Analysis Tools for Holographic Particle Image Velocimetry (HPIV)

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Abstract An image compression algorithm has been incorporated into an existing PIV code in order to improve the performance of HPIV correlation calculations. It involves compressing an enhanced image and computing the correlation directly from the compressed data. With the procedure attaining a compression ratio of 20:1, typical for sparse HPIV images, the data processing speed is 5 times faster compared to a procedure without compression. The accuracy of obtaining the axial location (depth) of a particle from its axial intensity distribution is investigated by examining a reconstructed volume from two orthogonal holograms that are recorded simultaneously. Doubly exposed images of the same volume are used to determine the accuracy of using auto-correlation in the axial direction to find the corresponding velocity component by comparing it to the in-plane auto-correlation from the orthogonal view. The results show considerable loss of accuracy.

1 Introduction

In our present HPIV measurement of a turbulent water flow in a square duct (Zhang, et al., 1997; Tao et al., 1999), two perpendicular, double exposure holograms of the test section are recorded simultaneously (Fig. 1). Each hologram is individually reconstructed and scanned with a CCD camera at high magnification. Each scanned field provides a series of composite 2-D images obtained at different depths. These composite images are analyzed using a PIV auto-correlation procedure to determine the in-plane velocity components. Combining the sets of 2-dimensional vector maps from each of the holograms produces a three-dimensional velocity field. This procedure ensures that high accuracy is maintained in obtaining all three velocity components. The geometrical dimensions (the boundaries of the test section) are used for precision matching of the two images. The spatial correlation of the redundant \( v \)-component is also used to match the two views after the velocity measurements. Typically, HPIV images are reconstructed at high magnification and as a result the images are “sparse” in particle traces. For instance, using the current magnification of 5 \( \mu \text{m/pixel} \), a 640 \( \times \) 480 pixel\(^2\) video frame has an average of 25 particle pairs (Fig. 2). The total number of particles per 50 \( \times \) 50 \( \times \) 50 mm\(^3\) volume is between 1 –5 million. Each patched digitized plane consists of 9600 \( \times \) 9120 pixel\(^2\). Sampling the entire hologram at this resolution results in a database of 11 GB.

Fig. 1. Optical setup for recording two perpendicular off-axis holograms.

Fig. 2. A 5 mm \( \times \) 5 mm portion of reconstructed doubly-exposed HPIV image after image enhancement.

Considering that these HPIV images, except for a small number of the pixels, are predominantly blank, (e.g. only around 1% of pixels contain useful information for velocity extraction.) the data size necessary to determine the particle displacements can be significantly reduced with little loss in accuracy. Similar to Hart (1998), an image compression based direct correlation calculation kernel is developed and incorporated into the PIV code of Roth, et al (1999) for HPIV data processing. As discussed in sections 2 and 3, this algorithm allows for substantial reduction of space required for storing the HPIV images, and high
efficiency in the computationally intensive process of calculating the velocity.

It is also desirable to obtain all three velocity components from a single hologram, to further improve the efficiency of HPIV, as performed by Meng (1999). Although stereoscopic type methods such as off-axis viewing have been used to obtain the out-of-plane component, this approach is not a viable means for hologram images projected with relay lenses (e.g. present setup), due to the restricted viewing angle. The accuracy of obtaining the axial location of a particle from its intensity distribution along the out-of-plane axis is investigated in this paper by comparing the axial intensity distribution of a particle to the “exact” location determined from the perpendicular hologram. We also examine the accuracy of velocity measurements based on correlation of the particle axial intensity distributions, and compare it to the in-plane auto-correlation from the orthogonal view.

2 Image Compression

Images are compressed at the time when image enhancement is applied to further improve the signal-to-noise ratio of the particle traces. It involves setting pixel levels below a certain threshold to zero and using localized histogram equalization on the remaining part of the intensity spectrum (Roth & Katz, 1999). The enhanced “particle portion” of the image is then saved into a binary file that maintains the intensity and location of the pixels with levels different than zero in a sequential format, in which each pixel occupies a 40-bit unit. The lower 8 bits store the pixel value, and the upper 32 bits store the pixel location (x and y). The maximum image size that can be stored in this format is 64 K x 64 K bytes.

