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Development of a Recursive Local-Correlation PIV Algorithm and Its Performance Test

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Abstract: The hierarchic recursive local-correlation PIV algorithm with CBC(correlation based correction) method was developed to increase the spatial resolution of PIV results and to reduce error vectors. This new algorithm was applied to the single-frame and double-frame cross-correlation PIV techniques. In order to evaluate its performance, the recursive algorithm was tested using synthetic images, PIV standard images from Visualization Society of Japan, real flows including ventilation flow inside a vehicle passenger compartment and wake behind a circular cylinder with riblet surface. As a result, most spurious vectors were suppressed by employing CBC method. In addition, the hierarchical recursive correlation algorithm improved largely the sub-pixel accuracy of PIV results by decreasing the interrogation window size, increasing spatial resolution significantly.

Keyword: Recursive Correlation Algorithm, CBC(Correlation Based Correction), PIV, Performance Test

1. Introduction

The conventional PIV algorithm which is widely used in nowadays is based on statistic correlation of particle images, i.e. auto-correlation for single-frame multiple exposure images or cross-correlation for double-frame single-exposure particle images. These correlation algorithms divide each single image into a number of sub-regions, so-called interrogation windows. For each interrogation window the correlation function is calculated and the position of displacement peak is determined on the correlation plane, then the average velocity in the window is determined by dividing the displacement value by the time interval between two exposures. Since the displacement peak obtained by spatial correlation method represents the average movement of particles in each interrogation window, the spatial resolution of vector field measured by PIV technique is directly related with the size of interrogation window. If the interrogation window is large enough in size and covers some small-scale turbulent structures or vortex structures, all these detail flow field information might be lost during the correlation analysis, and the PIV may not be continuous. Further more, the differential quantities such as vorticity should be derived from these velocity information representative for each interrogation window, therefore the obtainable spatial resolution of the differential estimates will be limited by the spatial resolution of the velocity field and the results of vorticity is local average of an already spatial-averaged velocity field. In addition, the magnitude of vorticity may be much smaller than the actual value. In order to achieve velocity and vorticity results in high spatial resolution, the size of interrogation widow should be decreased as small as possible.

However, Keane & Adrian (1990) mentioned that at least ten-tracing particle images are needed in each individual interrogation window to obtain accurate estimation of average displacement, for the conventional PIV algorithm based on correlation analysis. This limitation should be fulfilled by choosing interrogation window size to have adequate numbers of particles in the window. With this restriction, it is difficult to improve dramatically the spatial resolution of vector field by decreasing the interrogation window size for conventional correlation PIV techniques. In recent years, some new algorithms for improving the spatial resolution of PIV results (Super-resolution PIV) using hierarchical recursive operation were proposed by Hart(1999), Scarano & Riethmuller(1999) and Hu et al.(2000). Hart (2000) adopted the CBC(Correlation Based Correction) algorithm together with the recursive correlation scheme to eliminate spurious vectors in PIV results during data processing.

In this paper, we employed the hierarchical recursive correlation algorithm with CBC processing and window offset to both single-frame and double-frame cross-correlation PIV systems, and tested its performance for various flows including synthetic particle images, standard PIV images of Visualization Society of Japan (VSJ) and real flow PIV images.

2. Hierarchical Recursive Correlation Algorithm and CBC

2.1 Hierarchical Recursive Correlation

The concept of the hierarchical recursive correlation algorithm is very simple. If basic information on the magnitude and direction of local displacement in the sub-region of a PIV image is available, the size of interrogation widows can to be reduced and offset by following the prediction of prior local displacement information. The in-plane loss of pairs caused by out-of-boundary particle motion can then be compensated during correlation operation. This procedure can be recursively conducted to reduce the interrogation window size hierarchically, the spatial resolution of vector field is therefore increased.

We implemented following steps to accomplish the hierarchical recursive PIV correlation operation:

a) Carry out a conventional PIV correlation routine for a usual interrogation window in which proper number of particle images are involved so that prominent signal to noise ratio can be obtained on the correlation plane, perform peak detection and get displacement information for each interrogation windows.
b) Store the resulting displacement information to be used as a predictor in the further coming steps.
c) Divide the interrogation window to half-sized regions according to one quarter rule as shown in Fig.1. Predict the offset of smaller interrogation windows using the estimated displacement date obtained from prior step to compensate the in-plane loss of pairs caused by out-of-boundary particle motion(Fig.2).
d) Perform the correlation operation for smaller interrogation windows. The resulting values in this step must plus with corresponding predictor value and then produce sub-pixel displacement with higher accuracy.
e) Repeat the steps from (b) to (d) until get a proper spatial-resolution in the PIV results.

