear filter are: Mean displacement in both the X and Y directions was identically 0.499 pixels, RMS in the X direction – RMSx = 0.01 pixels.
RMS in the Y direction – RMSy = 0.012 pixels. Due to the fact that such optimization is time-consuming, we only applied it to the simpler and faster SI1 algorithm. In case of the SI2 algorithm, we can assume there will be an even more pronounced increase in the precision of the displacement detection. However, the price we will pay for the increased precision is the computing time required for the analysis. Due to the fact that in its FlowManager program, the Dantec Dynamic Company also provides a high-precision module calculating the displacement, our task will be to compare both methods and – using real data obtained from experiments – to check their performance or to invent other methods enabling us to obtain high-quality flow field even from noisy data and subsequently establish other flow parameters.

**References:**


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