Software, Algorithm, and Procedures for Evaluating PIV Images in the PIV Challenge 2001 Packages

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Abstract The custom-written software package EDPIV is used to evaluating PIV images in the two packages provided by PIV Challenge 2001. The evaluation algorithm implemented in the software for these PIV images combines the most recently developed PIV evaluation methods, i.e. the central difference interrogation, continuous window shifting and image pattern correction, and it enables a reliable and accurate evaluation of digital PIV recordings taken in strong vortex and shear flows. Some digital image processing techniques included in the software are used to reduce the background noise and improve the image quality. Some details of the software, algorithm, and processing procedures are provided in this paper.

1
INTRODUCTION

The PIV Challenge 2001 organizes a worldwide comparison of the evaluation and analysis methods for PIV recordings. Real and synthetic PIV images of nine cases in two packages are provided for the test. As the contributor team of Purdue University, we used the custom-written software EDPIV to process these PIV images. EDPIV is usually used as a platform for testing new PIV algorithms and applications, so it is easy to be changed to fit the current purpose.

EDPIV was developed with Visual C++ for "Windows 95/98/2000/NT" from 1997 to 1998 in the Institute of Fluid Mechanics at the University of Essen in Germany for evaluating digital recordings of Particle Image Velocimetry (PIV). It can be used to evaluate a double exposed recording, a single exposed recording pair, or a group of double/single exposures. For convenience and comparison purpose, the software includes four different evaluation algorithms: traditional correlation-based interrogation (Cenedese and Paglialunga, 1990; Adrian, 1991; Willert and Gharib, 1991; Heckmann et al. 1994), correlation tracking (Huang et al., 1993; Kemmerich and Rath, 1994; Okamoto et al., 1995), MQD method (Gui and Merzkirch, 1996a, 2000), and MAD method (Gui and Merzkirch, 1997). These algorithms can be accelerated with two methods, i.e. FFT and sparse array (Hart, 1996) technique. Arbitrarily sized interrogation windows can be chosen for the FFT-accelerated correlation interrogation with a padding technique (Gui and Merzkirch, 1998). For dealing with multiphase and boundary problems, a mask technique (Gui and Merzkirch, 1996b; Gui et al., 1997a; Merzkirch et al., 1997; Lindken et al, 1998, 1999) is provided. Normal and special digital image processing tools are also provided in the software for possible improvements of PIV image quality and identification of particle images, some of which were described by Gui (1998). For evaluating low-image-density (LID) PIV recordings, two kinds of particle image tracking (PTV) techniques are available (Gui et al., 1996; Gui et al., 1997b). Fixed and adaptive window shifting techniques can be selected to avoid erroneous vectors (Willert, 1996; Westerweel et al., 1997). For detecting and correcting evaluation errors, the median filter, aim vector technique, and reversibility checking technique (Gui, 1998) are implemented. In addition, the software includes simulation tools for generating synthetic PIV images of different kinds to test new algorithms.

This software has been and will continue to be updated to follow the evolution of the PIV technique. From 1999 to 2000 the software was improved in the Iowa Institute of Hydraulic Research (IIHR) at the University of Iowa in the United States by adding window masks for reducing the bias errors and increasing spatial resolution in the turbulent flow measurement (Gui et al 2000, 2001a). A 3-D median filter is constructed in the post processing procedure to reduce the measurement uncertainty (Gui et al, 2001b). Recently, the software was updated at Purdue University by applying ideas of average correlation (Mainhart et al., 2000), central difference interrogation (Wereley and Mainhart, 2001), continuous window shifting (Gui and Wereley, 2001), and image pattern correction (Wereley et al., 2001). The most recent update of the software is the use of the central difference image correction (CDIC) method (Wereley and Gui, 2001).

Compiled by Visual C++ 6.0 with MFC applications, the software has a very convenient interface between the user and computer. The input files, i.e. digital PIV images, are usually required to be in the Windows Bitmap format. But some device-dependent digital image formats are also accepted, e.g. "IMG" format from DANTEC, TSI and LAVISION system. There are two output data types, the EDPIV format and Tecplot data format. The EDPIV format can be further processed with accompanying Matlab programs. High quality plots can be made with Tecplot using the Tecplot data format. In the following the evaluation algorithm and digital image processing techniques will be described. Details in the processing of each PIV Challenge image set will be provided.

