Measurement technique for solid-liquid two-phase flow using a Normal-line Hough Transform method

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Abstract. Image processing method is proved to be an available and important approach for the measurement of multi-phase flow in the past researches. But there still remain some difficult technical issues such as to separate and position the overlapped particle phase in a dispersed two-phase flow, and to carry it out in an efficient way. In our research, we firstly proposed a Normal-line Hough Transform (NHT) method which can solve the problems in an efficient manner than the past ones. Then, we observed the measurement ability and validated the accuracy of the proposed method via a simulation experiment using a pair of pseudo particles. The result revealed that our proposed method could be a practicable one with a high efficiency of 114 times than usual Hough Transform method. What’s more, we also compared the usability of our method with other existed ones using a Monte Carlo method, and the result reveals that our method is a robust one with a wider applicability.

1. INTRODUCTION

Researchs concerning the construction of interfacial area transport equation model have attracted much attention in the fields of multi-phase flow for many years. For which, detail interfacial information of two-phase flow under various of flow regimes, such as void fraction, interfacial velocity and interfacial area concentration, are necessary (Ishii et al., 2005). An image processing method, which can observe the interfacial information directly without disturbing the flow and provide us with a high time-space resolution, has become an important measurement technique along with the development of the computer image processing technology.

Many image processing methods for measuring a two-phase flow have been developed in the past. Among these methods, the most conventional method is the particle detection based on the edge tracking and labelling method as well as the template matching technique(Zabulis et al., 2007). Though they are relative efficient methods for the detection of particles and to reconstruct their interface in dispersed two-phase flows under a low particle density condition, however, the recognition and separation of the overlapped dispersed particles become very difficult when the particle density increases to a certain level.
On the other hand, Shen et al. (2000) proposed a method to divide a planar curve into circle arcs based on a curve-rotate breakpoint detection method, after the arcs belong to the same circle are identified and clustered using an area cross-correlation method, overlapped particles can be recognized in a certain approving accuracy. Unfortunately, the area cross-correlation method has a threshold of area correlation coefficient for about 0.85, thus, the proposed method would become invalidate when the center of two particles are adjacent to each other in an extreme manner.

Furthermore, Qu et al. (2004) employed a two-dimensional median filter together with a triangular Bézier patch method. The proposed method is proved to be an efficient one with a high accuracy in detecting and isolating the small-scale phases from those of the large ones, such as to isolate PIV tracer particles from bubble phase. But it still remains a problem in recognizing and separating overlapped particles that are similar in area fraction.

Besides, the other methods are base on the detection of interface curvature extrema (Fujitsuka et al., 2004). However, the edge gradient breakpoint cannot be obtained easily in practice owing to a low image resolution. Therefore, the development of an appropriate method, which can recognize particles and separate the overlapping ones from defective edge information are eagerly demanded.

In our research, firstly, we proposed a technique, Normal-line Hough Transformation method (NHT), that is able to detect the solid particle phase even though the particle edge was concealed and interrupted each other. We applied this method to solid-liquid two-phase flow images and confirmed that this method is more effective than the existing ones. Secondly, we compared the detection result of NHT with the actual relative position information of a pair of pseudo particles that were adjusted by a traverse, and the accuracy of the proposed method was evaluated in detail. Moreover, a Monte Carlo method is carried out to clarify the measurement limit and the validity of the proposed method, which demonstrates the relationship between the average volume rate of uniform particles and the extraction rate of each method.

2. NORMAL-LINE HOUGH TRANSFORM

The most conventional circle extraction method was the circular arc detection based on the Hough transformation (Duda et al., 1972; Yu et al., 2006). Supposing we are to extract a circle of radius \( r \) from an image use a Hough transformation. Usually edge of the particle image is detected, then each edge pixel contributes a circle of radius \( r \) to an output accumulator space (Fig. 1a), which we call it voting parameter space. If the circle radius is unknown, the algorithm should be run for all possible radiiuses to form a three-dimensional voting parameter space, in which, two dimensions represent the coordinate position information of the circle center, and the third dimension represents the variable radiiuses. The voting parameter space will have a peak where these contributed circles cross at the center of the detecting circle.

