Accelerated Super-Resolution PIV based on Successive Abandonment Method

by

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ABSTRACT

The super-resolution PIV based on the recursive division of interrogation window has attracted interest recently. This approach needs careful error checks because results are largely affected by the pre-step displacements obtained by large interrogation windows. Hart (2000 Experiments in Fluids Vol.29-1) proposed the error check method by multiplication between correlation distributions of overlapped neighboring interrogation windows. However, the recursive calculation with ordinary cross-correlation method requires too much computational time. In order to reduce it, Hart (2000 J. Flow Visualization Vol.3-2) used image compression techniques. In this study, we use not image compression but characteristic pixel selection to accelerate the super-resolution PIV. Our PIV is based on successive abandonment (SA) method (Kaga et al. 1993 J. Flow Visualization and Image Processing Vol. 1-4). In the SA calculation with the characteristic pixel selection, 1000 candidates are narrow down to only one at over 50 % of measurement points. And also difference between correct candidate and other ones becomes clear by characteristics of selected-pixel as shown in Fig. 1, so the number of error vectors is reduced. Comparing the time per velocity vector, our super-resolution PIV is 10 times faster than the former ordinary resolution PIV. In all recursive processes, error checks are carefully done using the summation of cumulative intensity difference distribution to be suitable for SA method. Another feature of our PIV is that the velocity vectors are obtained near the boundary of images and masked regions as shown in Fig. 2. Velocity vectors near the boundary of images and masked regions are calculated carefully by extrapolation of predicted displacement, pattern matching using small interrogation window and error elimination. By these procedures, High-speed high-density PIV was achieved.

Fig. 1. Distribution of cumulative difference of intensity (the direction of vertical axes is opposite). (a) using n pixels of centerline of interrogation window; (b) selected n pixels. n=32.

Fig. 2. Results of super-resolution PIV for VSJ standard image PIV#04. (image size 256x256, interrogation sizes are 32x32 pixels at level0 and 4x4 pixels at the last level, search sizes are 35x35 pixels at level0 and 7x7 in other levels.
1. INTRODUCTION

Particle image velocimetry (PIV) is useful as a powerful tool that can measure the spatio-temporal distribution of fluid velocity. Recently, as development of photographing tools such as cameras, illuminations and so on, high-density particle images can be obtained. Along with such development, some algorithms of the super-resolution PIV have been proposed (Kean et al. 1995, Hart 2000a, Sitou & Riethmüller 2001). In particular, Hart’s algorithm is useful technique that has simple algorithm and makes resolution higher with removing erroneous vectors carefully. He proposed the error check method by multiplication between correlation distributions of overlapped neighboring interrogation windows. However, the recursive calculation with ordinary cross-correlation method requires too much computational time. In order to reduce it, Hart (2000b) used image compression techniques. In this study, we use not image compression but characteristic pixel selection to accelerate the super-resolution PIV.

Our PIV is developed based on successive abandonment (SA) method (Kaga et al. 1993). In the former SA method that calculates cumulative intensity difference per line in an interrogation window, calculation speed depends on the intensity pattern in interrogation windows and non-effective abandonment leads to the occurrence of error vectors. In this paper, we introduce the new algorithm of SA method. The new algorithm is using selected characteristic pixels which have the highest intensity and the lowest one in a line of an interrogation window. By this method, difference between correct candidate and other ones becomes clear and the SA method can be accelerated. Combined by this selected pixel approach and error detection suitable for SA, high-speed super-resolution PIV was achieved.

Another feature of our PIV is that the velocity vectors are obtained near the boundary of images and masked regions, in which large interrogation window hinder calculation of displacements. In this study, velocity vectors in that region are obtained by applying the recursive approach.

2. CALCULATION METHOD

Our super-resolution PIV is achieved by recursive repetition of pattern matching, error check and displacement detection. Finally sub-pixel accuracy displacements are calculated and region near the boundary is examined. In this section, each part will be explained.