Since the data enhancement procedure is not information loss-free, it is important to select a threshold level that keeps most of the particle pixels and in the meantime, suppresses the background noise. Nevertheless, because the pixel intensities in our HPIV images are strongly bimodal, i.e., particle traces are much brighter than the background, the precise threshold level is not critical in practice. Therefore the compression ratio (original image size / compressed data size) in this scheme is dependent upon the parameters of image enhancement. If we define \( \rho \) as the percentage of pixels that survive the image enhancement, representing mostly the particle traces, then the resulting compression ratio, \( \gamma \), is \( \gamma = \frac{1}{5\rho} \).

We have also tried commercial image compression routines that are based on wavelets (which would have resulted in considerably more saving in data size), but we have found that the procedures modify the location of the particles to a level that has significant effect on the velocity measurement uncertainty.

3 Correlation Computation

As in PIV, HPIV vectors are determined by dividing the particle images into interrogation windows and then calculating the mean displacement of all particles within each interrogation window by evaluating the correlation function of the intensity distribution

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\Phi(u, v) = \sum_{x} \sum_{y} I_1(x, y)I_2(x + u, y + v),
\]

where \( I_1 \) and \( I_2 \) are the intensity distributions in the first and second image, respectively (for auto-correlation, \( I_1 = I_2 \)), \((u, v)\) is the displacement, and the summation in \( x \) and \( y \) covers the whole interrogation window (or part of it) (Roth & Katz, 1999).

Direct calculation of \( \Phi \) requires \( O(N^2M^2) \) multiplications, where \( N \) is the size of the interrogation window and \( M \) is the range over which the correlation function is to be computed. The computational cost increases drastically with the increase of \( N \). Therefore, use of conventional correlation (Roth et al, 1995) on HPIV data processing would be rather inefficient due to large interrogation windows (presently \( 192 \times 192 \) pixel\(^2\)).

During the execution of the correlation routine, the compressed data file is loaded and converted into a cross-linked node structure in memory, as shown in Fig.3. In order to obtain a correlation map, pixel values in a base window (defined by its size and location) are multiplied by values at corresponding locations in a shifted window. However, for each pixel in the base

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\text{Fig. 3. Compressed image data structure in memory, where } x \text{ and } y \text{ are the pixel coordinate and } I \text{ is the pixel value. Cross-linked node structure is used for fast indexing of individual pixels with minimum overhead of keeping track the node pointers in each non-empty row.}
\]

\( M \) is typically much less than \( N \), and with the commonly implemented adaptive vector extraction scheme, \( M \) represents a small search area surrounding a candidate vector.

\( * \)}
window multiplication only takes place if a corresponding pixel exists in the compressed map at the relative location in the shifted window. There is no operation if there is no match. Further increase in efficiency is achieved by using the truncated multiplication algorithm (Roth and Katz, 1999) and by calculating the correlation map in a smaller search window \((M < N)\) around a candidate vector. Consequently the multiplication operations is reduced to \(O(N^2M^2/g^2)\). Even with the added overheads for implementing the data structure, we should still see a significant improvement in processing speed.

Figure 4 shows a comparison between the uncompressed scheme (Roth et al, 1995, 1999) and the current scheme. A 2k x 2k portion of a HPIV sample image is used in carrying out test runs. The benchmarking system is a Pentium II 450 MHz single processor PC running Windows NT 4.0. Interrogation widow size, \(N\), of 128, 192, and 256 pixels have been used. As is evident from this plot, at compression ratios greater than 20, the current procedure results in significant computational savings (~ 6 times). Note that at compression ratio 7.5, the two schemes are even. Therefore, as long as large compression can be achieved, there is considerable improvement in processing efficiency. For the same compression ratio, the time ratio stays roughly the same regardless of interrogation window size. Thus the present processing time is proportional to \((MN/g)^2\). Subsequent data evaluation and error checking routines including high gradient correction are the same as in Roth & Katz (1999). The high gradient correction (averaging of multiple correlation peaks) is critical since increasing magnification frequently results in multiple peaks, each from an individual particle pair in the same interrogation window. This trend will be used in the future for particle tracking.