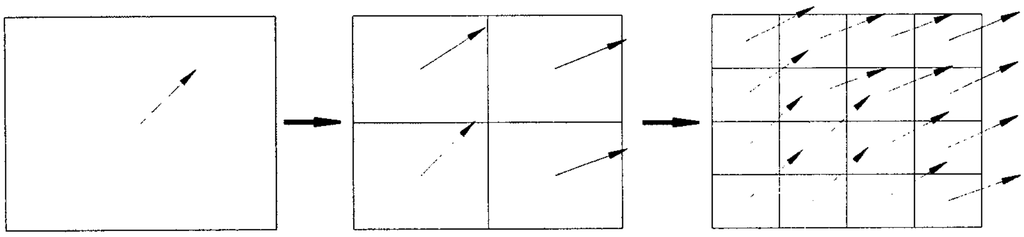


Fig.1 Schematic of hierarchical recursive algorithm

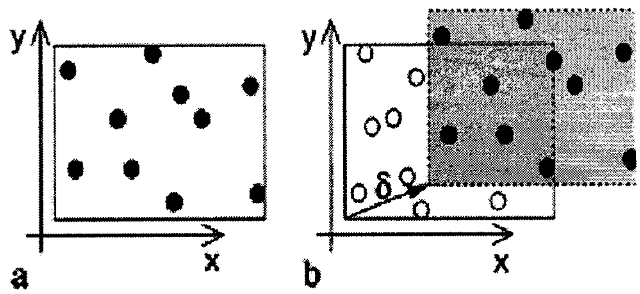


Fig.2 Principle of interrogation window offset

2.2 Correlation Based Correction(CBC)

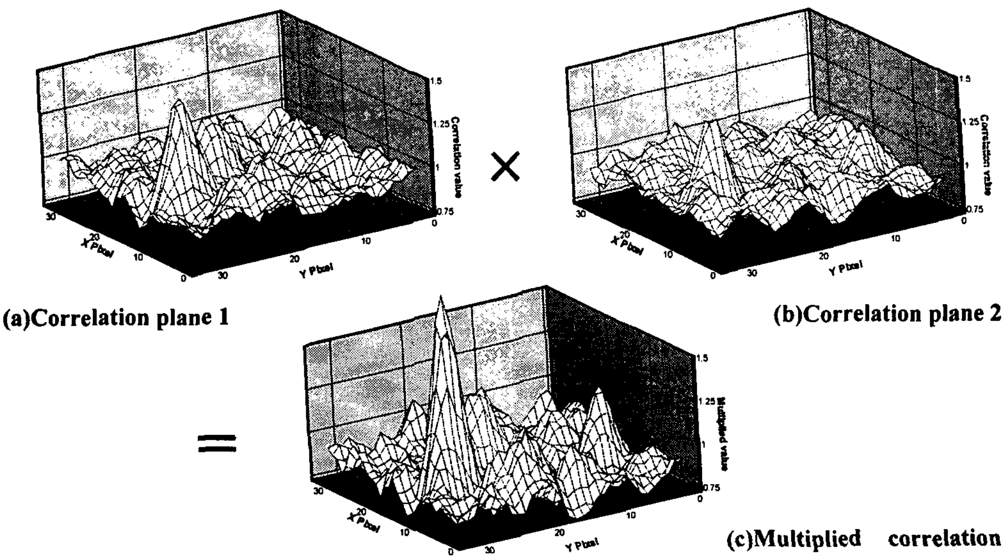
If the number of particle images inside a interrogation window is insufficient at the first step on the hierarchical recursive algorithm, the SNR (signal-noise ratio) will be very poor on the correlation plane. This may cause the displacement peak to merge in the random background noise. It is difficult to perform the displacement peak detection in this case and some spurious vectors may appear in the result. Supposing this inaccurate displacement information are used to predict the offset of smaller interrogation windows in the succeeding steps, more error vectors will be generated. In General, the conventional PIV method employs the interpolation to replace these spurious vectors during post-processing.

Hart(2000) developed CBC(correlation based correction) and it showed good performance in eliminating error vectors caused by anomalies correlation. The CBC processing is based on the principle of the element-by-element multiplication of a correlation plane generated from one interrogation window by other correlation planes generated from one or more adjacent interrogation regions, on the resulting plane, the SNR will be improved significantly.

Fig.3 illustrates the procedure of CBC method. The correlation plane 1 from the first interrogation region is multiplied by correlation plane 2 from an adjacent interrogation region which is 50% overlapped with the first interrogation region. The SNR is quite low in both of correlation planes 1 and 2, while on the multiplied correlation plane a prominent displacement peak is observed. The correlation anomalies are remarkably reduced and the error vectors can be easily eliminated before the vector is determined.

The basic idea of CBC technique is that the location of noise peaks on a correlation plane are always random and the positions of displacement peak is almost identical on correlation plane of adjacent interrogation region, after multiplication of these tow correlation planes, the back ground noise peaks keep same level as on the individual correlation planes, while the magnitude of displacement peak is increased prominently. The efficiency of reducing anomalies errors during CBC processing increases as the size of overlapped region decreases. However, the optimum overlapping depends on flow structure of testing and the seeding density. In general, the

50% overlapping is adopted in most correlation algorithms. Hart (2000) suggests 50% overlap rate is a acceptable value to evaluate the performance of CBC algorithm. We also conducted 50% overlapping rate in testing the performance of our program.



