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PTV METHODS FOR OVERLAPPING BUBBLE IMAGES

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Abstract

This study presents four Particle Tracking Velocimetry (PTV) methods that measure the velocities of bubbles that are overlapping in the image. That means that the velocities of individual bubbles from a group of overlapping bubbles are measured. The performance of the PTV methods is studied with a set of simulated images of overlapping ellipsoidal bubbles. The methods presented in this study, enable multiphase-PIV measurements in denser bubbly flows with an increased reliability and accuracy of the measurement results.

1 Bubble image segmentation and separation of overlapping bubbles

The bubble images are recognized from an acquired bubbly flow image using the grey scale information and the local gradient of the grey scales as parameters in the segmentation procedure. The local grey scale gradients, i.e. sharp edges of bubble images, are detected with Sobel operators from the pre-processed image. A threshold value for local grey scale gradients is determined by criteria for in-focus bubble image. In the image of a dense bubbly flow, a considerable number of detected segments are created by a group of bubbles and not by individual bubbles. If a common grey scale thresholding method (Chigier 1991) is applied and two or more bubbles overlap in the image, they are detected as one big bubble and only one size and velocity is measured for the whole group. This causes errors in measured size and velocity distributions of bubbles. Thus, a robust algorithm that separates the overlapping bubble images is needed. An overlapping object separation algorithm (presented in Honkanen and Saarenrinne, 2003) is used to separate and individually detect the overlapping in-focus bubbles in the image. The algorithm calculates the overall perimeter of a segment, finds the points at the perimeter that represent the connecting points (i.e. also referred as "breakpoints") of overlapping bubbles. Then it a) pairs the connecting points and connects each pair with a line that separates the overlapping segments (i.e. separation method) or b) fits ellipses on the separated arcs of the perimeter using a direct least square ellipse-fitting method, presented by Fitzgibbon et al. (1999). Only the arcs that satisfy the in-focus criteria are selected.

2 PTV methods for overlapping bubble images

The velocities of individual bubbles from a group of overlapping bubbles are measured. The PTV methods under study are a cross-correlation based FFT-CC method and centroiding methods: a) simple centroiding (SC), b) intensity weighted centroiding (IWC) and c) fitted ellipse centroiding (FE). The centroiding methods find the centroid of a bubble by a) simply measuring the average of the x- and y-coordinates of the pixels inside the segment and b) by weighting the edge pixel coordinates with the normalized intensity of the pixel and c) by fitting an ellipse on the segment and defining the centroid of the ellipse. The bubbles in consecutive image frames are paired with a particle tracking technique that searches for a similar size of bubble that is closest to its pair. The FFT-CC method is also referred to as Individual Particle Correlation (IPC) (Stitou et al. 2004) and it is described in (Honkanen and Saarenrinne, 2002). In this study the FFT-CC method is extended to dense bubbly flows with a mask technique (Gui et al. 2003) in order to correlate only the separated perimeter arcs of each bubble group. Everything else is masked in the image other than the edge pixels of bubble images. The edge pixels are defined with a 2x2 pixel kernel following the perimeter arc of a bubble. The separated perimeter arcs of each bubble group from a first image frame are correlated one by one with the whole perimeter of a bubble group in a second frame.

When the overlapping object separation algorithm is employed with a procedure that pairs the connecting points and separates the segments, SC and IWC methods can be applied to each separated part of the segment. The problems occur, when the bubbles in a bubble group have unequal velocities and consequently they overlap unequal amount in consecutive image frames. Sizes of separated segments change between the frames and therefore, movement of the segment's centroid does not correspond to the movement of the bubble centroid. When the overlapping object separation algorithm is employed with an ellipse-fitting procedure, the velocity of a separated bubble can be estimated from a movement of an ellipse centroid. This fitted ellipse centroiding method is reliable, but it does not obtain high accuracy. Higher accuracy might be obtained with a combination of FFT-CC method and a mask technique. In this case, problems occur, when the bubbles are rotating and deforming significantly.

