PHASE-SEPARATION OF PIV MEASUREMENTS IN TWO-PHASE FLOW BY APPLYING A DIGITAL MASK TECHNIQUE

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Introduction

Particle image velocimetry (PIV) is an ideal method for measuring the velocity of dispersed particles in multiphase flow systems. Reported examples of applications include the measurements of droplets in a spray jet [1], bubbles in water flow [2], cavitation bubbles [3], solid particles in a mixing tank [4]. Such experiments require a sufficiently high degree of transparency of the multiphase system in order to allow illumination of the dispersed particles by a light sheet [5]. For simultaneous measurements of the dispersed phase and the continuous phase in two-phase flow it is necessary to seed the continuous phase with tracer particles. A problem arises in separating the signals resulting from the two different phases. The use of fluorescent tracers is one way of solving this problem. With the aid of optical filters one may thus separate the radiation scattered by the fluorescent and the „neutral“ (here: dispersed) particles [6,7,8].

In this note we describe a technique for separating the signals from two phases that have a significant difference in the size distribution of the respective particles, e.g., small tracer particles and big dispersed particles. The technique consists of applying a mask to a digital PIV record such that the images of particles that are either smaller or larger than a predetermined threshold value disappear. The remaining distribution of particle images belonging to one of the two phases can then be evaluated by means of the Minimum Quadratic Difference (MQD) method [9] as described in this note.

Such a discrimination according to different size classes has also be performed by Jakobsen et al [10]. Different from there our approach also accounts for the fact that images of small tracer particles may be obscured by the presence of a big particle, a problem that is of particular unfavorable influence when large differences in the velocity distribution of the two phases occur, e.g., with large bubbles rising in a liquid stream. Also, the areas of masked particle images are not automatically assigned to the background. We avoid therefore a high noise level of the background that would again unfavorably affect the evaluation procedure.

The mask technique

We describe the mask technique with application to an evaluation of the PIV records by means of the Minimum Quadratic Difference (MQD) method [9]. This is in no way a restriction of the applicability of the technique. The MQD method requires to search for the minimum of the quadratic difference

$$D(m,n) = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left[g_1(i,j) - g_2(i+m, j+n)\right]^2 \quad (1)$$

in order to determine the displacement (m*, n*) experienced by an ensemble of particle images during a time interval Δt. The ensemble is a „pattern“ or window of size $M \times N$ pixels in the digital PIV recording. We assume here that two consecutive single exposures, separated by the time interval Δt, are taken; g_1 and g_2 are the gray values of the pixels in the two exposures, respectively. Eq. (1) is identical with eq. (2) in [9], where it is shown that the MQD method, in principle, is a tracking algorithm that can be used for both PIV double exposures and consecutive single exposures.

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 $\Delta(i,j)$ superimposed to the $M \times N$ pixels of the patterns (windows) is defined such that

$$\Delta(i,j) = \begin{cases} 0 & \text{if pixel } (i,j) \text{ belongs to phase A} \\ 1 & \text{if pixel } (i,j) \text{ belongs to phase B} \end{cases} \quad (2)$$

In order to determine solely the velocity distribution of the dispersed phase A, a mask $\Delta_1(i,j)$ is superimposed to the pattern in the first exposure and then applied to eq. (1), thus resulting in

$$D_A(m,n) = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left[g_1(i,j) - g_2(i+m, j+n)\right]^2\left[1-\Delta_1(i,j)\right]}{\sum_{i=1}^{M}\sum_{j=1}^{N}\left[1-\Delta_1(i,j)\right]} \quad (3)$$

The denominator on the right side is the sum of all pixels assigned to phase A. According to eq. (3) 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.

This procedure is exemplified with the simulated PIV recordings shown in Fig. 1. The two recordings on the left and right side of Fig. 1a are two consecutive exposures taken at times t and t+Δt. 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. 1a 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. 1c, 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.