In our current HPIV data analysis, an interrogation window of 192 x 192 pixel\(^2\) is used with a 65% overlap between adjacent windows. Compression ratio of 22 ~ 25 is achieved, resulting in an overall increase of processing speed of about 5 compared to the uncompressed procedure. The resulting 3-D vector map consists of 136 x 130 x 128 vectors. It takes about 96 hours to acquire and process this data (2 holograms). Sample data is present in Tao et al (1999).

4 Determining the 3-D location of a particle from a single hologram

As noted before, we presently record two perpendicular holograms simultaneously (Figure 1) and reconstruct/analyze each hologram independently. Each reconstructed field provides the 3-D distribution of two velocity components. In this way we maintain the same level of accuracy for all three velocity-components. This approach avoids the “depth of focus” problem (Barnhart, et al, 1994; Meng & Hussain, 1995; Zhang et al, 1997) which extends the axial (out of plane) dimension of each particle, typically by about two orders of magnitude. However, recording two holograms is restrictive and in many applications impossible. In this section we examine whether it is possible to determine the 3-D location of a particle from a single hologram, i.e. whether it is possible to overcome the elongation. We examine the out-of-plane intensity distribution of several particles and compare them to the “exact” location available from the second hologram (refer to Fig. 5 for the coordinate system). In

![Figure 5](image-url)
other words, we compare the intensity distributions in the Z direction within the image of hologram No. 2 to the location and displacement of a particle available from the hologram No. 1.

To obtain the axial distributions of intensity in each of the reconstructed fields we record images in parallel planes, every 5 µm, within 3 mm deep subsections of the sample volumes (600 frames each). We then need to spatially match the two views precisely, i.e. we need the exact relation between coordinates. Assuming that the distortions are negligible, only spatial displacement is necessary. Because our test section does not have a reference structure/object that can be viewed in both holograms (besides the windows of the facility whose location can be measured to within ± 50 µm), we rely on matching the location of 50 particle pairs. “Coarse” matching, less than vector spacing (330 µm), can be achieved by correlation of the redundant velocity component. Fine-tuning to determine the exact offset is performed by correlation of particle centroids in the two reconstructed fields. In hologram 2 we select a volume that includes the entire particle image. The Y coordinate of the centroid is obtained by averaging the intensity in the X directions and visually examining the intensity profile in the Y - Z plane. The X coordinate of the centroid is obtained by averaging the intensity in the Y directions and performing visual examination in the X - Z plane. The Z coordinate is determined by averaging the location of the peaks in the two views. A similar procedure to is performed on each particle in hologram No. 1. Then, by performing a concise 3-D correlation (based on the centroids) we match the coordinates of the two reconstructed fields from the location of the maximum. Using this approach we have found the offset in Y to be within 3 pixels (15 µm) of the location determined from the velocity correlations, i.e. well within the expected accuracy.

Visual confirmation of the matched images is presented in Fig. 6. The left side is an X-Y plane and the right side is a Y-Z plane, showing orthogonal views of the same volume. Both consist of superpositions of two matched images in the corresponding perpendicular

Figure 6. Superimposed sample orthogonal views of matched X-Y (left side) and Y-Z (right side) planes of the same sample volume. For example, in the Y-Z plane the elongated traces are obtained by combining data recorded every 5 µm within the reconstructed image of hologram 2. The small circular traces are obtained from hologram No. 1. The circled traces are particle pairs found in both views.
views. On the right side, the image of hologram No. 1 contains the particle pairs and the image of hologram No. 2 consists of horizontal streaks (obtained by combining many planes), illustrating the extent of elongation. On the left side the streaks are obtained from hologram No. 1 and the points are from hologram No. 2. Both views are projections of the maximum intensities found within the volume, enabling us to observe particles distributed in the volume.