However, in practice, a large number of points have to be accumulated in the parameter space in order to construct peaks. Furthermore, the Hough transformation also suffers from the storage problem (Yuen et al., 1996). In this paper, we present an innovative method to recognize overlapped circle particles in images. It makes use of the property that the normal-line of every edge point on a circle consequentially passes through the circle center. We combine the normal-line gradient algorithm to a Hough transformation, which is proved to be an efficient one than the Hough transformation.

In our research, low density dispersed particles with the same radius are used. As a result, all the circles in an image are of identical known radius, here we suppose the radius are of length \( r \), and the three-dimensional voting parameter space can be reduced to two-dimensional. The objective is to find the coordinates of the centers. Assume that all the circles are of radius \( r \), the center of a circle will certainly fall on the extending line of gradient vectors with a distance of \( r \) from the edge pixel. Thus, each edge point contributes one point (Fig. 1a) instead of a circle (Fig. 1b).

The normal-line direction of the edge is obtained according to the gradient, which is calculated by the edge operator. Generally, an image is described as function of brightness, such as \( f(x, y) \), in which, variable \( x \) and \( y \) represent the coordinates of two dimensions. The first order differential (gradient) of the image function is shown in form of vector in equation (1).
Here, we use \( \hat{u}_x, \hat{u}_y \) to indicate x and y axial direction unit vector. By equation (1), the gradient can be calculated by the space differentiates of brightness of the image, and the direction of the gradient can be obtained by equation (2),

\[
\nabla f(x, y) = \frac{\partial f(x, y)}{\partial x} \hat{u}_x + \frac{\partial f(x, y)}{\partial y} \hat{u}_y
\]

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\[
\theta = \tan^{-1}\left(\frac{f_y(x, y)}{f_x(x, y)}\right)
\]

where \( \theta \) stands for the vertical direction (normal-line direction) on the circle edge point. Therefore, the direction of the normal-line is obtained from the gradient on each edge point of the particle. Afterwards, we make use of the property that the center of circle is on the normal-line of edge point, and draw all the normal-lines in the voting parameter space. As a result, the intersecting point of all normal-lines will be the circle center.

In this research, we utilized both the Hough transform method and NHT method under the same experimental condition (CPU: Pentium M 1.8GHz, Memory: 1G, Display Memory: 64M, Image resolution: 640*480) to process about 800 particles with a 13 pixels radius in 56 piece of solid-liquid two-phase flow images. The number of average votes of each method in detecting one particle is \( V_{HT} = 4538 \), \( V_{NHT} = 55 \), and the processing time is \( t_{HT} = 15748ms \), \( t_{NHT} = 138ms \). The NHT method improves the processing speed by decreasing the amount of votes dramatically, and obtained a remarkable efficiency as a result.

3. VERIFICATION OF MEASUREMENT ACCURACY

To verify the accuracy of the proposed NHT method, we carry out an additional verification experiment using a pair of pseudo particles (particle diameter: 2.381 mm, test tube diameter: 9.0mm). Firstly, we fix the position of particle 1 to the center of the test tube, and move particle 2 in horizontal direction with a unit distance of 250 \( \mu m \) using a traverse. Secondly, we compare the actual distance between the two particles with the measured one using NHT method, and then, the measurement accuracy of the NHT method is investigated according a quantitative analysis. Figure 2 shows the extraction result of the pseudo particles in the accuracy verification experiment. Figure 3 shows the result of the accuracy evaluation. The result shows that the standard deviation of the actual position and the measured position is about 0.014, accordingly, the proposed method is proved to be able to detect the overlapped solid particle with a relative accuracy.
To investigate the transition of the extraction rate of NHT and the past methods under various of particle phase volume rate, a simulation experiment using a pair of pseudo particles with a 13 pixels radius was carried out. In addition, a simulation experiment surveying the extraction rate of each method at various of particle phase volume rates was conducted. In detail, firstly, in order to investigate the measurement limit of the proposed method as well as the past ones, we detach the two

Fig. 2 Extraction result of normal-line Hough method in the accuracy evaluation experiment.