3 Accuracy of the PTV methods

The accuracy of overlapping bubble velocity measurements is depended on many parameters: firstly the bubbles have to be segmented correctly with proper threshold values. Then the segments that consist of overlapping bubbles have to be detected and separated correctly to obtain correct information of each bubble. The detection of connecting points on the segment perimeter includes challenges related to the stochastic nature of the bubble perimeter, noise and visibility. The same challenges appear further in fitting an ellipse and pairing of connecting points. The difficulty increases with increasing the overlapping of bubbles. Even though the size and the centre point of an overlapping bubble are not detected accurately its movement can be estimated well from the movement of its perimeter arc. The errors in locating a centroid of an overlapping bubble can be about 1-5 pixels, but the errors in measuring bubble movement are about 0.1-1.5 pixels.

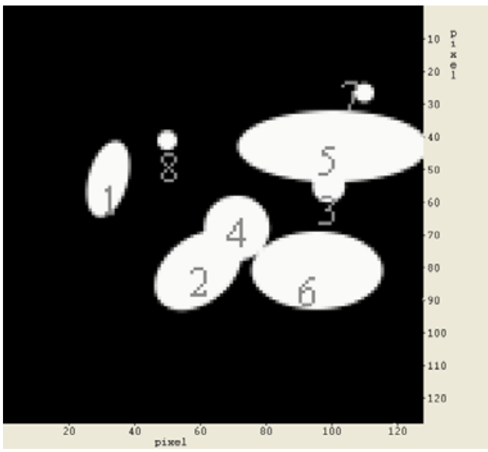

Fig. 1: Simulated image of eight ellipsoidal bubbles

The accuracy of the studied PTV methods is investigated with simulated bubble images. Firstly the accuracy of the methods is studied with simulated bubbles that are not overlapping. Then the overlapping bubble images are created by combining simulated spherical and ellipsoidal bubble images to form different types of bubble groups. A system of 8 overlapping bubbles is studied within a set of 30 images. Figure 1 shows a simulated image of 8 bubbles and their labels. The actual bubble displacements are known, so the accuracy of PTV methods can be defined and the effects of a bubble image overlapping can be studied.

3.1 Simulation of a single bubble image

Firstly a single, spherical bubble is simulated and its velocity is measured with the PTV methods. The simulations are done with different types of tracer particle images in the background and the bubble sizes range from 4-42 pixels with displacements of [0,0.02,0.04,…,4.0]. For a single, spherical bubble case, the overall results relative to varying bubble diameter can be seen in Figure 2a. The simulation shows that the FFT-CC method provides the RMS error of about 0.10 pixels for all bubble sizes. The accuracy of centroiding methods improves with increasing bubble image size. The error level of SC and FE centroiding methods is around 0.04-0.2 pixels. The IWC method can attain the smallest error level, 0.02-0.08 pixels. In this case, the FE and FFT-CC methods are not able to analyze bubbles smaller than 6 pixels in diameter due to low signal-to-noise ratio. Figure 2b shows that the measured bubble displacements are biased towards the nearest integer values (i.e. peak locking effect) due to the discretized information of the digital image. The bias error is largest for the FE method (not shown in Figure 2b), remarkable for SC method, but IWC method gives already much better results. Only very small peak locking effects occur for the FFT-CC method.

