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A Study on Particle Identification in PTV
— Particle Mask Correlation Method —

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***Abstract*:** An algorithm for particle identification in PTV, which is classified in the category "particle mask correlation method, " is presented and tested. A typical brightness pattern of a particle image is referred to as a particle mask. The particle mask is centered on a pixel in the image plane and the cross correlation between the particle mask and a region of the image plane centered on the given pixel is calculated. The particle mask is scanned over the entire image plane and the cross correlation coefficient is calculated at each pixel location. Small subareas with high correlation coefficients indicate central areas of particle images.

***Keywords*:** particle mask, particle image extraction, particle tracking velocimetry.

1. Introduction

PTV(Particle Tracking Velocimetry) is one of the most promising methods used to measure three dimensional and temporal velocity fluctuation of flows (Adrian, 1991). For three-dimensional PTV(3D-PTV), many automatic tracking algorithms have been proposed (e.g. Etoh and Takehara, 1995; Keane et al., 1995; Kasagi and Nishino, 1991; Okamoto et al., 1995). One fundamental problem, however, still remains in 3D-PTV. If an insufficient number of particles are extracted from a particle image plane, deterioration of spatial resolution in the measurement results.

When we use a video camera, the maximum number of particles extracted from a particle image plane is about a thousand. If we have a thousand particle images in a two dimensional measurement, then, the spatial resolution, which is about 30(H) $\times$ 30(V) ($\cong$ 1000), provides sufficient resolution for most applications in fluid dynamics. In three dimensional analysis, however, the spatial resolution, which is 10 $\times 10 \times 10$, is insufficient for understanding flow structures in detail. This is the best resolution expected in current practice (e.g. Keane et al., 1995; Kasagi and Nishino, 1991). For measurement of complicated flows, the number of extracted particles can be reduced to a hundred.

The spatial resolution of a film image is much higher than that of a video image. However, three-dimensional measurement of particle movements by using film cameras is difficult, because synchronization of a couple of film cameras is more difficult than that of video cameras.

Consequently, development of an effective particle extraction technique is still an essential target in development of 3D-PTV technologies.

The following experiences and difficulties in the extraction of particle images in 3D-PTV have motivated this study.

(1) Loss of images due to thresholding

Commonly, in extraction of particle images, a certain level of brightness is chosen as a threshold for binarization of an image. If the brightness of a particle is lower than the threshold due to lack of focus of the particle image, uneven illumination, etc., the particle disappears on the binarized image.

(2) Loss of images due to image overlap

If the seeding density in the fluid is sufficiently high, closely located particle images result with possible overlap of images. In the binarized images, the overlapping particle images cannot be separated into individual particle images. This also occurs in binarization of excessively bright areas, even if the particle images do not overlap.

(3) Loss of images due to neglected edges

The presence of linear elements, such as the image of the edges of a water tank or an immersed body, sometimes remain on binarized images. It is difficult to automatically erase linear element images without losing particle images on a binarized image.

2. Outline of the Particle Mask Correlation Method

2.1 Definition of a Particle Mask

A particle mask is a typical brightness pattern of a particle image. It is known as a template in pattern matching (Brown, 1992; Rosenfeld and Kak, 1982). Generally, the brightness pattern of a particle image has a peak near the center of the image, and the brightness concentrically decreases as the distance from the peak location increases. In the proposed algorithm, the particle mask is assumed to have a shape of the two-dimensional Gaussian distribution. Many particle masks have been proposed. For example, Ushijima (1996) employed a two-dimensional quadratic surface.

The two-dimensional Gaussian distribution is expressed as follows:

$$I(x, y) = a \bullet \exp\left[-\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma^2}\right] \tag{1}$$

where, $I(x, y)$ is the brightness value at (x, y), a is the peak brightness, σ is the standard deviation(representative radius), and (x_0, y_0) is the location of the center of a particle image. Four parameters, a, σ, and (x_0, y_0) determine the shape and the location of the particle mask. The peak brightness, a, can be fixed at an arbitrary value, when the cross-correlation coefficient between the particle mask and the particle image plane is calculated, because the correlation coefficient is normalized so as to vary in range from -1.0 to 1.0 regardless of the value of a. Therefore, the value of the cross-correlation coefficient is dependent on three parameters, σ, and (x_0, y_0).