(a)Correlation plane 1

(b)Correlation plane 2

(c)Multiplied correlation

Fig.3 Principle of CBC algorithm

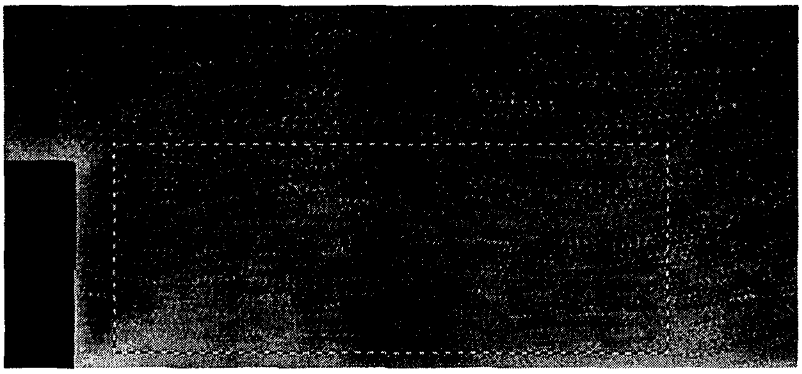
3. Performance Tests

We applied the hierarchical recursive algorithm CBC processing to the digital cross-correlation PIV program for both single-frame and double-frame particle images. The performance test include evaluation of efficiency of CBC processing to analyze real flow field image, accuracy assessment of the recursive algorithm for synthetic particle images, comparison of standard PIV images from Visualization Society of Japan(VSJ) by varying the interrogation windows size, and finally for real flow field testing.

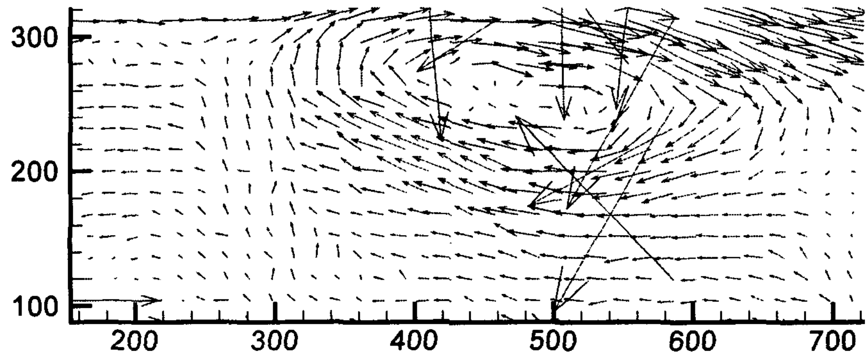
3.1 Efficiency of CBC Processing

A single-frame multiple-exposure PIV particle image of backward-facing step flow was used to test the efficiency of the algorithm. The second particle image was shifted by 9 pixels with image-shifting technique, shown in Fig.5(a). The convention FFT based single-frame cross-correlation PIV method and CBC processing were applied to the flow image with 32×32 pixel^2 interrogation window to compare the spurious vectors in the final velocity field. Fig.5(b) shows several error vectors in the velocity field obtained by conventional FFT based correlation method. The spurious vectors have to be interpolated by proper data during post-processing, but it will not contribute to increase the sub-pixel accuracy evaluation.

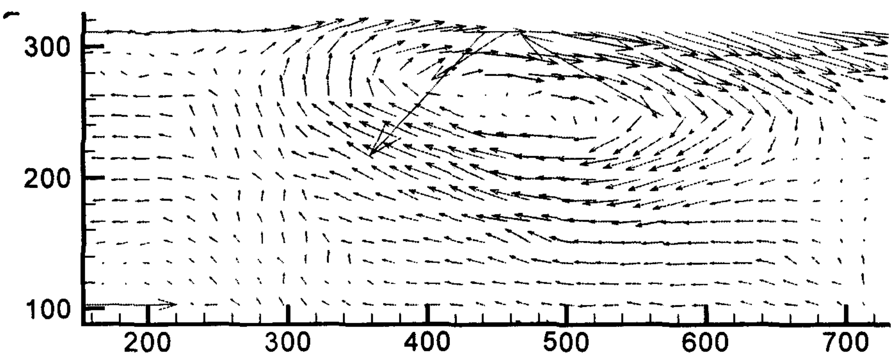
Fig.5(c) shows the velocity map obtained with CBC processing, which multiplied correlation planes from two adjacent interrogation regions, in the result the appearance of spurious vectors is decreased and the sub-pixel accuracy is also improved. If correlation planes from more (three or four) adjacent interrogation regions are multiplied, we can obtain preferable velocity field result.



(a) Single-frame double-exposure particle image



(b) Conventional FFT based PIV method (32×32pixel^2)



(c) Correlation based correction method (32×32pixel^2)

Fig.4 Comparison of conventional FFT and CBC method for the backward facing step flow (32×32 pixel^2)

3.2 Accuracy assessment

There are several methods to assess the accuracy of PIV measurement results. One approach is to use particle images taken from real flow with known quantity of particle displacement. Another method commonly applied is to use synthetic particle images generated by numerical simulation, by varying the parameters of particle images, known information of displacement can compared with the PIV result. Synthetic particle image was generated with 8-bits gray-scale randomly distributed particles having Gaussian intensity distribution. The flow images containing 4000 particles have 640×480 pixel^2 resolution with particle diameter of 4 pixels. The second exposed particle image was imposed by a pre-set displacement (0~11 pixels) from the first particle image horizontally to simulate a uniform flow.