2.1. Pattern matching and its acceleration

As a template matching method, successive abandonment (SA) method proposed by Kaga et al. (1993) is used. SA method uses cumulative intensity difference $D$ as the matching index,

$$D(i, j) = \sum_{i=-n/2}^{n/2} \sum_{m=-n/2}^{n/2} |f(i+l, j+m) - g(l, m)|$$

where $g$ is the intensity of a template image and $f$ is the image intensity of the next frame. When the $D$ is minimum, the point $(i, j)$ is considered as the destination of the template image. Here, the candidate pattern is largely different from the template pattern, equation (1) become large value before finishing the calculation of all summation. So, in the SA method, cumulative difference is calculated line by line, and then candidates are abandoned by threshold as shown in Fig. 3.

In the former SA method that calculates cumulative intensity difference per line in an interrogation window, calculation speed depends on the intensity pattern in interrogation windows and non-effective abandonment leads to the occurrence of error vectors. So, we introduce the new algorithm using selected characteristic pixels. By using these characteristic pixels, difference between correct candidate and other ones becomes clear. We chose the highest intensity pixels and the lowest ones in every two lines of interrogation windows as characteristic pixels as shown in Fig. 4. When the size of a interrogation window is set to $n \times n$ pixels, the number of selected pixels is $n$. Candidates are narrowed down by calculation of cumulative difference of intensity for these selected pixels.

Fig. 5 shows a sample of distribution of cumulative difference of intensity. Fig. 5(a) is the case by using $n$ pixels of centerline of interrogation window and Fig. 5(b) is by selected $n$ characteristic pixels, where $n=32$. Images used in this sample are the PIV standard images provided by Visualization Society of Japan (Okamoto et al. 2000). It is found that the selected pixel approach makes the peak of cumulative difference intensity clear. As the
The number of calculated pixels

Fig. 3. Diagram of successive abandonment

Cumulative Intensity difference

Fig. 4. Characteristic pixel selection

Fig. 5. Distribution of cumulative difference of intensity (the direction of vertical axes is opposite). (a) using n pixels of centerline of interrogation window; (b) selected n characteristic pixels. n=32.

Table 1. The rate of measurement points whose candidates for the number of candidates not abandoned.

<table>
<thead>
<tr>
<th>The number of candidates not abandoned</th>
<th>rate of measurement points [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>line calculation</td>
</tr>
<tr>
<td>1~10</td>
<td>32.5</td>
</tr>
<tr>
<td>11~500</td>
<td>63.8</td>
</tr>
<tr>
<td>500~1089</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Table 2. The rate of measurement points whose candidates are narrowed down to less than 1% for the number of calculated lines.

<table>
<thead>
<tr>
<th>The number of calculated lines</th>
<th>rate of measurement points [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>selected pixels</td>
<td>former</td>
</tr>
<tr>
<td>1~4</td>
<td>35.2</td>
</tr>
<tr>
<td>5~8</td>
<td>11.7</td>
</tr>
<tr>
<td>9~16</td>
<td>14.0</td>
</tr>
<tr>
<td>17~24</td>
<td>5.3</td>
</tr>
<tr>
<td>25~32</td>
<td>33.8</td>
</tr>
</tbody>
</table>
result of abandonment for this distribution, the number of residual candidates is 97 for (a) and 4 for (b). So, the calculation using only $n$ pixels can determine the approximate displacement in this sample case. Table 1 shows the rate of the number of measurements points for the number of candidates not abandoned. At over 50% of measurements points, candidates are narrowed down to less than 1% (the size of search window is 33x33, then the number of total candidates is 1089).

At the residual measurement points where the candidates are not narrowed down, cumulative differences of one line are calculated and candidates are abandoned after calculation at line by line. In this calculation, a line which contains the highest intensity pixel is selected out of lines not calculated yet. Table 2 shows the rate of measurement points whose candidates are narrowed down to less than 1% for the number of calculated lines. Present algorithm can narrow the candidates down to 1% at 99% of measurement points by 1/4 calculation of interrogation window.