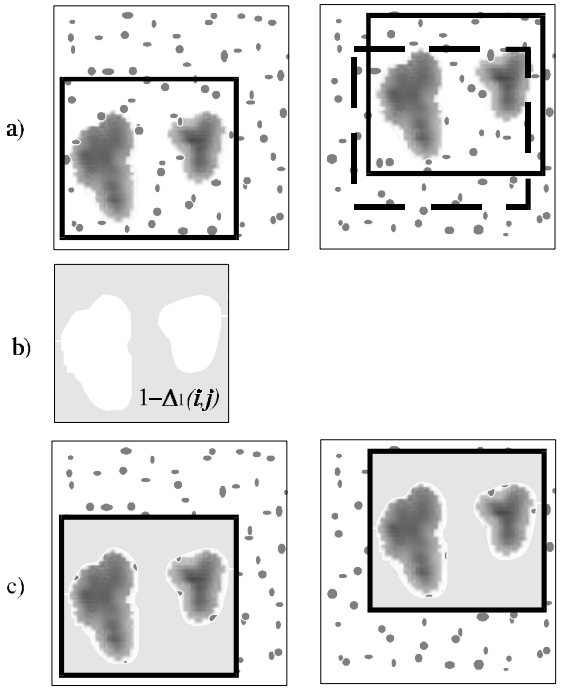

Fig.1: Simulated PIV recordings of a two-phase flow with small tracer particle images and images of the big dispersed particles.
a) Two consecutive exposures (left, right) separated by time interval Δt. A quadratic interrogation pattern (or window) is chosen for the evaluation.
b) Shape of the mask for obscuring the small tracer particle images.
c) Measurement of the displacement of the dispersed particles with the mask applied to the quadratic interrogation pattern.

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. 2 that presents the same simulated particle image patterns as shown in Fig. 1. Determining the minimum of the difference D_B for the continuous phase according to eq. (1) 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. 2a, 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. 2a, right), 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. 2b).

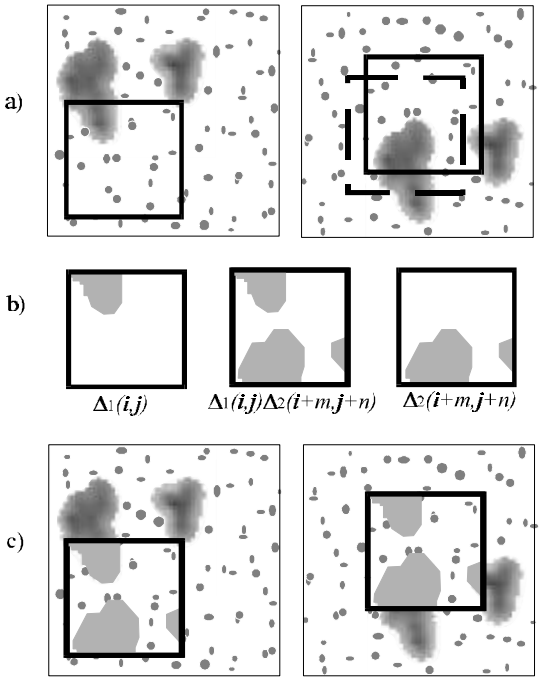

Fig. 2: The same simulated recordings as in Fig. 1.
a) Application of the quadratic interrogation pattern to the unmasked first exposure (left) and viariable position of the pattern in the second exposure (right).
b) Definition of the total mask (middle) composed of Δ_1 (left) and the variable mask Δ_2 (right).
c) Application of the total mask obscuring the dispersed particle images for measuring the displacement of the tracer particle images.

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 D_B. The minimum of D_B is determined for the tracer particle image patterns in the unmasked areas as shown in Fig. 2c. The difference is thus described by

$$D_B(m,n) = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left[g_1(i,j)-g_2(i+m,j+n)\right]^2 \Delta_1(i,j)\Delta_2(i+m,j+n)}{\sum_{i=1}^{M}\sum_{j=1}^{N}\Delta_1(i,j)\Delta_2(i+m,j+n)} \quad (4)$$

From eqs. (3) and (4) 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.

a)

b)

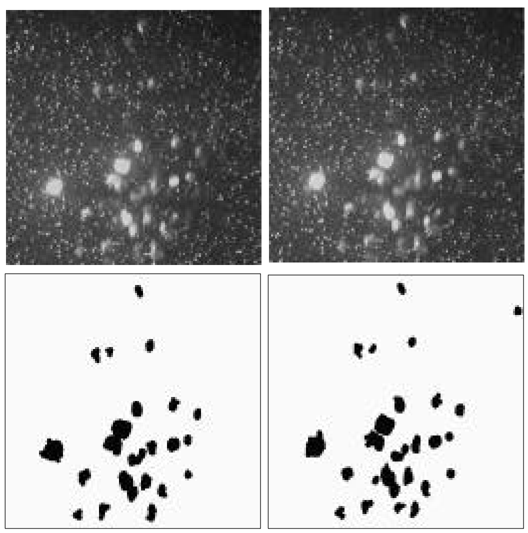

Fig.3: a) Two consecutive digital recordings showing the distributions of small tracer particles and big dispersed buoyant particles in a water tank. Field of view is 450×450 pixels = 9×9 cm^2. Time interval between exposures is Δt= 20 ms.
b) Application of the mask for separating the regimes of phase A and phase B