2.2 Procedure of the Particle Mask Correlation Method

In the calculation of the particle mask correlation method, the brightness pattern of a particle mask is fixed. The peak brightness, a, is fixed at unity and the representative radius, σ, takes a proper value, which is discussed in the Section 3.2. The center of the particle mask, (x_0, y_0), scans all pixels in the particle image plane. The particle mask correlation method has the following steps.

(1) Calculation of cross-correlation coefficients

The cross-correlation coefficient between the brightness pattern of the particle mask, centered at (x_0, y_0), and the interrogation area of the particle image plane, centered also at (x_0, y_0) and with the same size, is calculated. The cross-correlation coefficient can be calculated by the following equation.

$$r(x_0, y_0) = \frac{\sum_{i=x_0-m/2}^{x_0+m/2} \sum_{j=y_0-n/2}^{y_0+n/2} \left(I(i,j) - \hat{I}\right)\left(I_m(i,j) - \hat{I}_m\right)}{\sqrt{\sum_{i=x_0-m/2}^{x_0+m/2} \sum_{j=y_0-n/2}^{y_0+n/2} \left(I(i,j) - \hat{I}\right)^2} \sqrt{\sum_{i=x_0-m/2}^{x_0+m/2} \sum_{j=y_0-n/2}^{y_0+n/2} \left(I_m(i,j) - \hat{I}_m\right)^2}} \tag{2}$$

Here, $r(x_0, y_0)$ is the cross-correlation coefficient at (x_0, y_0), $I(i, j)$ is the brightness value of particle image plane at (i, j), and $I_m(i, j)$ is the brightness value of the particle mask at (i, j). The interrogation area, $m \times n$, is chosen as $1.5\sigma_m \times 1.5\sigma_m$ in this study. $\hat{I}$ and $\hat{I}_m$ are spatial averages of the brightness of the particle image plane and the particle mask image in the interrogation area, respectively. The particle mask scans all pixels on the particle image plane, which produces a correlation coefficient plane.

(2) Binarization

The calculated correlation coefficient plane is binarized by a threshold chosen to locate particle images. In the binarized image, a pixel belonging to a particle image takes unity, otherwise, 0.

(3) Extraction of particle image area

An automatic algorithm to locate independent unified areas is applied to search the binarized correlation plane for particle images.

(4) Estimation of particle location and size

The particle location and size are estimated for each unified area. The location and size of the particle are calculated as the center of gravity and the equivalent radius of the unified area, respectively.

(5) Estimation of peak brightness of particle image

The peak brightness of a particle image is estimated as the brightness at the center of the unified area.

(6) Other informations

If necessary, the major and minor axes of the unified area are calculated.

It should be noted that, in the particle mask correlation method, the cross-correlation coefficient between the particle mask and a particle image plane is produced before the binarization. This provides the following advantages.

(1) Peak brightness of a particle image is replaced by a cross-correlation coefficient which is normalized between -1 to 1. The cross-correlation coefficient depends on the brightness pattern, not on the peak brightness. For example, even if a particle image has a relatively low peak brightness, if the brightness pattern distributes similar to the assumed particle mask, the cross-correlation coefficient reaches near 1.0. Even if a particle image has a high peak brightness at the center, the cross-correlation coefficient does not exceed 1.0. It is especially advantageous in applications to three-dimensional measurement, in which the brightness of a particle image is distributed over a very wide range.

(2) Linear elements on the original image plane are automatically eliminated. By ordinary simple binarization with a constant brightness threshold, the linear elements such as edges of a water tank remain on the binarized image plane. Cross-correlation coefficients between the particle mask and linear elements do not exceed 0.7 as shown later in Section 3.3. Therefore, a threshold value larger than 0.7 eliminates linear elements.

On the other hand, the particle mask correlation method has the following disadvantages.

(1) The particle mask correlation method is too sensitive. For example, if an image is not a particle image and has a concentric convex brightness pattern, the cross-correlation coefficient between particle mask and the image has a value over the threshold.

(2) For a particle image which has saturated brightness, the cross-correlation coefficient decreases. Especially, the center of a particle image which has a larger area of saturated brightness than the particle mask size cannot be extracted by this method. In order to solve this problem, it is recommended that the level of peak brightness of the brightest particle images be set under maximum brightness by adjusting the illumination intensity or the sensitivity of the image sensor. Even if there are some particle images which have low peak brightness, the particle mask correlation method can extract the particle images from the image plane.

