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A FAST MASK TECHNIQUE FOR THE PHASE-SEPARATED EVALUATION OF TWO PHASE PIV RECORDINGS

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Abstract
In this paper we describe a new algorithm, that can be combined with the digital mask technique, so that the two-phase PIV recording can be evaluated at a higher speed. This algorithm is based on a simplification of the „minimum quadratic difference" (MQD) technique, that is a method for tracking ensembles of particle images. The new algorithm is tested by a simulation, and the fast mask technique is exemplified with an application.

1. Introduction
A typical situation for the application of particle image velocimetry (PIV) to the study of two-phase flow is that the tracer particles with which the continuous phase is seeded are much smaller than the particles dispersed in the continuous phase. Since the optical signals resulting from the two phases are received simultaneously in the PIV recording, considerable measurement errors arise if a difference in the velocities of the two phases exists. This has called for technical means of separating the signals representing the two phases. One way is the use of fluorescent tracers (see, e.g. [1]) which radiate at a different wavelength than the „neutral" dispersed particles. Another approach relies on the significant difference in the sizes of the tracer and dispersed particles. This approach is realized in form of a digital mask technique that is described in [2]. The mask technique was described in [2] with application to an evaluation of the PIV recordings by means of the „minimum quadratic difference" (MQD) tracking algorithm [3]. This is in no way a restriction of the applicability of the technique. It can also be combined with other tracking algorithms.

The evaluation of two phase PIV recordings by using the MQD tracking algorithm when combined with the digital mask technique requires considerable computer time or capacity, because the Fast Fourier Tansformation (FFT), with which the correlation and MQD algorithm can usually be highly accelerated, can not be used here. In this paper we describe a new tracking algorithm, that allows evaluation of two-phase PIV recordings at a higher speed than the MQD tracking method. This algorithm is based on a simplification of the MQD method. It requires to search for the minimum of the absolute difference of the tracked image patterns rather than that of the quadratic difference by the MQD method. This simplification enables the evaluation of PIV recordings to be carried out using addition and subtraction processes only. Avoiding the multipulication (square) makes the new algorithm performing faster. This idea has already been used to increase the evaluation speed of the correlation technique [4].

2. MQD tracking and simplification

Unlike the „traditional“ tracking schemes no single particles but ensembles of particle images, that we call here „patterns“, are tracked in the PIV recordings with high particle number densities. By two single exposed PIV recordings an image pattern **G** is selected in the first exposure at the evaluation point (x_0, y_0). The image patterns at different positions in the second exposure **G**’ are compared with this image pattern, and the differences of the gray value distributions between **G** and **G**’ are examined. The displacement of the particle images in the pattern is determined by the minimum of the differences of the gray value distribution. This tracking process is shown in Fig.1.

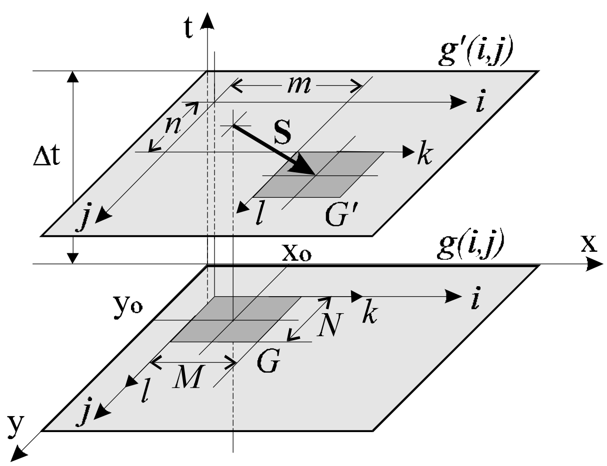

Fig. 1: Tracking ensembles of particle images

If **G**, **G**’ are limited in areas („patterns“) of size M×N pixels and mathematically considered to be two matrices

$$\mathbf{G} = \{G_{k,l}\} = \begin{Bmatrix} G_{11} & G_{21} & \cdots & G_{M1} \\ G_{12} & G_{22} & \cdots & G_{M2} \\ \vdots & & & \vdots \\ G_{1N} & G_{2N} & \cdots & G_{MN} \end{Bmatrix} \text{ and } \mathbf{G}' = \{G'_{k,l}\} = \begin{Bmatrix} G'_{11} & G'_{21} & \cdots & G'_{M1} \\ G'_{12} & G'_{22} & \cdots & G'_{M2} \\ \vdots & & & \vdots \\ G'_{1N} & G'_{2N} & \cdots & G'_{MN} \end{Bmatrix},$$