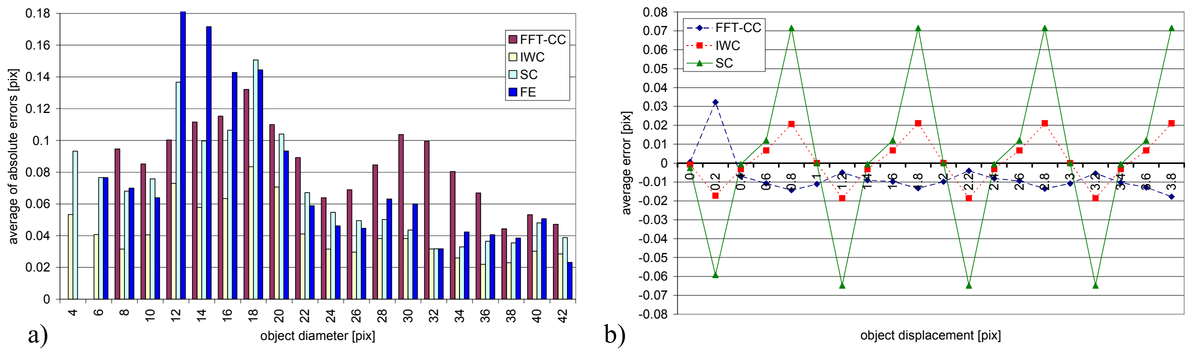

Fig. 2: a) RMS measurement errors of simulated bubble's velocity relative to the varying bubble diameter. b) Average measurement errors of bubble's velocity in an image without background noise relative to the varying bubble displacement.

Similar results are obtained for an ellipsoidal bubble. However, when the bubble is rotating or deforming, the FFT-CC and FE-methods become more inaccurate. The standard cross-correlation analysis studies a linear translation of an image and therefore it cannot take into account rotation and deformation of a bubble. A rotating ellipsoidal bubble is shown in Figure 1 (bubble nr. 1), is studied in 10 simulated images. The bubble moves one pixel vertically and horizontally and rotates 5 degrees between the image frames. The centroiding methods (SC and IWC) are able to capture the motion without any error. The FE method produces a slight RMS-error of 0.008 pixels vertically and 0.007 pixels horizontally. FFT-CC method gives a RMS-error of 0.21 pixels vertically and 0.05 pixels horizontally. The error is vertically larger than horizontally, because this ellipsoidal bubble is vertically oriented producing vertically flat correlation peak.

3.2 Simulation of a group of bubbles

The situation changes when there are many bubbles in the image. When bubbles are close to each other, there will be more than one bubble in an interrogation window typical for FFT-CC method. Even though the neighbouring bubbles are digitally masked in the first image of a correlation analysis, the FFT-CC method does not succeed in distinguishing the movement of a small bubble near large bubbles. The measured velocity of a small bubble is biased towards the velocity of the nearest large bubble. This error of the FFT-CC method increases decreasing the bubble size. In order to prevent the error, the bubbles have to firstly be paired with the particle tracking technique and then the mask technique is applied to both image frames. The particle tracking algorithm might pair wrong bubble images in case, where bubbles with similar sizes are overlapping in the image. In addition, the segmentation algorithm is not able to detect the bubble segment, if other bubble segment exists closer than 2 pixels distance from the segment's top left corner.

A system of 8 bubbles is simulated in 30 images. The images are analyzed with FE, SC/IWC and FFT-CC methods with constant analysis parameters. The simulated bubbles are moving in plane with a constant velocity. Bubbles 1 and 2 are also rotating with a constant speed. Bubble number 5 is deforming. There is no background noise added in the image. Table 1 lists properties of each bubble images in pixels. The RMS-errors of bubble displacements measured with used PTV methods are also shown in Table 1. The bubbles from 2 to 6 are overlapping in most of the images. In those cases the FE method performed most accurately with an average RMS-error of 0.30 pixels and a data rate of 64 %. The SC method obtained a RMS-error level of 0.38 pixels, but gave valid data only in 48 % of the cases. The IWC method gives better accuracy than the SC method, but it has as low data rate as SC method (48 %). The maximum data rate (78%) was given by FFT-CC method, but it suffered from loss of accuracy with an average RMS-error of 0.49 pixels.