3. Performance of the Particle Mask Correlation Method

3.1 Performance Factors

Factors relating to performances of the particle mask correlation method are tested. To evaluate the performances of the particle mask correlation method, one or two particle images are artificially generated on an image plane, which give an exact solution. The following factors are tested.

(1) Dependence of cross-correlation coefficients on the ratio of the sizes of the particle mask and a particle image

The particle mask size is fixed in the calculation of the correlation coefficient plane. Hence, it is necessary to estimate the most effective size of a particle mask in order to extract various sizes of particle images.

(2) Elimination of linear elements

Linear elements are classified into two types: a step type and a ridge type. Cross-correlation coefficient between a ridge-type linear element and a particle mask takes a larger positive value. Linear elements are expected to be eliminated by employing a threshold value larger than an expected maximum correlation coefficient between a ridge-type linear element and a particle mask.

(3) Separation of closely-located two particle images

The performance of separation of two closely-located particle images is evaluated by the distance between the centers of the two particle images which can be separated. The distance depends on the ratio of peak brightnesses and on the sizes of the two particle images.

The brightness pattern of the artificial particle image is assumed as a two-dimensional Gaussian distribution.

3.2 Dependence of Cross-correlation Coefficients on the Ratio of the Sizes of the Particle Mask and a Particle Image

Dependence of cross-correlation coefficients on the sizes of the particle mask and a particle image is evaluated. The representative radius of particle mask, σ_m, is fixed at 3.0 pixels, and the representative radius of an artificial particle image, σ_p, varies from 0.5 to 30.0 pixels. Thus, σ_p/σ_m varies from 0.167 to 10.0.

The result of the relationship between σ_p/σ_m and the cross-correlation coefficients is shown in Fig. 1. The following are observed.

(i) The cross-correlation coefficient, r, increases rapidly as σ_p/σ_m increases from 0.167 to 1.0. When σ_p/σ_m equals 1.0, r reaches the maximum value, 1.0. The value of r decreases gradually as σ_p/σ_m increases from 1.0 to 10.0.

(ii) For example, assume that the threshold of cross-correlation coefficient is 0.7, which automatically separates particle images from linear elements as shown in Section 3.3. Then, particle images, where σ_p/σ_m is greater than 0.3 and smaller than 8.0, are extracted by the binarization of a correlation image plane. The cross-correlation coefficient between the particle mask and a particle image does not change much when the value of σ_p/σ_m is greater than 1.0.

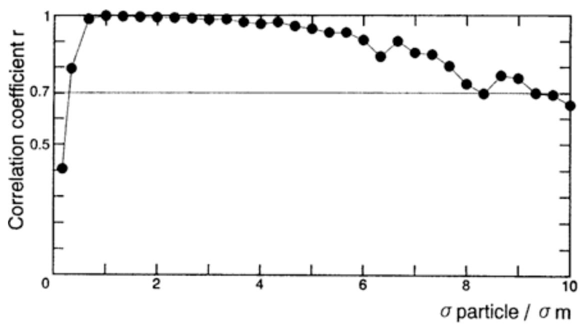


Fig. 1 σ_p/σ_m vs. the cross-correlation coefficient.

Consequently, it is concluded that a size of particle mask can be fixed at a constant value. The size of the particle image extracted by a constant threshold value 0.7 ranges from 0.3 σ_m to 8 σ_m. It should be noted that the particle mask correlation method also extracts images with large size concentric brightness pattern, which are not particle images.

3.3 Elimination of Linear Elements

The cross-correlation coefficient between a linear element and a concentric brightness pattern takes a positive value. When the expected highest cross-correlation coefficient between a linear element and a particle mask is selected as a threshold, linear elements are automatically erased from the binarized image.