Fig.6 shows the rms(root-mean-square errors) error of conventional FFT based correlation PIV method and hierarchical recursive correlation PIV method as a function of particle image displacement. From this, we can compare the accuracy of two PIV algorithms for different interrogation window size. The conventional FFT correlation result shows higher RMS error due to the in-plane loss of particle pairs. For the recursive correlation PIV results, the RMS error is less than half for the same interrogation window of conventional PIV method. In addition, as the interrogation windows size increases, the RMS error is decreased. Because the seeding density is relatively sparse in this synthetic particle image, higher SNR value can not be obtained for 16×16 pixel^2 interrogation window, it shows better performance compared with the conventional PIV method with 32×32 pixel^2 interrogation window.

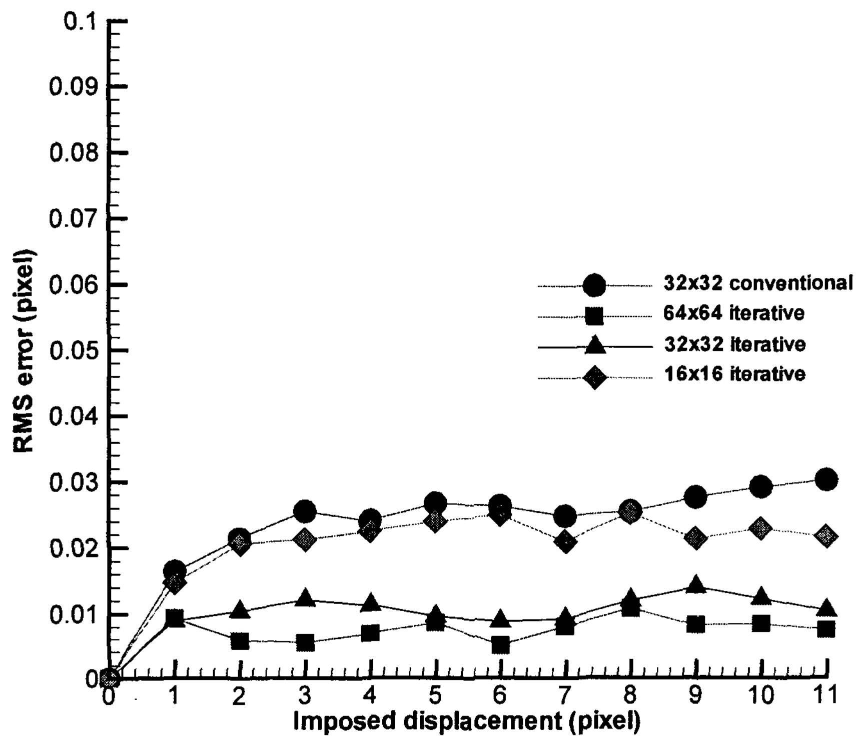
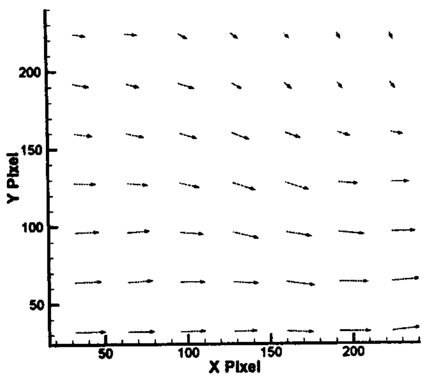


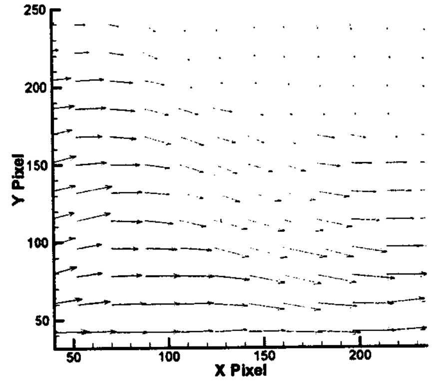
Fig.6 Measurement error as a function of particle displacement

3.3Standard PIV Images

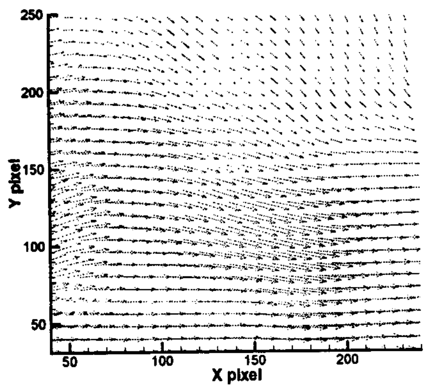
Visualization Society of Japan(VSJ) provides standard PIV images simulated by numerical algorithm to evaluate the effectiveness and accuracy of PIV programs. In this study, the standard PIV image of impinge jet flow was used to test the performance of the recursive correlation based PIV program. The resolution of flow image is 256×256 pixel^2 with 4000 seeding particles and 5 pixels of particle diameter. Figs.7 and Figs.8 represent the variation of velocity fields and vorticity distributions of the impinge jet flow by varying the interrogation window size. The results of the conventional FFT based correlation PIV method are shown at the first level of spatial resolution of 64×64pixel^2 interrogation window size. As the interrogation window size is decreased recursively to 32×32 pixel^2 and 16×16 pixel^2, it gives more detailed flow structure and vorticity distribution with enhanced spatial resolution. The recursive PIV results for 8×8 pixel^2 interrogation window size give much finer vortex structure from the same particle images, compared with the only 2 or 3 vortices for the case of 64×64pixel^2.