Table 1: The properties of simulated bubbles: label, centre coordinates in the beginning (xp, yp), displacements (dx, dy) between image frames and the RMS-errors of measured displacements in both directions.

properties					FE method		SC method		FFT-CC method	
bubble	xp	yp	dx	dy	rms x	rms y	rms x	rms y	rms x	rms y
1	30	55	1	-1	0.007	0.008	0.000	0.000	0.047	0.208
2	60	85	-0.3	-2	0.211	0.077	0.242	0.424	0.227	0.265
3	100	56	-0.4	-0.4	0.169	0.361	1.464	0.326	0.666	2.082
4	70	70	0.6	-1	0.200	0.600	0.081	0.019	0.166	0.637
5	100	50	0.2	-3.5	0.113	0.178	0.246	0.040	0.200	0.052
6	96	86	-0.2	-2.5	0.965	0.078	0.372	0.611	0.356	0.224
7	110	25	0	0.8	0.000	0.004	0.000	0.083	3.111	1.688
8	50	40	0	0.6	0.000	0.003	0.000	0.077	0.104	0.224

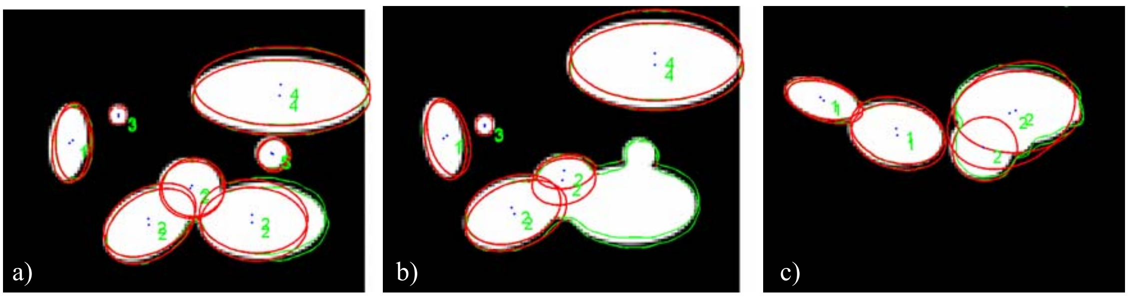

Fig. 3: The ellipse-fitting method has fitted ellipses on bubble images in consecutive frames.
a) frames 5 and 6. b) frames 8 and 9. c) frames 20 and 21.

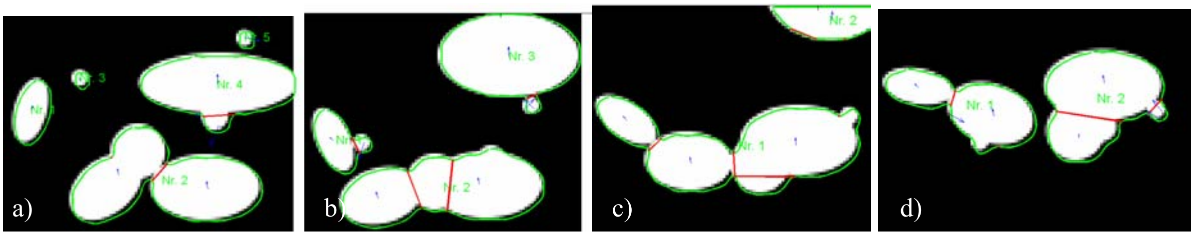

Fig. 4: The overlapping bubbles are separated with lines between paired connecting points and the FFT-CC method has measured displacements of separated bubbles between consecutive frames. a) frame 3, b) frame 11, c) frame 17, d) frame 22.

Figures 3 and 4 show some example cases of simulated bubble groups analyzed with the ellipse-fitting method and with the separation method, respectively. In both cases, the Curvature-profile method (Honkanen and Saarenrinne, 2003) is applied to detect the connecting points of overlapping bubbles. This procedure has succeeded in almost every bubble group. The ellipse-fitting shows problems with large groups of bubbles and it tends to underestimate the bubble size, if the perimeter arc of a bubble is too short (See bubble group number 2 in Figure 3b.). Figure 4 shows how challenging it is for the separation method to pair the correct connecting points. The success of the separation method has a direct influence on the performance of the SC, IWC and FFT-CC methods.