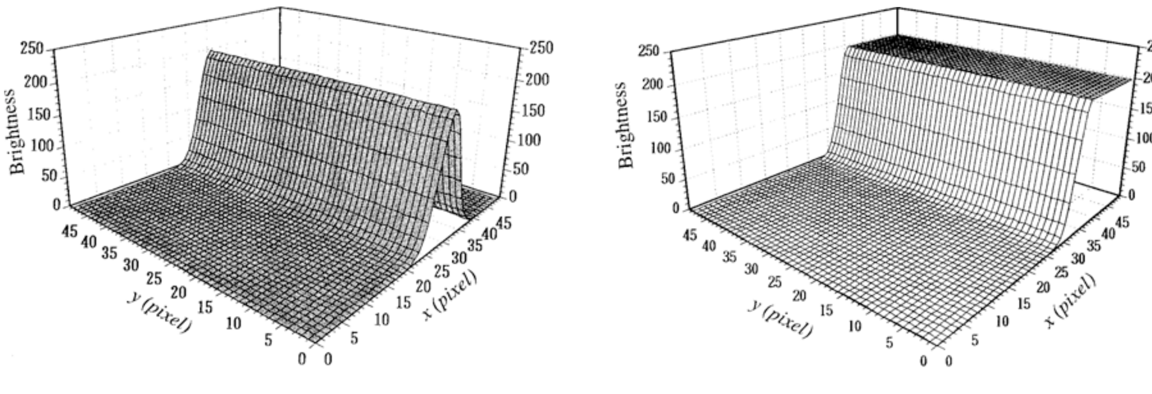


Fig. 2. Linear element images.

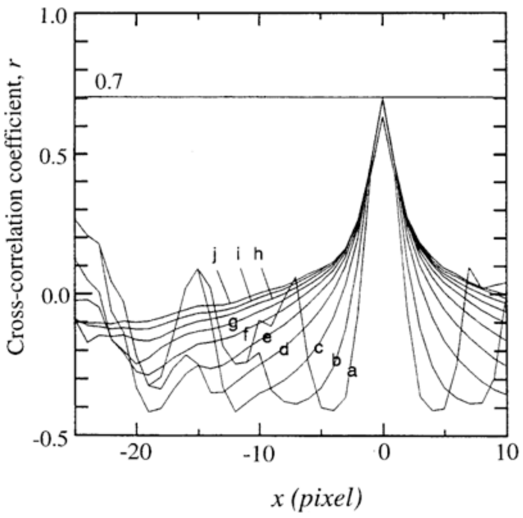


Fig. 3. Cross-correlation coefficients between the particle mask and linear elements.

Table 1. Calculated cases.

Width of a linear element	a	b	c	d	e	f	g	h	i	j
σ_l(pixel)	1	2	3	4	5	6	7	8	9	10
σ_l/σ_m	0.33	0.67	1.0	1.33	1.67	2.0	2.33	2.67	3.0	3.33

Linear elements have typical two types of brightness patterns, as shown in Fig. 2. The highest correlation coefficient is expected between the particle mask and the ridge-type brightness pattern (one-dimensional Gaussian distribution) depicted in Fig. 2(a). In this section, the dependence of the cross-correlation coefficient on the ratio of width of the ridge type linear element to the size of a particle mask is evaluated.

Test cases are listed in Table 1. The size of the particle mask, σ_m, is a constant representative radius of 3.0 pixels. The representative width of linear element, σ_l, varies from 1.0 to 10.0 pixels. In calculation of cross-correlation coefficient for a fixed linear element width, the center of the particle mask starts far from the linear element, and passes through the linear element to search a maximum value.

Calculated cross-correlation coefficients are shown in Fig. 3. The results are as follows.

(i) The maximum cross-correlation coefficients appear when the center of the particle mask coincides with the center of the linear element, i.e., $x = 0.0$.

(ii) In the case where the width of a linear element is equal to the size of the particle mask, i.e., the case c in Fig. 3, the correlation coefficient reaches the maximum value.

(iii) The maximum cross-correlation coefficient is about 0.7.

(iv) When the width of a linear element is small, i.e., cases a and b, fluctuations in the value of cross-correlation coefficient are generated. The absolute value of the fluctuations, however, remains under 0.4.

It is concluded that a value of 0.7 is suitable as the threshold for binarization of the cross-correlation coefficient plane.

3.4 Separation of Closely-located Two Particles

A critical distance is proposed in this paper to evaluate performance of separation of two closely-located particle images, which is defined as the minimum distance between centers of the two particle images which can be separated. The critical distance depends on the ratio of sizes of the two particles and magnitudes of peak brightness. The following cases are tested for the evaluation of performance of separation.

(a) Separation of two closely-located particle images of the same size and peak brightness
(b) Separation of two closely-located particle images of the same size and the different peak brightness

(a) Separation of closely-located two particle images of the same size and peak brightness

The cases with two closely-located particles, of which the size and peak brightness are the same, are tested. The representative radius and peak brightness of the particles are fixed at 3.0 pixels and 200, respectively. Brightness patterns of two closely-located particle images are shown in Fig. 4 along a line which passes through the centers of the two particles. The center of one particle is fixed at 0.0 on the *x*-axis, and the center of the other particle moves from 1.0 to 10.0 pixels.