the difference of the two matrices can be expressed by

$$|\,\mathbf{G} - \mathbf{G}'\,| = \sqrt{\sum_{k=0}^{M-1} \sum_{l=0}^{N-1} \left(G_{k,l} - G'_{k,l}\right)^2} = \sqrt{\sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \left(g(i,j) - g'(i+m, j+n)\right)^2} \quad . \tag{1}$$

g(i,j), g'(i,j) are here the gray values of the pixels (i,j) in the two separated recordings of particle image fields with a time interval Δt. (m,n) is the position of the pattern **G'** relative to **G**. The areas covered by **G** and **G'** are only small fractions of the whole particle image field. According to Eq.(1) the displacement of the tracked pattern (m*,n*) can be found by determining the minimum of the quadratic difference (MQD)

$$D(m,n) = \frac{1}{M \cdot N} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \left(g(i,j) - g'(i+m, j+n) \right)^2 \qquad (2)$$

in varying the values of m and n.

In evaluating two successive PIV single exposure the MQD tracking method is similar to the cross-correlation algorithm, the difference is that no maximum but the minimum indicates the displacement (m*,n*) here. In application to a PIV double exposure, one has the superposition of two particle image patterns, and the difference (2) is found to have a central minimum D=0 for (m,n)=(0,0). Two minima with D_{min}>0 appear almost symmetrically on both sides of the central minimum, and the displacement to be determined follows from the positions (m*,n*),(-m*,-n*) of the second order minima. This form of D(m,n) is similar to the case, when the PIV double exposure is evaluateted by means of an autocorrelation algorithm, and like there, a directional ambiguity is involved in the evaluation.

A direct evaluation of PIV recordings with Eq.(2) requires considerable computer time or capacity. This is similar to the case, when the PIV recordings are evaluated by a correlation algorithm without using FFT. A means for increasing the evaluation speed is avoiding the multipulication in the algorithm. The evaluation of PIV recordings can be carried out very rapidly when using integer additions and subtractions only [4]. Making use of this idea the MQD tracking method is simplified as follows:

$$\tilde{D}(m,n) = \frac{1}{M \cdot N} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \left| g(i,j) - g'(i+m, j+n) \right| \qquad (3)$$

The new algorithm requires to search for the minimum of the absolute difference in order to determine the displacement of the tracked particle pattern. Test runs on a workstation for various sample evaluations have shown that the gain in evaluation speed is about a factor 3 as compared to the original MQD method.

The accuracy of the new algorithm, which can be called minimum absolute difference (MAD) method, is exemplified with a simulation. 40 Pairs of synthetic PIV recordings are generated with different displacements of particle images. The locations, sizes and mean brightness of particle images in the synthetic recordings are determined by means of a particle image recognition in a real PIV recording with a resolution of 768×512 pixels. The gray value distribution of each particle image is assumed to be a continuous nonsymmetric Gaussian (exponential) function. The image density in the synthetic recordings is 10 - 30 particle images in a 64×64 - pixel interrogation window, and the particle-image diameter 3 - 6 pixels, see e.g. Fig.2. The displacement of the particle images in a pair of synthetic PIV recordings can be determined precisely.

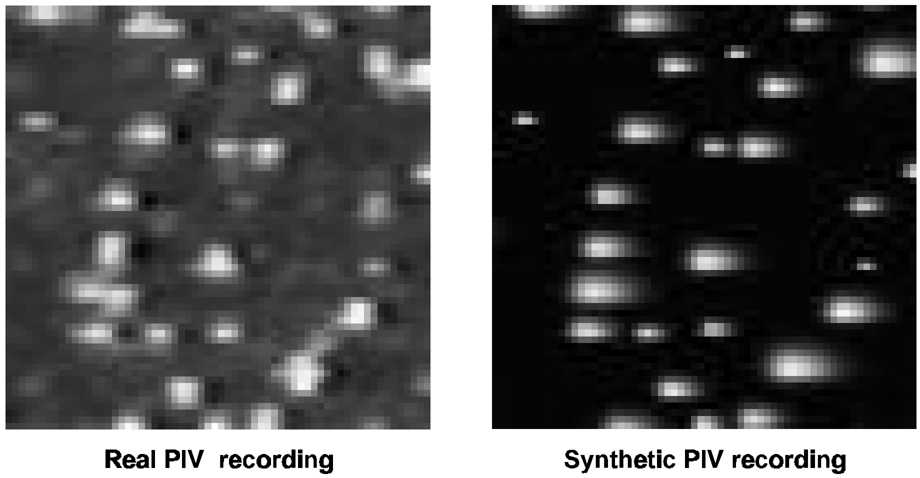

Fig.2: Simulation of the PIV recordings in a 64 × 64 - pixel interrogation window