4 Application

Rising bubble swarms in stagnant water are studied. In order to carry out simultaneously the PIV analysis of the fluid flow, fluid is seeded with tracer particles with a diameter of 30 μm. Bubbles are injected to the fluid 13 cm below the measurement area that has a size of 9x12 mm^2. The measurement volume is illuminated with a pulsed diode laser (808nm) in a back-light alignment and the thickness of the measurement plane is controlled by the aperture of the camera objective. Shadow images of bubbles and particles are recorded with a PCO camera. Figures 5 and 6 show some overlayed double-frame bubble images that are analyzed with the present methods.

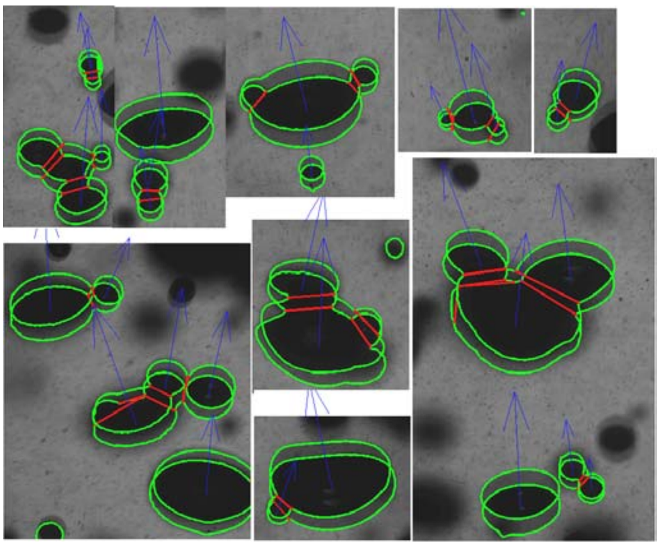

Fig. 5: Overlayed two-frame images, analyzed pairing connecting points, separating segments and calculating the velocities of separated bubbles with SC method (arrows show un-scaled velocities).

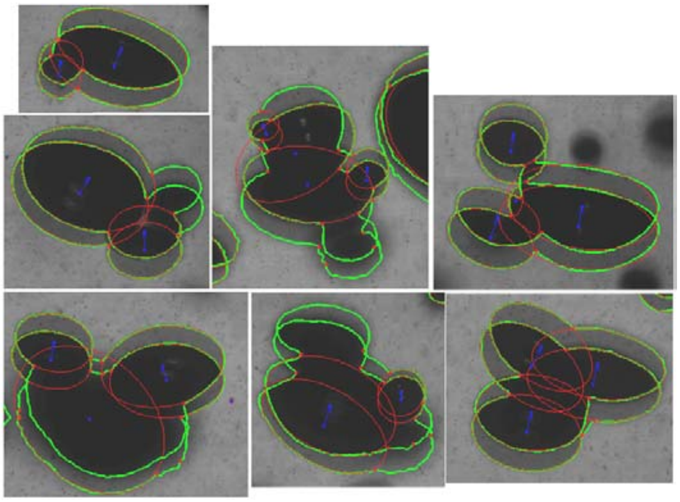

Fig. 6: Overlayed two-frame images, analyzed with ellipse-fitting method and calculating the velocities of separated bubbles with FE method (arrows show scaled velocities).

5 Conclusions

The velocities of individual bubbles from a group of overlapping bubbles are measured with four PTV methods. The simulations of bubble groups show that a measurement of a velocity of overlapping bubble image does not provide accurate result in sub-pixel level. However, all the methods are able to give rather good velocity estimations with a high data rate and with an error level less than 0.5 pixels. The relative accuracy can be increased by increasing the time delay between the consecutive frames. The most reliable and accurate way of studying bubbly flows is still to remove all the overlapping bubbles from the analysis and to measure the velocities of single bubbles with the IWC method. If the overlapping bubble images have to be studied (which is a case in dense bubbly flow), the FE method seems to be the most reliable PTV method for that purpose. The FFT-CC method provides good results for large overlapping bubbles, but it has problems in distinguishing the movement of a small bubble near large bubbles and in measuring velocities of rotating and deforming bubbles. However, the performance of a basic FFT-CC method can be improved applying a digital mask technique for both frames and using robust image correlation.

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