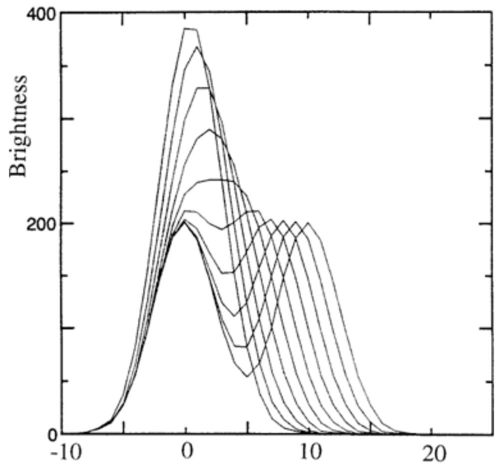


Fig. 4. Brightness pattern of two closely-located particle images with the same size and peak brightness.

The cross-correlation coefficient between two closely-located particle images and the particle mask is calculated. The change in the cross-correlation coefficient along the centerline is shown in Fig. 5(a).

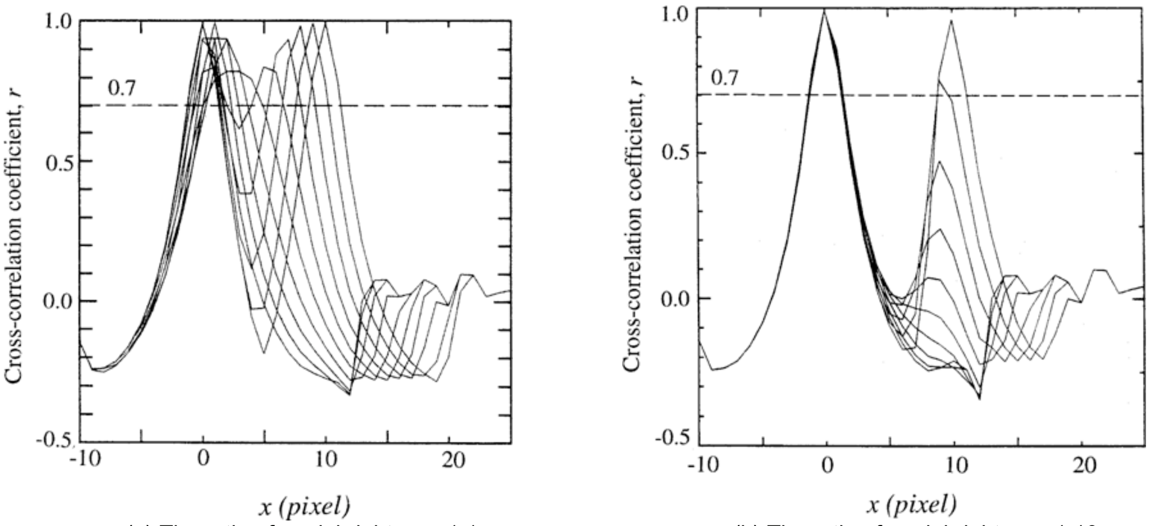
In the range where the distance of two particle images varies from 1.0 to 5.0 pixels, the cross-correlation coefficient has one peak, and the peak gradually decreases with the distance between two particles.

In the range where the distance varies from 6.0 to 10.0 pixels, the cross-correlation coefficient has two peaks and the depth of the depression, i.e., the difference between average height of two peaks and the bottom of the depression, increases as the distance between two particle images increases. When the bottom of the depression is smaller than the threshold for the binarization, the two particle images can be separated on the binarized image plane.

The proper threshold of correlation coefficient is evaluated at 0.7 as stated in Section 3.3 to automatically eliminate linear element images. Therefore, if the bottom of the depression in the cross-correlation coefficient is smaller than 0.7, the two particle images can be separated.

In order to standardize the distance L between two particle images, the representative diameter of a particle image $2\sigma_p$ is selected as the representative length scale. Then, the standardized distance is presented by $L/(2\sigma_p)$.

Subsequently, the following are concluded from Figs. 4 and 5.



(a) The ratio of peak brightness,1:1 (b) The ratio of peak brightness,1:10

Fig. 5. Cross-correlation coefficients of two closely-located particle images.