Fig.3 shows the results of the simulation for the root-mean-square (RMS) error in pixels (px) of the displacement estimated with the three-point exponential curve fit [5] by using the cross-correlation, the MQD method and the MAD method:

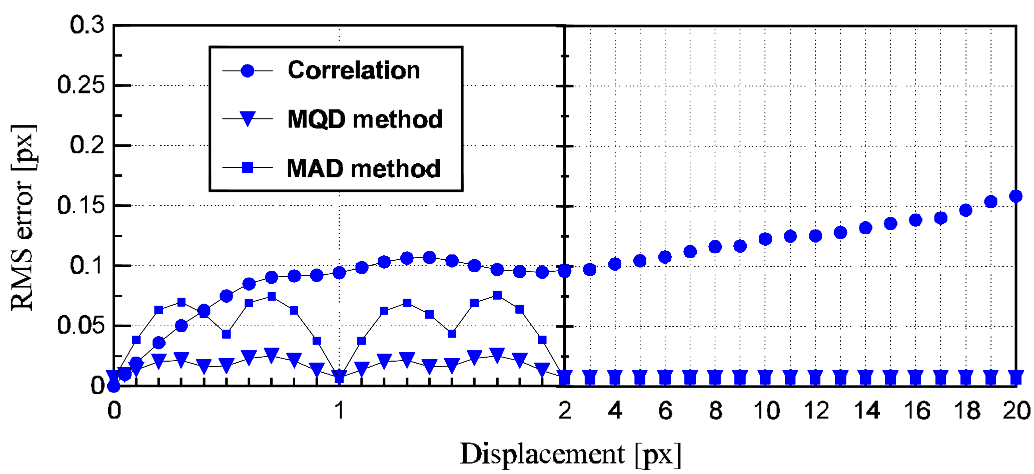

Fig.3: The RMS estimation errors of the displacement for a 64 × 64-pixel interrogation window by using different algorithms

The results of the simulation demonstrate that the evaluation errors of the MQD and the MAD method are periodical functions of the particle image displacement with a period of one pixel and not dependent on the discrete part of the displacement like that of the correlation algorithm. The evaluation error of the MAD method is not as small as that of the MQD method, but obviously smaller than the evaluation error of the correlation algorithm in most situations.

3. Mask technique

We describe the mask technique here with application to an evaluation of the PIV recordings by means of the minimum absolute difference (MAD) method. We assume a two-phase flow in which phase A is dispersed in the continuous phase B that is seeded with small tracer particles. For separating the information resulting from the two phases a mask Δ(i,j) superimposed to a two phase PIV recording is defined such that

$$\Delta(\mathrm{i,j}) = \begin{cases} 0 & \text{if pixel } (\mathrm{i,j}) \text{ belongs to phase A} \\ 1 & \text{if pixel } (\mathrm{i,j}) \text{ belongs to phase B} \end{cases} \tag{4}$$

In order to determine solely the velocity distribution of the dispersed phase A, a mask Δ_1(i,j) is superimposed to the pattern in the first exposure and then applied to eq. (3), thus resulting in

$$\tilde{D}_A(m,n) = \frac{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\left|g_1(i,j) - g_2(i+m, j+n)\right| \cdot \left[1-\Delta_1(i,j)\right]}{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\left[1-\Delta_1(i,j)\right]} \; . \tag{5}$$

The denominator on the right side is the sum of all pixels assigned to phase A. According to eq. (5) only the „pattern“ belonging to phase A is tracked, while the images of particles representing the continuous phase B in the first exposure are masked, i.e. removed from the investigated pattern.