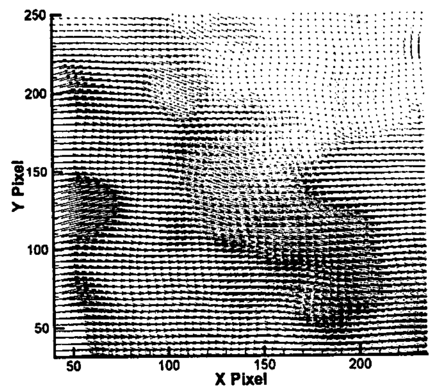
(a) 64×64 pixel^2



(b) 32×32 pixel^2

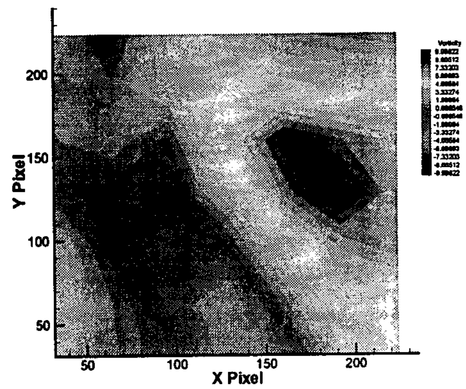


(c) 16×16 pixel^2

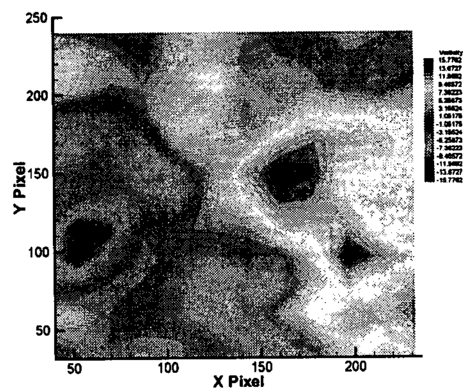


(d) 8×8 pixel^2

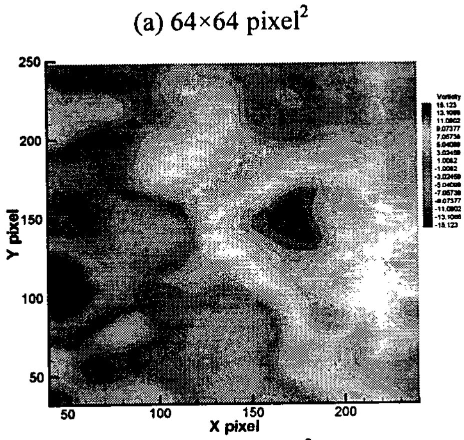
Fig.7 Variation of velocity field for standard PIV image



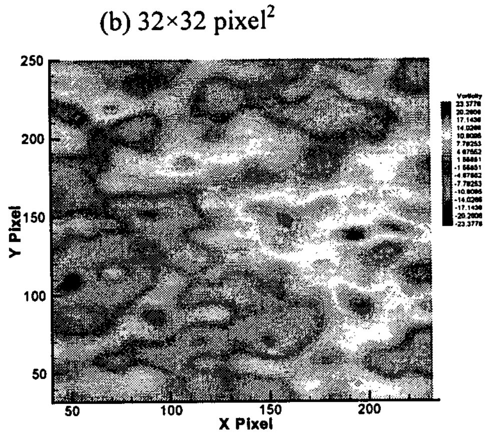
(a) 64×64 pixel^2



(b) 32×32 pixel^2



(c) 16×16 pixel^2



(d) 8×8 pixel^2

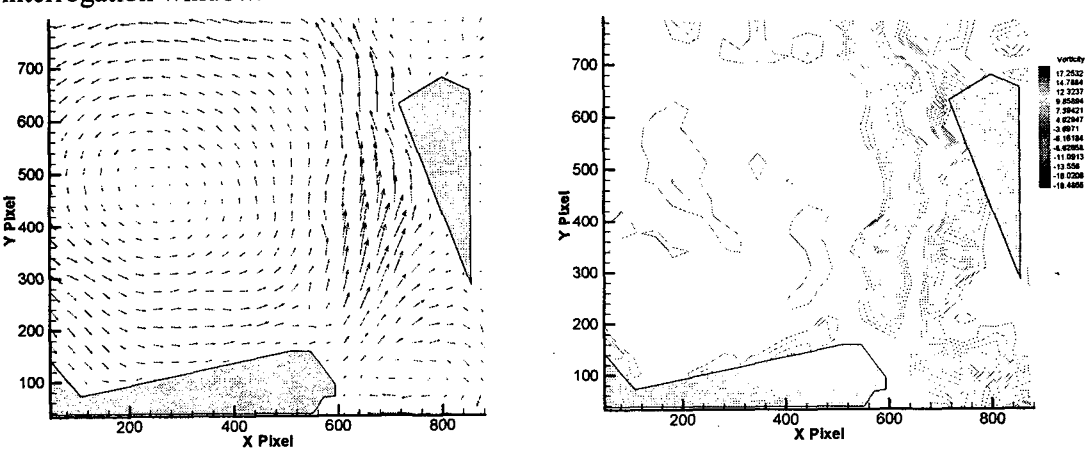
Fig.8 Variation of vorticity contour with respect to the interrogation window size