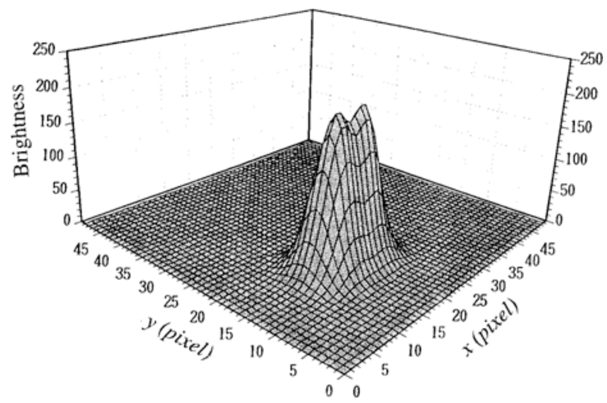
(i) When the standardized distance $L/(2\sigma_p)$ varies from 1.2 to 2.0, the brightness patterns have a depression as shown in Fig. 4.

(ii) In the range where the brightness patterns have a depression, i.e., for $1.2 < L/(2\sigma_p) < 2.0$, the correlation coefficient plane also has a depression as shown in Fig. 5.

(iii) When the standardized distance equals 1.2, the bottom of the depression in the correlation coefficient plane is approximately 0.6, and is lower than 0.7, which automatically eliminates linear element images.

Thus, the standardized critical distance $L/(2\sigma_p)$ is about unity to separate the two particle images with the same size and peak brightness.

For the critical distance, the brightness pattern is shown in Fig. 6. In this case, the composed brightness pattern has a depression



. Fig. 6. Brightness pattern of the two particle images with the same size and peak brightness for the critical distance.

(b) Separation of two closely-located particle images of the same size and the different brightness

The separation performance of two closely-located particle images of the same size and the different peak brightness is tested. The ratio of the peak brightness of the two particle images varies from 1(1:1) to 1/20(1:20). An example of the calculated cross-correlation coefficient plane is shown in Fig. 5(b) for the ratio of peak brightness of the two particle images being 1/10. The followings are observed from Fig. 5(b).

(i) When the standardized distance $L/(2\sigma_p)$ varies from 0.2 to 1.0, the cross-correlation coefficient plane has one peak.

(ii) When the standardized distance $L/(2\sigma_p)$ varies from 1.2 to 1.6, the cross-correlation coefficient plane has two peaks. The peak corresponding to the particle image with high peak brightness is larger than 0.7. The other peak is less than 0.7. Therefore, the two particle images cannot be separated.

(iii) When the standardized distance $L/(2\sigma_p)$ is greater than 1.8, the cross-correlation coefficient plane has two peaks. Both peaks exceed the threshold 0.7. Therefore, the two particle images can be separated.

The same observations are applied to cases of the ratio of the peak brightness 1, 1/2, 1/4, 1/10 and 1/20. The results for this separation test are shown in Fig. 7. Open circles, ○, indicate that two particle images can be separated, and solid circles, •, indicate that they cannot be separated. The followings are concluded from Fig. 7.

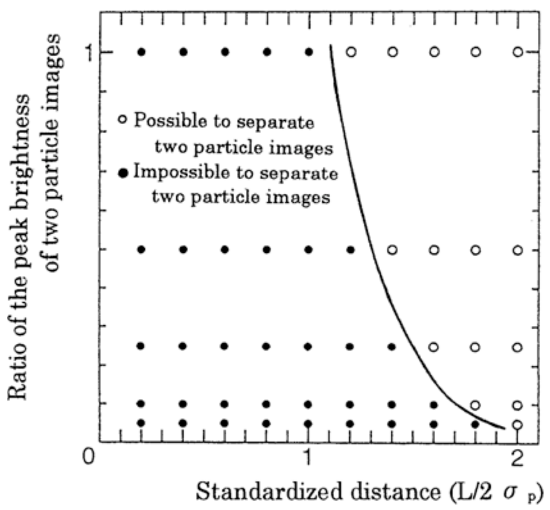


Fig. 7. The critical distance vs. the ratio of peak brightness of two closely-located particle images.

(i) When the two particle images have the same size and the different peak brightness, the standardized critical distance $L/(2\sigma_p)$ for separation increases as the difference of the peak brightness of the two particle images increases.