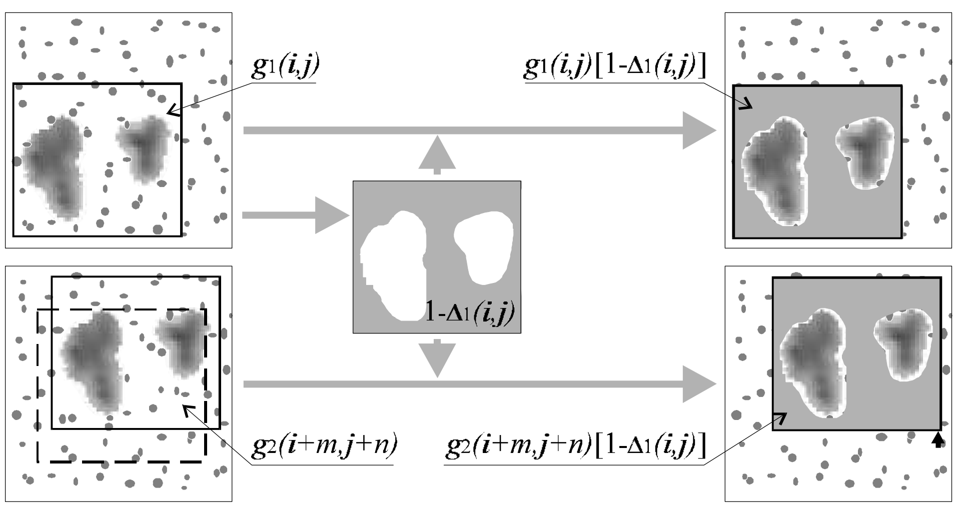

Fig.4: Mask technique for the dispersed phase

This procedure is exemplified with the simulated PIV recordings shown in Fig. 4. The two recordings on the left side of Fig. 4 are two consecutive exposures taken at times t (top left) and t+Δt (bottom left). The recordings include images of a great number of small tracer particles and the images of two big dispersed particles that move at a velocity different from that of the continuous phase. A pattern or window g_1(i, j) of quadratic shape is chosen. The evaluation of the unmasked patterns in Fig.4 is dominated by the influence of the very big particles; the small tracer particle images only contribute a certain „noise“ so that the resulting velocity, as an average of the whole pattern, is slightly different from the velocity of the big particles. This „noisy“ influence is removed in the masked patterns shown in Fig.4 right, except for a few tracer particle images that partly overlap with the images of the big particles and thus are taken as being part of the big particle images.

A modified form of the mask technique is used for determining the velocity of the continuous phase B. This is explained with the aid of Fig.5 that presents the same simulated particle image patterns as shown in Fig.4. Determining the minimum of the difference $\tilde{D}_B$ for the continuous phase according to eq. (3) and simultaneously masking the dispersed particle images is done in several steps: First, a pattern (or window) $g_1(i, j)$ is selected in the first exposure (Fig. 5, top left). The dispersed particle images included in this exposure are masked; this is described by $\Delta_1(i, j)$ which is only one portion of the total mask. The position of the pattern in the second exposure, $g_2(i+m, j+n)$, is then varied (Fig. 5, bottom left), and a variable mask $\Delta_2(i+m, j+n)$ masking the dispersed particle images in the second exposure is defined for each position (m, n). The total mask Δ is composed of the two portions Δ_1, Δ_2: $\Delta = \Delta_1(i, j) \cdot \Delta_2(i+m, j+n)$ (Fig. 5, middle).

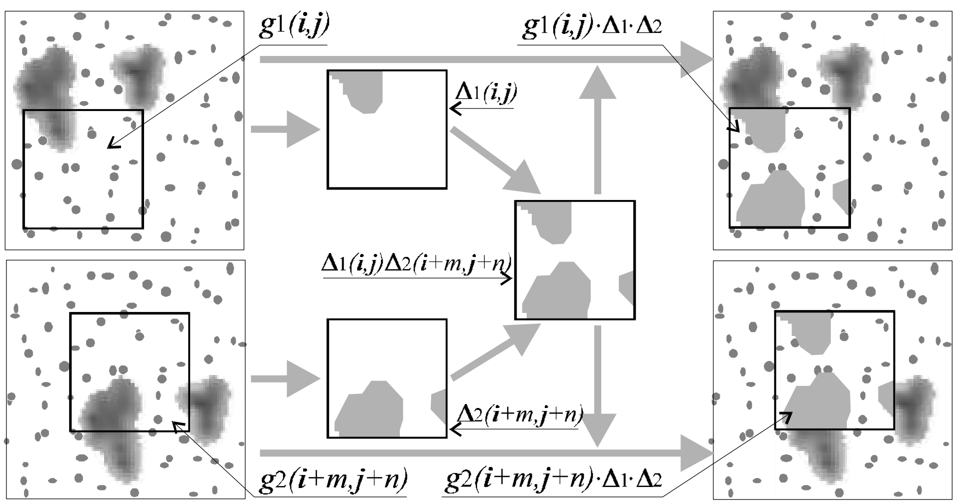

Fig.5: Mask technique for the continuous phase

In this way, tracer particle images appearing in the first exposure that are obscured by the big particles in the second exposure (and vice versa) do not contribute to the formation of the difference $\tilde{D}_B$. The minimum of $\tilde{D}_B$ is determined for the tracer particle image patterns in the unmasked areas as shown in Fig.5 right. The difference is thus described by

$$\tilde{D}_B(m,n) = \frac{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\left|g_1(i,j) - g_2(i+m, j+n)\right|\Delta_1(i,j)\Delta_2(i+m,j+n)}{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\Delta_1(i,j)\Delta_2(i+m,j+n)}, \qquad (6)$$