3.4 Real Flow Applications

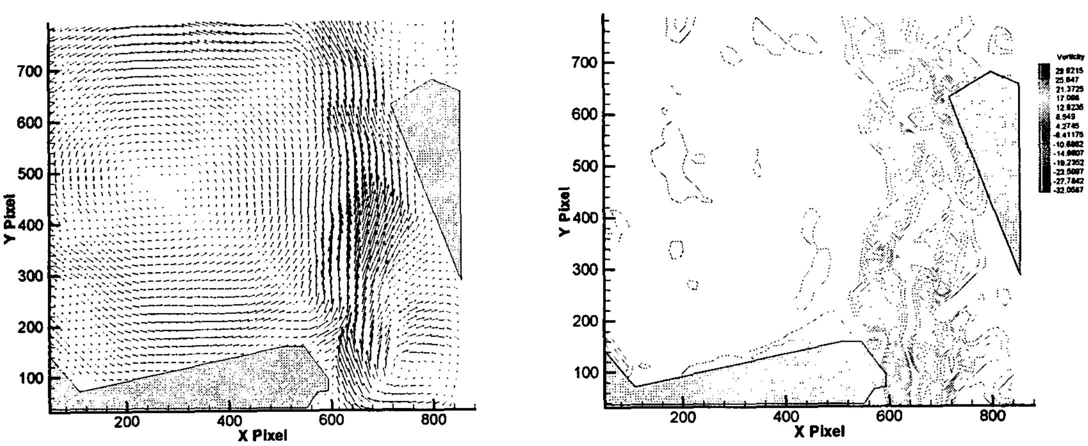
The effectiveness of the recursive correlation PIV technique was evaluated for two kinds of real flows; (1) ventilation flow in a vehicle passenger compartment and (2) wake flow behind a circular cylinder with riblet surface.

3.4.1 Ventilation flow in a passenger compartment

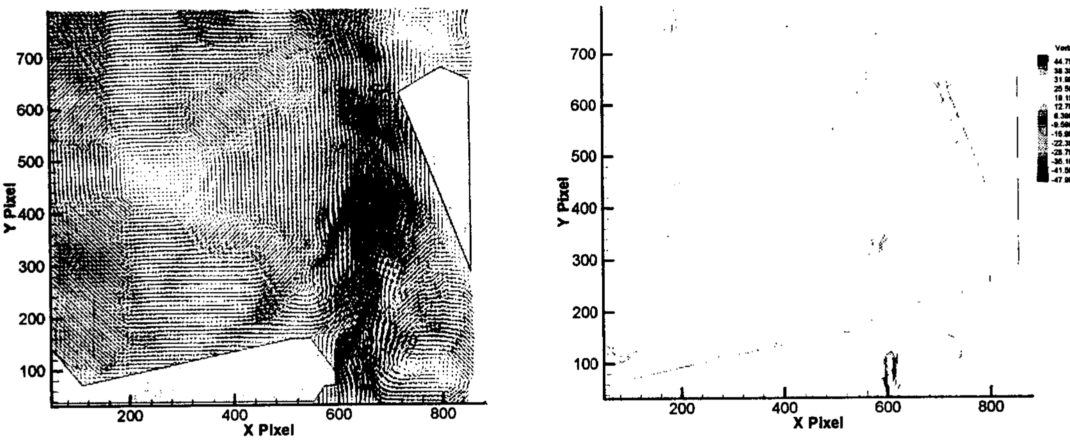
Particle images of the ventilation flow inside a vehicle passenger compartment model were captured with a high-resolution CCD camera of 2k×2k pixel^2, the velocity fields for the flow behind the front seat shown here were extracted from the entire velocity field maps. Fig.9 shows the comparison of the PIV results at three different spatial resolution levels having interrogation window size of 64×64 pixel^2, 32×32 pixel^2 and 16×16 pixel^2. For the first level of spatial resolution with 64×64 pixel^2 interrogation window, only large-scale flow motion can be observed and the vortex at the lower right corner just behind the front seat is hardly identified. By improving the spatial resolution to the second level of 32×32 pixel^2 interrogation window, the PIV results reveal some detailed flow structures and vortical distributions with the enhancement of spatial resolution. The contour of the vortex at down right corner is distinguished clearly and the maximum value of vorticity is increased about 70%. As the interrogation window size is further decreased to 16×16 pixel^2, the vorticity field shows that large-scale vortex structures are composed of many small-scale vortex structures and velocity field provides more subtle turbulent flow motion, the maximum vorticity value is about 50% higher than that of 32×32 pixel^2 interrogation window due to reduction of smoothing effect encountered in larger interrogation window.