Fig. 3 Accuracy evaluation result of normal-line Hough method.

4. TRANSITION OF EXTRACTION RATE
To investigate the transition of the extraction rate of NHT and the past methods under various of particle phase volume rate, a simulation experiment using a pair of pseudo particles with a 13 pixels radius was carried out. In addition, a simulation experiment surveying the extraction rate of each method at various of particle phase volume rates was conducted. In detail, firstly, in order to investigate the measurement limit of the proposed method as well as the past ones, we detach the two
totally overlapped pseudo particles from each other, with an one-pixel step in center distance. The least center distance between the two particles when they can be distinguished using visual observation is considered to be the visual measurement limit. Moreover, the measurement limit of interface curvature extrema method appears when the centers of two particles are close enough so as to lose the curvature extrem. Figure 4 shows the simulation result for surveying measurement limit of each technique. For easy observation, black particles of 13 pixels and a white background was utilized. The result indicates that the measurement limit of the visual method, interface curvature extrema method and the proposed NHT method are 2.3 pixels, 5 pixels and 1 pixel, respectively.

In the simulation experiment that evaluates the transition of extraction rate at a range of average particle phase volume rates, three-dimensional coordinates of particle centers are generated at random in the test tube in certain solid phase volume rate (by adjusting the quantity density of particles). Assume that two particles with a center distance closer than the measurement limit cannot be recognized. The theoretical detectable ratios of each method is calculated and illustrated, which concerns the extraction rate on average volume rate of uniform particles. Here, in order to simulate the dispersed two-phase flow in a realistic manner, the randomly generated coordinates of the particles are assigned to meet the additional restrictions of both equation (3) and equation (4).

\[
\sqrt{(x_n - x_i)^2 + (y_n - y_i)^2 + (z_n - z_i)^2} \geq 2r \tag{3}
\]

\[
\sqrt{(x_n - X_o)^2 + (y_n - Y_o)^2} \leq R - r \tag{4}
\]

Where \((x_i, y_i, z_i)\) stands for the three-dimensional coordinates of a particle center that has already been generated. \(r\) and \(R\) are radii of the particle and test tube, respectively. \((X_o, Y_o)\) indicates the tube center coordinates on the tube section. In each particle volume rate, 1000 cases of simulations are conducted. The simulated extraction rate of each method according to the average dispersed particle phase volume rate is shown in Fig. 5.

From Fig. 5, it is understood that the extraction rate of NHT method achieves 98.7% when the average particle volume rate is about 0.3, and it is proved to be more accurate than the past methods.

| Normal-line Hough method | Visual observation method |
|--------------------------|--------------------------|
| 0 pixel                  | 1 pixel                  |
| ![0 pixel](image1)       | ![1 pixel](image2)       |
| 2 pixels                 | 3 pixels                 |
| ![2 pixels](image3)      | ![3 pixels](image4)      |
| 4 pixels                 |                          |
| ![4 pixels](image5)      |                          |
| 5 pixels                 | 6 pixels                 |
| ![5 pixels](image6)      | ![6 pixels](image7)      |
| 7 pixels                 | 8 pixels                 |
| ![7 pixels](image8)      | ![8 pixels](image9)      |
| 9 pixels                 |                          |
| ![9 pixels](image10)     |                          |

Fig. 4 Measurement limit of each technique.
Moreover, it is confirmed that overlapping occurs more frequently according to the increase of particle volume rate, and a decrease in extraction rate consequently. Since the extraction rate of interface curvature extrema method and the visual observe method decreases remarkably in the case of a high particle volume rate, a miss-evaluating is considered to be possible.

5. EXPERIMENT RESULT

Subsequently, to measure the three-dimensional interfacial information of the flow, we utilize our new method to the solid-liquid two-phase flow images which were taken using the Takamasa’s Stereo Image Method (SIM) (Takamasa et al., 1993; Takamasa et al., 1997), and the interfacial transportation information of the disperse phase in the tube axis direction and the tube transect direction, such as the interfacial area concentration and interfacial velocity, etc, can be built up efficiently.