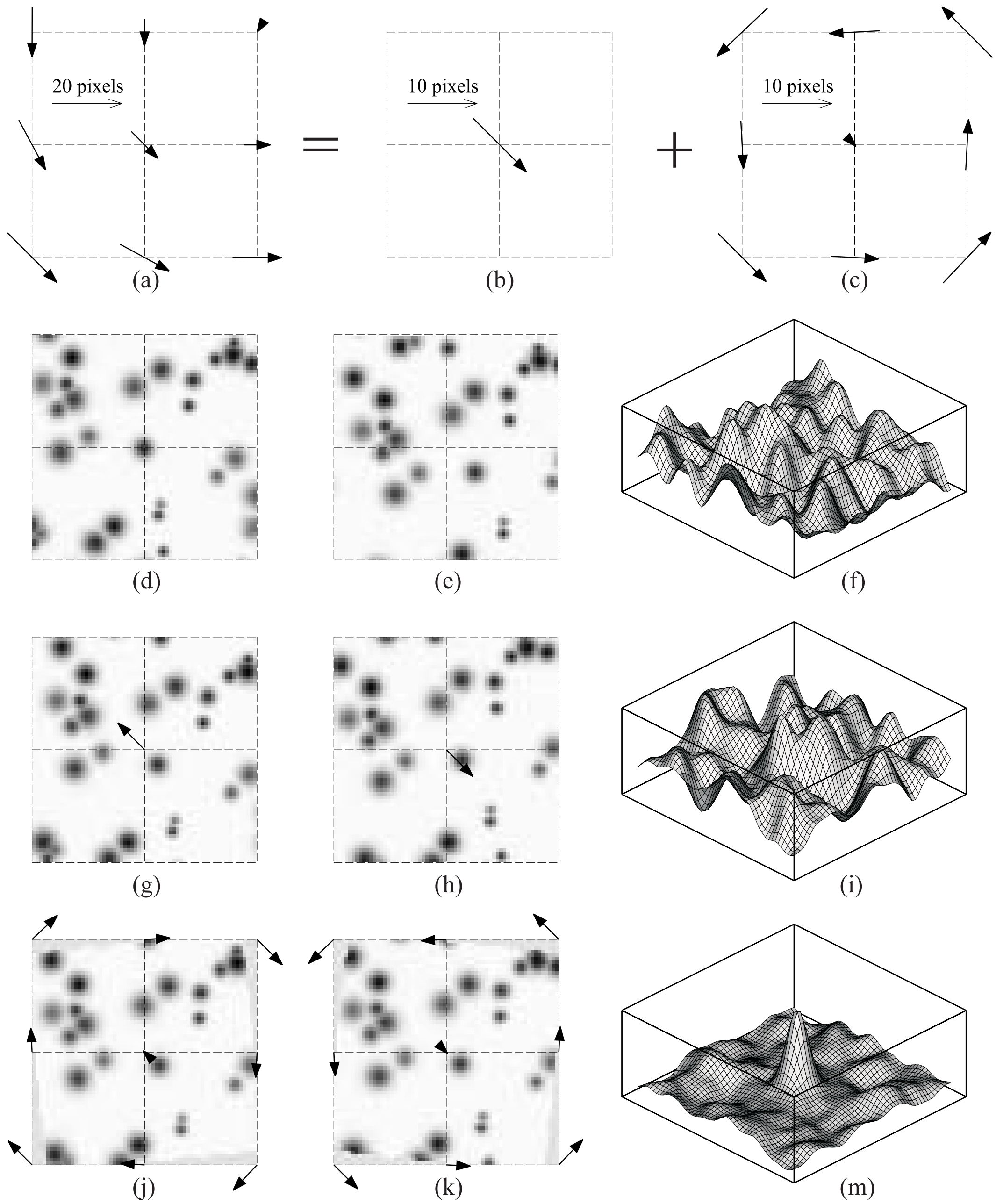

Fig. 1: Interrogation window shift and image pattern correction

2
ALGORITHM & IMAGE PROCESSING METHODS
Central difference image correction (CDIC)

The idea of central difference image correction is demonstrated in Fig. 1 by evaluating a synthetic PIV image pair near a strong vortex center with a 64 × 64-pixel interrogation window and a 50% overlap. The velocity distribution on the 3 by 3 interrogation grid (Fig. 1a) consists of a translation movement (Fig. 1b) and distortion (Fig. 1c) instantaneously. When using the traditional cross-correlation algorithm, the evaluation sample pair is obtained with an interrogation window centered at the evaluation point, e.g. Fig. 1d and 1e for the central point of 3 × 3 grid. The traditional correlation method works well in cases of small particle image displacement and relatively simple flow. But in the current case the image patterns in the sample pair do not match well, so that the correlation function (Fig. 1f) does not show a dominant peak for the particle image displacement. Considering the translation movement of the particle images in the evaluation sample pair, the interrogation windows for the first and second recording can be shifted backwards and forwards, respectively, to realize a central difference interrogation, see Fig. 1g and 1h, so that the image patterns match better to each other. However, the correlation function still does not present a very clear peak to reliably and accurately determine the particle image displacement (Fig. 1i). When considering the particle image distortion, i.e. pre-deforming the image patterns forwards and backward respectively for the first and second evaluation sample (Fig. 1j and 1k) based on the known displacements at the 9 grid points, a very good match of the image patterns is realized, so that a correlation function with a clear main peak is obtained (Fig. 1m). When using the FFT algorithm to accelerate the calculation, the correlation-based evaluation function is usually written as

$$\Phi(m,n)=\sum_{i=1}^{M}\sum_{j=1}^{N} g_1(i,j)\cdot g_2(i+m,j+n) \qquad (1)$$

where g_1 and g_2 are gray value distributions of the two evaluation samples, which are restricted in a rectangular interrogation window of size of $M \times N$ pixels. For traditional correlation algorithms with or without discrete window shifting, $g_1(i,j)$ and $g_2(i,j)$ are extracted directly from the discrete gray value distributions of the PIV recording pair $G_1(i,j)$ and $G_2(i,j)$, respectively. However, when using the central difference image correction, the shifts of pixels in the interrogation window are not limited to discrete integer values and, in most cases, are not a constant. We assume that the displacement of the image pattern at pixel (i, j) in the interrogation window is determined as X(i, j) and Y(i, j). The following bilinear interpolation function is used for determining the correlated function:

$$\begin{aligned} g(i,j) = &(1-x)\cdot(1-y)\cdot G(i+I, j+J)+ \\ &x\cdot(1-y)\cdot G(i+I+1, j+J)+ \\ &y\cdot(1-x)\cdot G(i+I, j+J+1)+ \\ &x\cdot y\cdot G(i+I+1, j+J+1) \end{aligned} \qquad (2)$$

wherein (I, J) and (x, y) are integer pixels and non-negative sub-pixel values, respectively; for $g=g_1$ and $G=G_1$: I+x=-0.5X, J+y=-0.5Y; for $g=g_2$ and $G=G_2$: I+x=0.5X, J+y=0.5Y. Because particle image displacement (X, Y) is unknown before evaluation, initial values are taken to be zero or determined with previous knowledge of the flow. Then the evaluation is iterated until the convergence condition is fulfilled. Instead of determining the particle image displacement (X, Y) at every pixel in the interrogation window like the conventional image correction methods, displacements at the four corners (4-point method) or also at five center points (9-point method) of the interrogation window are used to determine the correction of the distorted image patterns. For the 4-point method the interrogation window is taken as one rectangular cell, whereas for the 9-point method there are four cells in the interrogation window. Within each rectangular cell, the displacement (X, Y) is determined with a bilinear interpolation function similar to Eq. (2). A more detailed discussion of the CDIC method will be presented at the PIV ’01 Workshop by Wereley and Gui (2001).

Unsharp mask

The “unsharp mask” is a digital filter to increase the reliability and accuracy of PIV recordings by removing low-frequency noises from PIV images (Mass, 1992; Heckman, 1996). The unsharp mask operation with a mask size of (2r-1)×(2r-1) pixels is defined as

$$G'(i,j)=G(i,j)-\frac{1}{(2r+1)(2r+1)}\sum_{i=-r}^{r}\sum_{j=-r}^{r}G(i,j) \qquad (3)$$

where G(i, j) and G’(i, j) are the gray value distribution of original and filtered PIV image, respectively. The filter described in Eq.(3) is linear but may produce negative gray values. An additional linear transformation (normalization) can be used to avoid negative gray values. Another way of avoiding negative gray values is to set the pixel of the negative gray value as zero, and then the filter becomes non-linear. The non-linear unsharp mask may remove the background noise more effectively, but it may also take away part of the useful information of particle images.