(a) 64×64 pixel^2



(b) 32×32 pixel^2

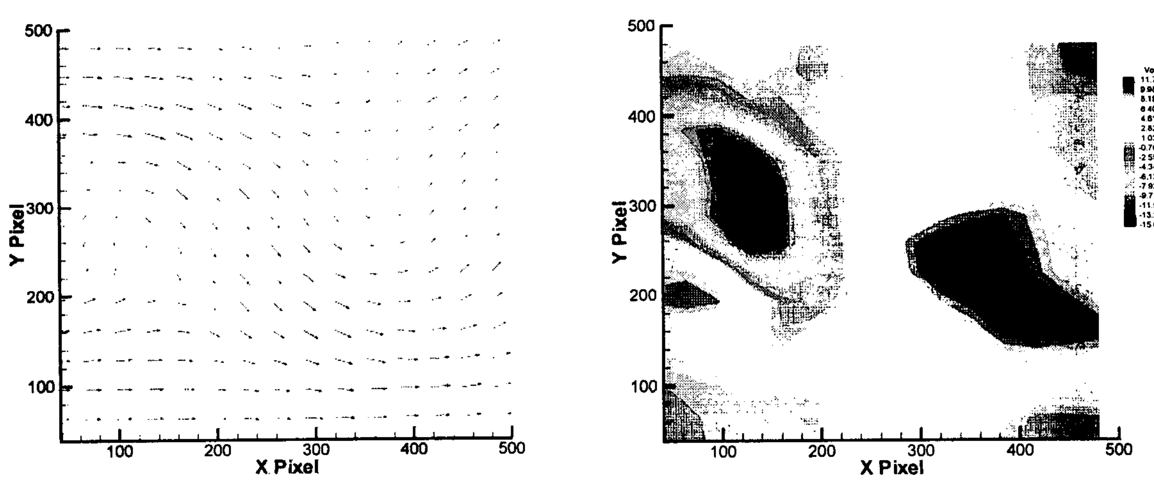


(c) 16×16 pixel^2

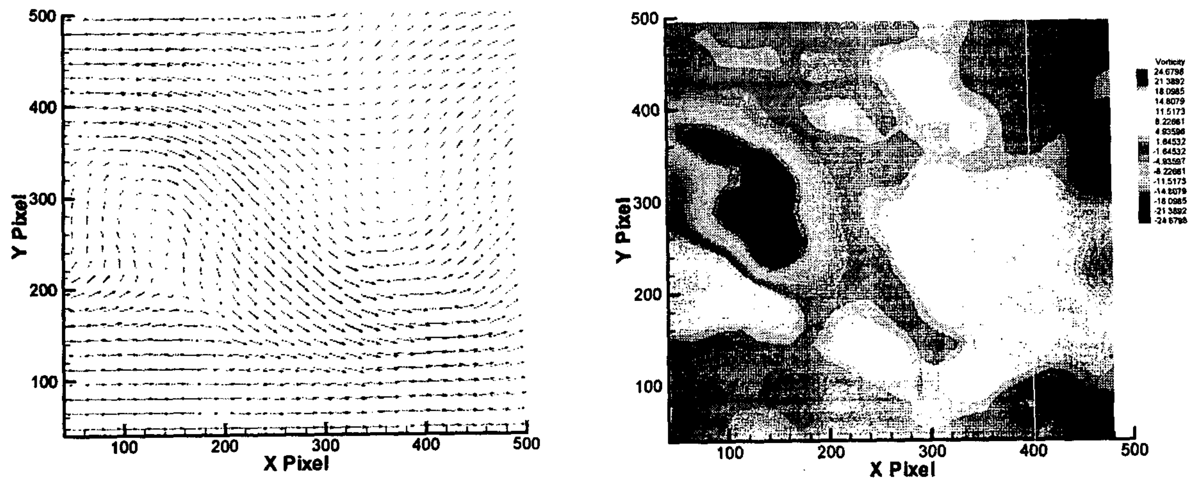
Fig.9 Velocity fields and vorticity contours of Ventilation flow in a vehicle passenger compartment