From eqs. (5) and (6) follow the displacements (m^*_A, n^*_A) and (m^*_B, n^*_B) experienced by the particles of the dispersed and continuous phase, respectively, during the time interval Δt and at the position of the interrogation „pattern" or window. This position assigned to the displacement or velocity must be determined separately for the two phases as the center of gravity of the particle images referring to phase A and phase B according to their distribution in the interrogation pattern. A further quantity needed for the application of this mask technique is the threshold value separating the two size classes of phases A and B. This value will usually follow from experience and knowledge of the individual experimental conditions.

4. Practical example

For demonstration purposes we describe the application of this fast mask technique to the flow induced in a water tank by large solid buoyant particles released to the water at the bottom of the tank. Two consecutive single exposures taken with a CCD camera at a time interval $\Delta t = 20$ ms are shown in Fig.6 top left. The (area) size of the images of tracer particles with which the water is seeded is between 5 and 20 pixels, while the dispersed particle images are significantly bigger than 30 pixels. Therefore, a threshold value of 30 pixels was chosen. The phase mask separating the regimes used for determining the velocity of phase A (black) and phase B (white) with the MAD method is shown in Fig.6 bottom left.

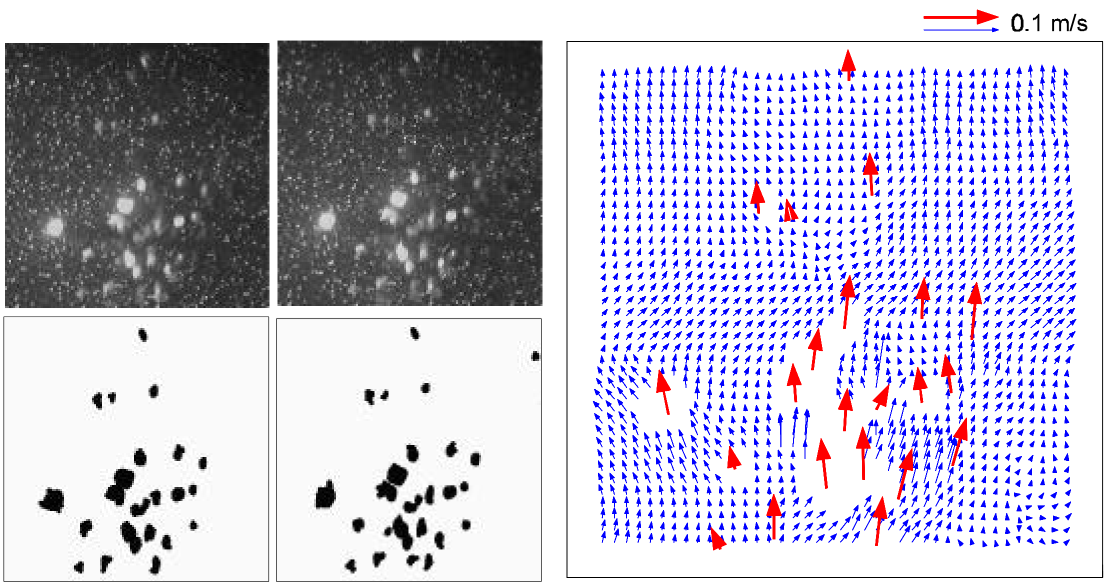

Fig. 6 Two-phase PIV recordings, digital phase-masks and the evaluation result

The result of the evaluation with the MAD method is shown in form of the vector plot in Fig.6 right. The size of the field of view is 9×9 cm^2, or 450×450 pixels in digital form. The interrogation window has a size of 40×40 pixels. The vectors referring to the two phases are easily distinguishable by their size. Most evident is the difference in absolute velocity of the two phases.

5. Summary

The described MAD tracking algorithm can be combined with the mask technique and used to evaluate two-phase PIV recordings. The results of the simulation demonstrate that the MAD tracking method is more accurate than the traditional correlation algorithm. The evaluation of the two-phase PIV recordings can be carried out at a higher speed by the MAD method than by the MQD method.

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