(ii) In the region where the standardized distance is greater than 2.0, two particle images can be separated even if the peaks of two particle images are quite different, i.e., 1/20.

4. Application

The proposed particle mask correlation method is applied to a synthetic particle image plane shown in Fig. 8. The synthetic particle image plane was designed in the work (Okamoto et al., 1997) of the collaboration project of The Visualization Society of Japan (PIV Standard Project). The images are provided as benchmark data for evaluation of performance of PIV/PTV algorithms.

The particle images are called "standard images" for PIV/PTV and can be obtained from the web-site "http://www.vsj.or.jp/piv/". In Fig. 8, the brightness of the particle image plane is inverted for clearer recognition of particle images. Therefore, the dark parts indicate particle images.

In the standard images, the particles are scattered in three-dimensional space and illuminated by a laser light sheet. The intensity of the laser light sheet is assumed to be a Gaussian distribution in the thickness direction of the laser light sheet. Saturation of images here does not occur and it is recommended to modify illuminating intensities or sensitivities of the image sensor in experiments to prevent it occurring there also. Therefore, overlapping particle images and out-of-focus particle images appear in the standard images.

In order to discuss the particle mask correlation method in detail, the square solid line region in Fig. 8 is tested. The particle mask correlation method is compared with the common binarization method by a certain brightness threshold.

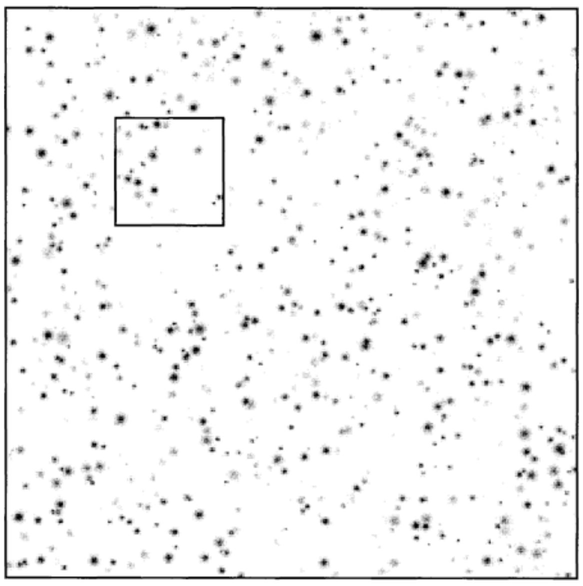
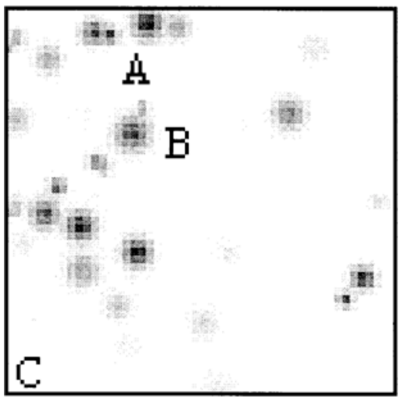
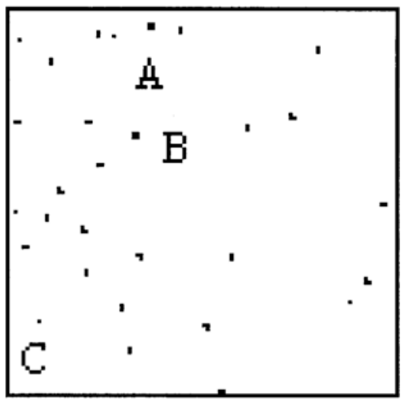


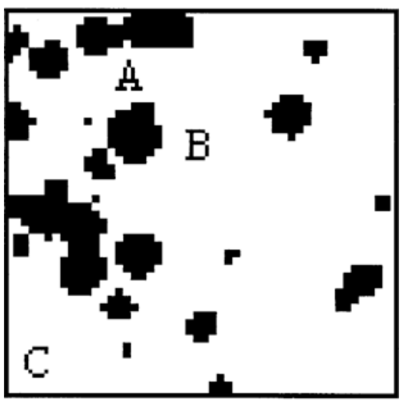
Fig. 8.   A standard particle image.