3.4.2 Wake behind a circular cylinder with riblet surface

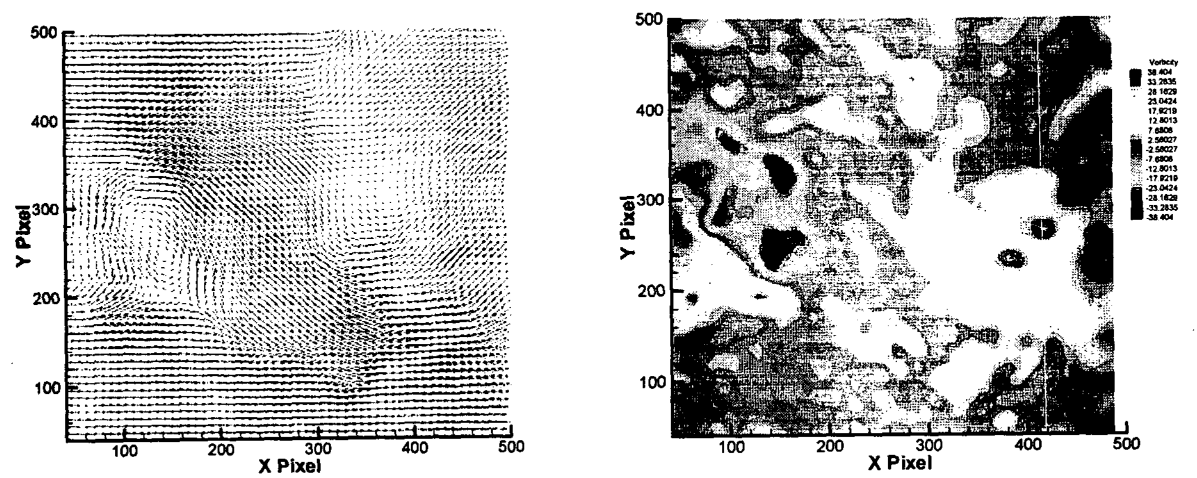
The near wake flow behind a circular cylinder with riblet surface is different from that of a smooth circular cylinder. For example, the position of vortex shedding is shifted toward the cylinder. The drag force acting on the riblet-surfaced cylinder is reduced, compared with that of the smooth cylinder. The PIV measurements were carried out in a circulating water channel having a test-section of $0.3m^W \times 0.25m^H \times 1.5m^L$. A circular cylinder of D=20mm in diameter was mounted horizontally in the water and field of view is 60mm×60mm just behind the cylinder. The Reynolds number based on the cylinder diameter is about 3000. The PIV results were obtained for three different interrogation window sizes of 64×64, 32×32 and 16×16 pixel^2. The resulting velocity fields and vorticity distributions of the cylinder wake are shown in Figs.10. In the first spatial resolution level of 64×64 pixel^2, the obscure outlines of large-scale vortices were observed. As the spatial resolution is improved to the second level of 32×32 pixel^2, the position of vortex shedding is distinguished clearly and a clockwise-rotating relatively small-scale vortex is also revealed. The shedding vortex procedure becomes more clear when the spatial resolution is further increased to higher level of 16×16 pixel^2. The position of the cylinder is at the left edge in the velocity maps.



(a) 64×64 pixel^2



(b) 32×32 pixel^2



(c) 16×16 pixel^2

Fig.10 Velocity fields and vorticity contours of near wake behind a circular cylinder with riblet surface

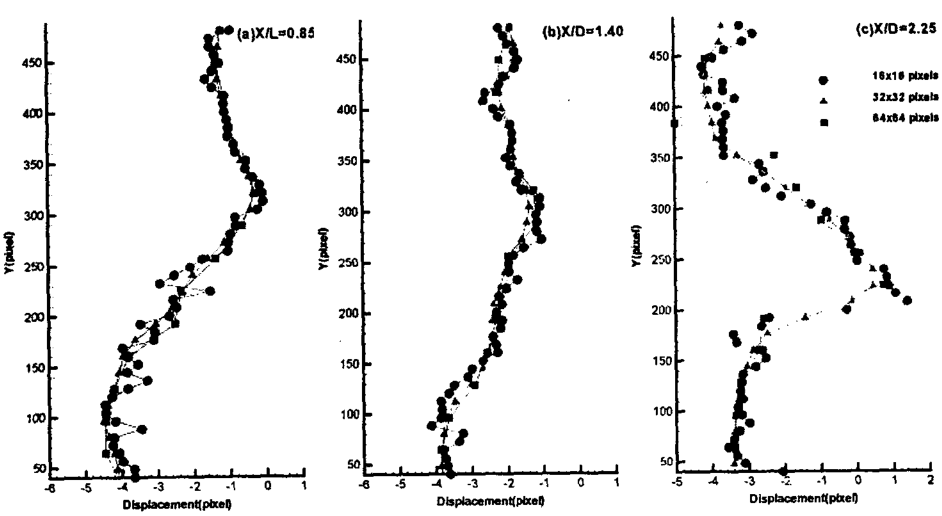


Fig.11 Comparison of stream wise velocity profiles for various spatial resolution levels

The quantitative comparison of stream wise velocity profiles extracted at X/D=0.85, 1.40 and 2.25 downstream locations from the PIV velocity field results (Figs.10) for different spatial resolution levels are illustrated in Fig.11. From these figures, we can see that the magnitude of PIV result is enhanced in principle with the increase of spatial resolution level, it indicates that the sub-pixel accuracy is improved and bias error is reduced.

4. Conclusion

The performance of hierarchical recursive correlation algorithm with CBC processing has been tested using synthetic particle images, standard PIV images and finally for real flow fields. Compared with conventional FFT based correlation PIV method, the CBC processing suppresses the number of spurious vectors notably and increased the SNR(signal to noise ratio) on multiplied correlation plane, improving the efficiency of peak detection and sub-pixel accuracy of PIV measurement. The hierarchical recursive correlation PIV algorithm was found to be very effective in improving the spatial resolution of velocity field results with decreasing the interrogation window size, more detail flow structures were obtained. The increased accuracy was demonstrated by quantitative comparison of PIV results at different spatial resolution levels.

Acknowledgement

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