### 2.2. Error check and displacement decision

After candidates are narrowed down at the all measurement points, error check is applied. Interrogation windows are set to be overlapped with neighboring ones in their half region. When displacements are calculated...
by using overlapped interrogation windows, the minimum value of cumulative intensity difference on the
neighboring points is obtained in the similar position. So the summation of cumulative intensity difference
distribution emphasizes the correct minimum value and weakens the wrong ones as shown in Fig. 6. The
position of local minimum value of cumulative intensity difference nearest to the position of minimum value of
summed one is determined as the displacement. Unlike Hart’s algorithm (Hart 2000a) using product of
correlation distribution, we use summation. That is because there is a possibility that neighborhoods of correct
peak are abandoned. By this error elimination, displacements from a few candidates can be determined, so the
SA does not have to narrow candidates to only one.

2.3. Recursive repetition

After these procedures, interrogation windows are divided in half size \((n/2 \times n/2\) pixels) and same procedures are
done. But, the search windows are limited to the region near the displacements calculated by previous level with
larger interrogation windows. And cumulative difference is calculated by only selected pixels except for final
level, because displacements can be detected by selected pixels in the small-size search windows. By repeating
these procedures recursively, super-resolution PIV is achieved with less computational efforts. At final level, all
pixels in the interrogation window are used to determine the displacement because the final level calculation is
directly concerned with accuracy and the time spent for calculation of small-size interrogation window is small.
After final level calculation, sub-pixel accuracy displacements are calculated by parabolic interpolation around
the peak of cumulative difference distribution.

2.4. Treatment of boundary region

Large interrogation window hinder calculation of displacements near the image boundaries. The nearest point to
the boundary is decided by half of interrogation window size plus search window size. At the outside of these
points, pattern matching cannot be done. In this study, velocity vectors in that region are obtained by applying
the following approach. At first, inner region is calculated till last level as mentioned above section. In one layer
of measurement points nearest to inner region, displacements are predicted by linear extrapolation. Using these
reference displacements, candidates are calculated with last-level interrogation windows and small-size search
window. The correct displacements are obtained by before-mentioned error elimination method. The same
procedures are repeated from inner region to boundary line by line. Of course, this calculation is not done when
a predicted displacement is out of the image.

In actual measurements, there are the cases that some objects are taken in PIV images. In such cases, mask
treatments are often applied. In mask treatment, only painting in black in the object region causes error vectors.
In our PIV mask regions are treated in the same way as boundary regions. At first, interrogation windows and
search windows are checked whether these windows hang in the mask region. At these windows which hang in
the mask region, velocity is not calculated till last level calculation. After final level calculation at other points,
velocities in these regions are calculated in the same approach as in the boundary region.

3. RESULTS AND DISCUSSION

Fig. 7 shows the results by present super-resolution PIV with and without boundary calculation for standard
image #04. The sizes of interrogation windows are 32x32 pixels at level0 and 4x4 pixels at the last level, and the
sizes of search windows are 35x35 pixels at level0 and 7x7 in other levels. It is found that very high-density
velocity vectors can be obtained by our PIV. Without boundary calculation shown in Fig. 7(a), outside of image is
ineffective (the region of over 35/2=17 pixel width is blank). On the other hand, with boundary calculation
shown in Fig. 7(b), velocity vectors are obtained effectively in the boundary limit (i.e. to just 2 pixel next to the
boundary in the upper stream and outflow limit in the down stream) and error vectors caused by out of image
motion are not calculated. It is found that our PIV can obtain the smooth velocity distribution as shown in Fig.
7(c), which is expanded image of enclosed region of (a) and (b).

Concerning the measurement accuracy, measured velocity data are compared to the attached data of PIV
standard images. Reference data at all measurement points are obtained by bi-linear interpolation and
extrapolation of original data. Fig. 8 shows the scatter plot of deviation of measured velocity from reference
velocity, where unit of velocity is pixels/frame. It is found that almost all error is within 0.5 pixels/frame. Then,
mean value of absolute error is 0.29 pixels/frame and root mean square of error is 0.40 pixels/frame.
Fig. 7. Results of super-resolution PIV for VSJ standard image PIV#04. (image size 256x256, interrogation sizes are 32x32 pixels at level0 and 4x4 pixels at the last level, search sizes are 35x35 pixels at level0 and 7x7 in other levels. (a) without boundary calculation, (b) with boundary calculation, (c) partially expanded image of enclosed region of (a) & (b)

Table 3 shows the time spent to calculate the velocity vectors in each level and the total time. It is shown that the selected pixel approach decreases the calculation time to about 70% of the former SA method. The former ordinary-resolution PIV takes 656ms/625vectors = 1.05ms/vector. So, the time per velocity vector by our super-resolution PIV is about 10% of the former ordinary resolution PIV.