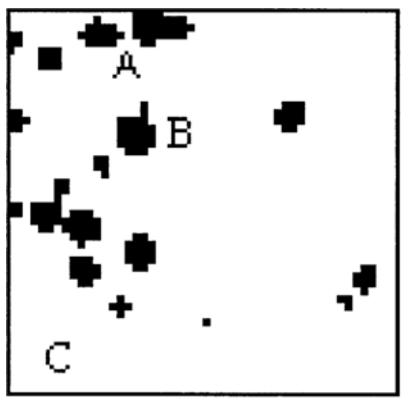
(a) Original image plane



(b) A result of particle mask correlation method



(c) Binarized image with the threshold (threshold = average)



(d) Binarized image with the threshold (threshold = average + standard deviation)

Fig. 9.   Performance of the particle mask correlation method.

The results of the comparison are shown in Fig. 9. Figure 9(a) shows the original image which is surrounded by the squared solid line in Fig. 8. The average and standard deviation of the particle image diameter are 2.5 pixel and 1.0 pixel respectively. Figure 9(b) shows the result of the particle mask correlation method which picked up the particle images by the cross-correlation threshold value of 0.7. In the particle mask correlation method, the representative diameter of the particle mask ($2\sigma_m$) is fixed to 3.0 pixel because the average diameter of particle images on the tested standard images plane is 2.5 pixel. Almost all particle images are extracted by the particle mask correlation method.

The results of the common binarization method by a constant brightness threshold are shown in Figs. 9(c) and (d). The average brightness and the average plus standard deviation brightness of a whole image plane are chosen as the threshold brightness for Fig. 9(c) and Fig. 9(d), respectively.

For example, a group of particle images, "A" in Fig. 9(a), is separated into each particle image correctly by the particle mask correlation method as shown in Fig. 9(b). In the common binarization method by using a certain brightness threshold, the group of the particle images is stuck together as shown in Figs. 9(c) and (d).

A few particle images disappeared as a result of the particle mask correlation method. The particle image, "B", in Fig. 9(a) has two closely-located particle images. The peak brightness of one particle image has the value of 192, and that of the other has the value of 107. From the result of Section 3.4, the critical distance to separate two closely-located particles $L/(2\sigma_p)$ requires 1.2. In this case, the diameter of larger particle image is about 15 pixel and the critical distance is estimated as 18 pixel. In fact, the distance between the two closely-located particles is about 7 pixel, which is smaller than 18. Therefore, the two closely-located particle images, "B", cannot be separated by the particle mask correlation method.

Very low peak brightness particle image, "C", in Fig. 9(a) can be picked up by the particle mask correlation method as shown in Fig. 9(b). The common binarization method and even human's naked eyes cannot pick up the particle image "C".

5. Conclusion

Proposed in this paper is a new technique for extraction of particle images, which is an essential part of PTV. It is called particle mask correlation method. A particle mask is of a typical brightness pattern of a particle image. A cross-correlation coefficient is calculated between the particle mask image and a segment of the particle image plane, i.e., a two-dimensional image with many particle images. The particle mask has a fixed shape of brightness pattern. The cross-correlation coefficient is calculated in a limited area which is called an interrogation area. The interrogation area scans the whole particle image plane. The particle mask correlation method generates a cross-correlation coefficient plane, which is binarized by a threshold to pick up particle images. The particle mask correlation method has the following advantages.

(1) Peak brightness of a particle image is replaced by a cross-correlation coefficient which is normalized between -1.0 to 1.0.
(2) Linear elements, such as edges of immersed bodies, on the original image plane are automatically eliminated.

Performance of the particle mask correlation method has been tested. The following conclusions have been reached.

(1) A value of 0.7 is suitable as the threshold for binarization of the cross-correlation coefficient plane, which automatically eliminates linear element images.
(2) The size of the particle mask can be fixed at a constant value. The size of the particle image that can be extracted by a constant threshold value 0.7 ranges from 0.3 σ_m to $8\sigma_m$, where σ_m indicates the representative radius of a particle mask.
(3) The standardized critical distance $L/(2\sigma_p)$ is about unity to separate two particle images with the same size and peak brightness, where L and σ_p indicate the distance of two particle and the representative radius of a particle image, respectively.
(4) When two particle images have the same size and the different peak brightness, the standardized critical distance $L/(2\sigma_p)$ for separation increases as the difference of the peak brightness of the two particle images increases.

(5) In the region where the standardized distance is greater than 2.0, two particle images can be separated even if the peak brightness of two particle images are quite different, i.e., 1:20.

Further investigation is necessary to combine the particle mask correlation method and the particle mask fitting method.

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