Regional normalization

The “regional normalization” is a non-linear filter that enables the particle images of different brightness to have a similar gray value level (Gui, 1998). This filter operation can be described as

$$G'(i,j)=\frac{(G'_{max}-G'_{min})\cdot\left(G(i,j)-G^{o}_{min}(i,j)\right)}{G^{o}_{max}(i,j)-G^{o}_{min}(i,j)}+G'_{min} \qquad (4)$$

where G'_{max}, G'_{min} are the maximal and minimal gray values given to the filtered digital image, respectively, whereas $G^{o}_{max}(i,j)$ and $G^{o}_{min}(i,j)$ are the regional maximum and minimum, i.e. the maximal and minimal gray values in the filter window centered at (i,j). The effect of the regional normalization filter depends on the image quality and the size of the filter window.

3 PROCESSING IMAGE PACKAGES

Package 1, Case A

Case A in package 1 includes a pair of digital PIV images with a strong vortex. The regional normalization filter of 11×11 pixel window is used to improve the image quality in the vortex center, where the particle images are very dark and the particle image number density is low. The effect of the filtering is shown in Fig. 2.

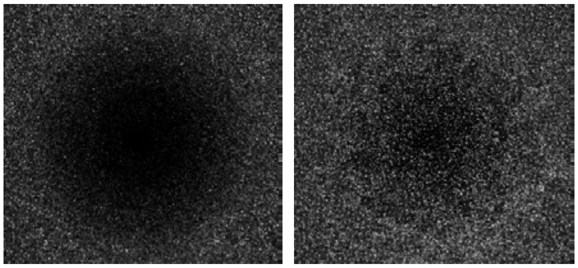

Fig.2: Original (left) and filtered (right) PIV image sample from case A.

When using the 4-point CDIC method with a 32×32-pixel interrogation window, the flow structure of the vortex is resolved without obvious wrong vectors in seven iterations, see Fig 3.

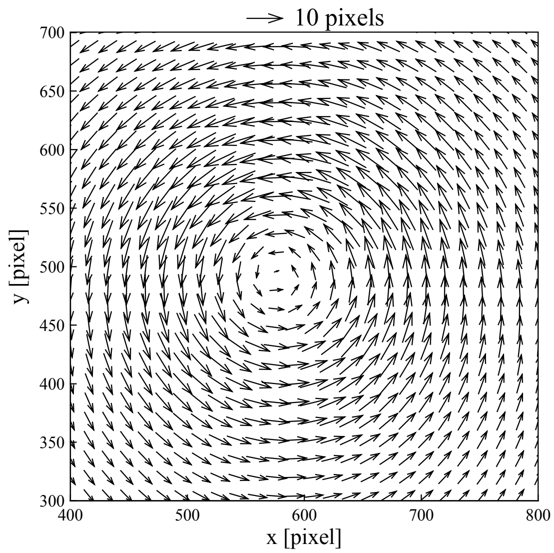

Fig.3: Displacement vector plot in the vortex center

Package 1, Case B

Case B in package 1 consists of 6 pair of synthetic digital PIV images with a strong vortex. Since the particle images are clear, no digital image processing is necessary for improving the image quality. Evaluations of these PIV image pairs using the 4-point CDIC method with a 32×32-pixel interrogation window converge within 10 iterations. For some of the PIV image pairs, a better convergence can be achieved using the 9-point CDIC method.

Package 1, Case C

For Case C in package 1, the mask is, at first, modified to reduce the influence of the strong wall reflection. For evaluating the PIV recording pair in this case, the 4-point CDIC method is combined with the mask technique originally described by Gui and Merzkirch (1996). The initial flow field for the first iteration is not set to zero as for the previous cases, but artificially determined according to a previous evaluation result. In this case the wrong vectors cannot be totally avoided, so that median filter and aim vector method (Gui, 1998) are used to detect and correct the erroneous vectors.

Package 1, Case D

Case C in package 1 is a double-exposed PIV image. A 11×11-pixel non-linear unsharp mask is used to reduce the background noise, and the effect of the filtering is shown in Fig.4.