Five of the particle pairs that are located within the intersecting volumes are circled (note that they not all the particles in the common volumes). Not all the lines and points match due to the long extent of traces of particles that are located outside of the intersecting volume (in both views).

![Figure 7](image_url)

**Fig. 7.** A comparison of the intensity variation within the elongated traces in hologram No. 2 to the actual locations of the particles obtained from hologram No. 1 (vertical lines). Trace numbers correspond to the circled images in Fig. 6 (right side).

A more quantitative look at the circled particle traces is given in Fig. 7. We present only samples from the Y-Z plane, but the X-Y plane results are quite similar. Each line is the intensity distribution at the Y coordinate of the centroid, averaged over the particle extent in the X direction. In each case the solid line denotes the first exposure and the dashed line shows the second exposure of the same particle. The vertical lines present the exact location of the particle as determined from the perpendicular hologram. Note that in the present samples the dominant flow is in the Y direction. As a result, the two traces of the same particle appear at essentially the same Z. As is evident from these characteristic samples, there is considerable variation in intensity along the elongated trace and the measured location of the centroid does not necessarily match with the location of the point of maximum intensity. Even the distributions that belong to the same particle vary significantly, i.e. the distribution is not a characteristic of the particle.

Also, using the standard definition of “depth-of-field” as the place where the intensity drops to 80% of the maximum value, the present depth of field is 1 mm. This value is a function of the numerical aperture of the system and the method used for recording the hologram (angle of reference beam – Meng and Hussain, 1995). Note, however, that we can manually determine the plane of focus of a particle to within about 100 μm, i.e. substantially better than what one would conclude from Figure 7. Intensity gradients at the edge of the particle (edge detection) are used for this purpose (Katz et al., 1999).

In attempt to determine the velocity in the Z direction from just one hologram, we correlate the intensity distribution of two exposures of the same particle, averaged in the X direction. Here we present results of correlating trace No. 3 to No. 4 and trace No 23 to No. 24. Enlarged traces along with the results of the correlation are presented in Figure 8. The correlation maximum for particle 23-24 is located at -0.46 mm, whereas the actual displacement in the Z direction, determined from the orthogonal view, is less than 5 μm. This discrepancy represents an error of about 350% compared to the total magnitude of the velocity. The primary cause for this discrepancy is the existence of multiple intensity peaks in the particle trace, clearly evident in Figure 8a. This non-monotonic distribution is caused by interference with another particle located at the same Y but at a different X. We get a slightly better correlation for particle 3-4, when the intensity distribution of the trace is not bimodal (i.e.

![Figure 8](image_url)

**Fig. 8.** (a) Enlarged traces of particle 23-24 shown in Figure 4; (b) cross-correlation of the traces in a; (c) enlarged traces of particle 3-4; (d) cross correlation of the traces in c.

it has a single maximum). However, even in this case the correlation peak is located at -0.12 mm, more than an order of magnitude larger than the expected value. Thus, unfortunately the correlations in both examples do not provide the correct velocity in the Z direction. It is possible that other methods of averaging or low-path filtering the intensity distributions would provide better
results. We plan to investigate such approaches in the future.

5 Summary

This paper is divided into two parts. The first summarizes methods for improving the data analysis procedures of HPIV data. Image compression along with direct correlation of the compressed data provides significant saving, both in the required storage capacity and in the speed of data analysis.

The second part examines the feasibility of obtaining all three velocity-components from a single hologram (we presently use two perpendicular holograms). The primary difficulty is caused by the depth of focus problem, that increases the extend of the out-of-plane dimension of reconstructed objects. Having perpendicular images available enables us to compare the elongated traces to the exact location of the particles. The results show that the intensity distributions within the elongated traces of some particles are not monotonic due to interference with traces of other particles. Consequently, there is considerable uncertainty about the location of the centroid. Correlations between elongated traces of the same particle do not provide the correct velocity in the out-of-plane direction. Methods to reduce the interference effect and reduce the depth of focus problem are clearly needed.

References