Concerning the mask treatment, Fig. 9 shows the effect of mask treatment for PIV standard images #04 partially painted in black. Fig. 9(a) is original image. Fig. 9(b) is result without special treatment. Fig. 9(c) is the result by present approach in the same way as the present boundary treatment. Without the special treatment, many error vectors are calculated. On the other hand, the present approach can obtain the velocity vectors as much as possible in the region where reasonable velocities can be obtained (i.e. to inflow limit in the upper stream and mask boundary in the down stream). The number of velocity vectors obtained by special treatment is 665. The number of velocity vectors different from the result of Fig. 7 is only 4 and maximum deviation is 0.57 pixels/frame. This results show that our approach is very effective for mask treatment.

Results for another test case is shown in Fig. 10. Fig. 10 (a) shows the test image (256x256 image size, mean particle diameter 4 pixels), which is made following the PIV standard image (Okamoto et al. 2000). Horizontal velocity has linear profile from 0 to 6.4 along the vertical axis and the shear rate 6.4/256=0.025. The size of interrogation window and mean particle diameter is 4 pixels, so velocity difference at 4 pixels is 0.1
pixels/frame.
Fig. 8. Deviation of measured velocity from reference velocity

Table 3. Computational time

<table>
<thead>
<tr>
<th>Level</th>
<th>without pixel selection</th>
<th>pixel selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>level 0</td>
<td>282</td>
<td>219</td>
</tr>
<tr>
<td>level 1</td>
<td>375</td>
<td>47</td>
</tr>
<tr>
<td>level 2</td>
<td>515</td>
<td>172</td>
</tr>
<tr>
<td>level 3</td>
<td>953</td>
<td>953</td>
</tr>
<tr>
<td>boundary</td>
<td>391</td>
<td>391</td>
</tr>
<tr>
<td>total</td>
<td>2516</td>
<td>1782</td>
</tr>
<tr>
<td>the number of vectors</td>
<td>15534</td>
<td>15534</td>
</tr>
<tr>
<td>time/vector</td>
<td>0.162</td>
<td>0.115</td>
</tr>
</tbody>
</table>

Fig. 9. Effect of mask treatment. (a) original image (PIV standard image #04) whose center region is painted black (b) without mask treatment (c) with mask treatment. (b) & (c) are partially expanded in the region near the black painted one.
Result in Fig. 10(b), which shows vertical distribution of horizontal velocity component, shows the tendency of pixel locking. The deviation of measurement results from correct velocity is shown in Fig. 10(c). It is found that almost all the deviations are within about 0.5 pixels/frame regardless of 0.1 pixels/frame velocity difference by linear shear. This result shows that the sub-pixel calculation needs to be improved. At the boundaries, the velocity vectors obtained by the present treatment of boundary are reasonable. A case of parabolic velocity distribution is also tested (the result is omitted in this paper). The accuracy does not depend on the velocity gradient and almost all the deviations are within about 0.5 pixels/frame like the results of Fig. 10.

4. CONCLUSIONS

New algorithm for recursive super-resolution PIV was introduced. Pattern matching was accelerated by the characteristic pixel selection approach. Error check of Hart’s algorithm was modified to be suitable for successive abandonment method. And treatment of boundaries and masks was proposed. The availability of our super-resolution PIV was examined by using PIV standard images and original synthetic images. As the results, the following points were shown. The proposed super-resolution PIV is 10 times faster than former ordinary-resolution PIV. The accuracy of it is fairly good. It can obtain velocity vectors effectively in the region near the boundaries and masks. It is necessary to continue examining the range of application and the accuracy.

REFERENCES