Practical example

For demonstration purposes we describe the application of this 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 Δt = 20 ms are shown in Fig. 3a. 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 MQD method is shown in Fig. 3b. Since the velocity vectors in this example are relatively low we choose for the origin of the resulting velocity vectors the mentioned centers of gravity of the respective phases in the first exposure. This facilitates particularly the determination of the center of gravity of the distribution of the tracer particle images (Fig. 2b, left), whereas determining this center after application of the total mask would be more difficult due to the variable geometrical shape of the unmasked area (Fig. 2b, middle). The coordinates x_B,y_B of the origin of the vector indicating the velocity of phase B are thus defined by (see Fig. 4)

$$x_B = x_c + \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left(i-\frac{M}{2}\right)\Delta_1(i,j)}{\sum_{i=1}^{M}\sum_{j=1}^{N}\Delta_1(i,j)}$$

$$y_B = y_c + \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left(j-\frac{N}{2}\right)\Delta_1(i,j)}{\sum_{i=1}^{M}\sum_{j=1}^{N}\Delta_1(i,j)} \quad (5)$$

x_c, y_c are the coordinates of the center of the interrogation pattern. Similarly one obtains the coordinates x_A, y_A as the center of gravity of the dispersed particle images in the first exposure:

$$x_A = x_c + \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left(i-\frac{M}{2}\right)\left[1-\Delta_1(i,j)\right]}{\sum_{i=1}^{M}\sum_{j=1}^{N}\left[1-\Delta_1(i,j)\right]}$$

$$y_A = y_c + \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left(j-\frac{N}{2}\right)\left[1-\Delta_1(i,j)\right]}{\sum_{i=1}^{M}\sum_{j=1}^{N}\left[1-\Delta_1(i,j)\right]} \quad (6)$$

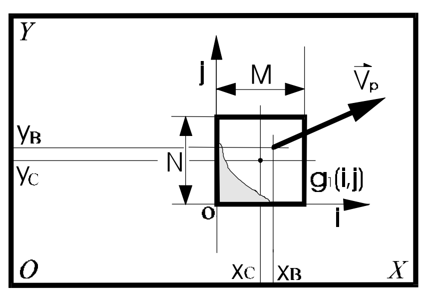

Fig. 4: Definition of the origin of the vector presenting the velocity of the continuous phase B in an interrogation pattern (window) of $M \times N$ pixels.

The result of the evaluation with the MQD method is shown in form of the vector plot in Fig. 5 The size of the field of view is 9×9 cm^2, or 450×450 pixels in digital form. 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.

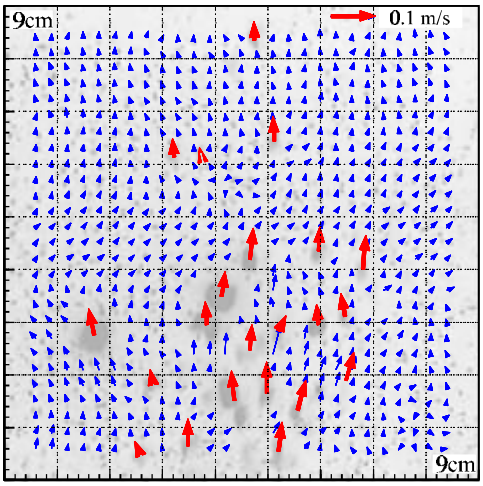

Fig. 5: Result of the velocity measurement for the experimental patterns shown in Fig. 3. The indicated reference velocity is 0.1 m/s. The velocities of the continuous and dispersed phase can be distinguished by the size of the vectors.

Summary

The described mask technique for separating the velocity measurements of the phases in a two-phase flow is based on the existence of a significant difference of the size distributions of the two phases. The technique also acounts for differences in the velocity distribution of the phases and for the fact that small particles can be obscured by big particles. We describe here the technique in combination with the Minimum Quadratic Difference (MQD) method that is used for determining the velocity [9]. Investigations on how this mask technique can be combined with correlation schemes are under way. It should be mentioned that the same principle of masking certain regimes of a PIV recording can be used for removing low frequency noise from the record.

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