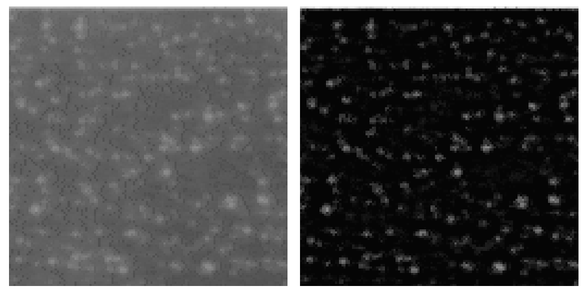

Fig.4: Original (left) and filtered (right) PIV image sample from case D.

The improved PIV image is evaluated using the 4-point CDIC method with an initial particle image displacement of 12 pixels in the horizontal direction. With the 64×64-pixel interrogation window, no erroneous vector is produced.

Package 1, Case E

The 8 synthetic PIV image pairs in case E have strong brightness variations in the x-direction. The brightness variation can be reduced with the 11×11-pixel linear unsharp mask, see Fig.5.

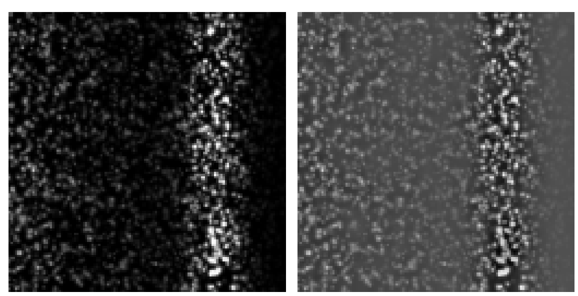

Fig.5: Original (left) and filtered (right) PIV image sample from case E.

For the first 6 PIV image pairs, there is no problem for using the CDIC method to obtain converged evaluation results based on the filtered particle image pairs. For the last three image pairs, since the displacement to be determined is very large (up to 38 pixels), and the interrogation window (16×16 pixels) is relatively small, the initial displacements must be set carefully to obtain converged, reasonable results. In addition, at some evaluation grid points near the edges of PIV image frame the interrogation window may be shifted far out of the image frame, so that no evaluation is possible with CDIC. When not considering the position deviation of the vectors, the conventional forward difference interrogation (FDI) method can be used to obtain displacement vectors at these points.

Package 1, Case F

No obviously erroneous vectors are observed when evaluating the four image pairs in case F of package 1 with the CDIC method. However, when animating these consecutively recorded PIV images, a few particles seem not move with the main particle flow. If these particles have adhered to the flow boundaries, they may cause bias to the evaluation results of CDIC.

Package 2, Case G

The evaluation of the first image pair in case G of package 2 is conducted on a 4×4-pixel grid structure using the 4-point CDIC method. The total iteration number is seven: A 32×32-pixel interrogation window is used in the first four iterations; then the interrogation window size is reduced to 16×16 pixels for the last three iterations.

Package 2, Case H

The PIV image pair in case H of package 2 is originally a 16-bit gray scale digital image. Since the software used here is designed only for the 8-bit gray scale bitmap, the 16-bit original PIV image pair is linearly transformed to 8-bit digital image pair. Then the transformed 8-bit PIV image pair is improved with the 11×11-pixel unsharp mask filter. The improved PIV image pair is evaluated with a 32×32-pixel interrogation window on a 16×16-pixel interrogation grid using the 4-point CDIC method. Because of the strong background noise, the erroneous displacement vectors cannot be totally avoided. The median filter and aim vector method are used to detect and correct the erroneous vectors.

Package 2, Case I

The evaluations of the image pairs in case I of package 2 are conducted on a 8×8-pixel grid structure using the 4-point CDIC method. The evaluation interrogation window has a size of 32×32-pixel in the first three iterations, and then it is resized to 16×16-pixel in the last three iterations.

4 SUMMARY

The software, algorithm, digital image processing techniques, and procedures used by the Purdue University contributor team for evaluating PIV images provided by PIV Challenge 2001 are reported in this paper. The evaluation results are not included here, because they will be examined, analyzed and compared by the committee in the conference time. Experiences show that the EDPIV software, especially with its evaluation function CDIC, is a powerful tool for dealing with evaluation problems in complex flow PIV measurements. An early version of the software can be downloaded from “http://eo.yifan.net/users/l/lcgui/”, and a new version will be available after the conference at “http://www.ecn.purdue.edu/microfluidics/”.

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