Figure 6 and 7 show one example of the measurement result that applies the NHT method to the

![Figure 5: Transition of extraction rate of each technique.](image)

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Figure 6 and 7 show one example of the measurement result that applies the NHT method to the

![Figure 6: One example of processing result using normal-line Hough method.](image)

![Figure 7: Particle distribution reconstruction.](image)
solid-liquid two-phase dispersed flow images. Firstly, three-dimensional coordinates are extracted and reconstructed from the position information of the particles in the stereo images, as being shown in Fig. 6, the particles are identified to be the identical one by comparing and pairing the tube axial coordinates in image A and image B. Then, the particle distribution information in the tube transect is reconstructed with the use of three-dimensional coordinates information consequently, and the result is shown in Fig. 7.

6. CONCLUSION
This paper describes a new method to detect particles using NHT in order to recognize and separate the overlapped particles and observe the interfacial distribution and velocity analysis in flow images. It makes an improvement in efficiency by combining a normal-line detection technique with the Hough transform method on the base of SIM method. And it is proved to be an applicable and efficient method for the separation and position measurement of overlapped disperse particles.

Moreover, we conducted a simulation experiment using a pair of pseudo particles to verify the measurement accuracy of the proposed technique. The standard deviation between the actual center distance of the two pseudo particles and the observed value of our method is very small. Thus, it comes to the conclusion that the present measurement method is suitable for detecting overlapped disperse particles with a high accuracy.

On the other hand, a Monte Carlo method to clarify the measurement limit and the validity of the proposed method as well as the previous methods is carried out. The result illustrates a comparison of the extraction rate of each method under a range of average volume rate of uniform particles, and clarify the proposed NHT method to be an available and promising technique.

Furthermore, in practice, we utilized the NHT method to the stereo images of solid-liquid two-phase flow taken under micro-gravity circumstance, and reconstructed the three-dimensional interface distribution information of dispersed particles. The result reveals that individual particles can be recognized and separated in the stereo flow images regardless of two or more of them are overlapping each other. It can also be expected to be utilized to the gas-liquid two-phase flow under micro-gravity circumstance, when the dispersed bubbles are assumed to be approximate circles in shape considering of the agravic effect.

REFERENCES
Duda, R. et al. (1972). "Use of the Hough Transformation To Detect Lines and Curves in Pictures", Communications of the Association for Computing Machinery, 15, pp. 11-15.

Fujitsuka, T. et al. (2004). "Study of Bubble Motion in Gas-Liquid Babbly Flow in Vertical Pipes", Proceedings of Japanese Society for Multiphase Flow, D110, pp. 155-156 (in Japanese).

Ishii, M. et al. (2005). "Thermo-fluid Dynamics of Two-Phase Flow", Springer.

Qu, J. et al. (2004). "Simultaneous PIV/PTV Measurements of Bubble and Particle Phase in Gas-liquid Two-phase Flow Based on Image Separation and Reconstruction", Journal of Hydrodynamics, Ser. B, 16(6), pp. 756-766.

Shen, L. et al. (1999). "A method for recognizing particles in overlapped particle images", Pattern Recognition Letters 21, pp. 21-30.

Takamasa, T. et al. (1997). "Measurement of Interfacial Configuration of Bubbly Flow under Normal and Microgravity Conditions using Stereo Image- Processing Method", Transaction of JSME, 63(606), pp. 40-47 (in Japanese).

Takamasa, T. et al. (1993). "Measurements of Bubble Interface Configurations in Vertical Bubbly
Flow using Image-Processing Method", Transaction of JSME, 59(564), pp. 63-69 (in Japanese).

Yu, X. et al. (2006). "Measurement of Solid-liquid Tow-phase Flow Using a New Robust Normal-line Hough Transform Method", Proc. 5th ISMTMF, 1, pp. 335-340.

Yuen, P.C. et al. (1996). "A novel method for parameter estimation of digital arc", Pattern Recognition Letters, 17, pp. 929-938.

Zabulis, X. et al. (2007). "Detection of densely dispersed spherical bubbles in digital images based on a template matching technique Application to wet foams", Colloids and Surfaces A: Physicochem. Eng. Aspects 309, pp. 96–106.