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Error Analysis of Flow Velocity Measured through Granular PIV Based on Interrogation Area, Frame Per Second, and Video Resolution

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상관 영역과 초당 촬영 수와 해상도에 따른 Granular PIV에서의 유동 속도의 오차 분석

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ABSTRACT

Research on general particle image velocimetry (PIV) has been conducted extensively, but studies on granular PIV are relatively insufficient. In addition, the parameters used for analyzing granular PIV need to be optimized. In this study, we analyzed the error of velocity measurements based on the interrogation area (64-192 pixel), frame per second (30-120 FPS), and video resolution [ultrahigh definition (UHD) and high definition (HD)] within the velocity range typically measured in hoppers. The estimated errors of the granular PIV were below 5%, which is generally acceptable. However, considering the data reliability, the flow velocity in the hopper could be measured with less than 5% error at 120 FPS or higher in the HD resolution and 30 FPS or higher in the UHD resolution.

Key Words : Granular PIV(분체 PIV), Interrogation Area(상관 영역), Resolution(해상도)

1. Introduction

The flow of a powder in a powder storage container of a hopper or silo is considered significant not only to geophysical phenomena including avalanches and debris flows, but also to industrial fields related to the use of industrial substances such as powder and pellets, in the processing of mineral, grain, or chemical substances, and in the supply of minerals such as coal and iron ore into furnaces. Although technical solutions for predicting or generating powder flows are required from industrial and academic perspectives, the mechanisms of powder flows have not been clearly identified. For this reason, experimental research on

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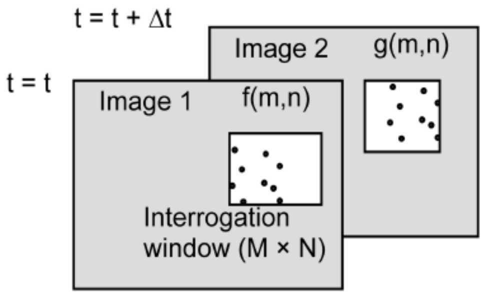
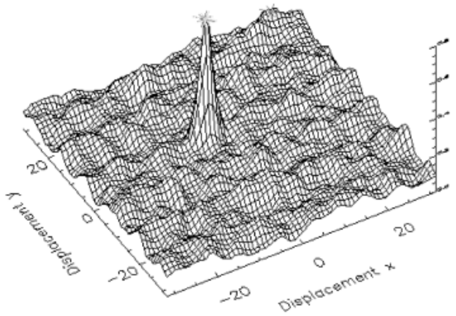


(a)



(b)

Fig. 1 Velocity measurement using displacement at interrogation area; (a) Interrogation window (b) a distribution of correlation[4]

analyzing such mechanisms has received great attention. Particularly, the flows of powder particles are difficult to identify, owing to the opaque exteriors of powder storage containers. In response, several studies have applied granular particle image velocimetry (PIV) to analyze the flows of powder particles; as such, the PIV method should be analyzed in depth.

PIV is a representative flow visualization method for analyzing an experimental fluid based on quantitative flow measurements, and was first developed in the 1980s[1-3]. This method uses a correlation between interrogation areas to derive the velocity field data for an entire flow based on two images. It generates a table of correlation values of correlation coefficients based on the interrogation area, as shown in Fig. 1(a). The entire displacement of the interrogation area is represented as the peak in the correlation value table, as shown in Fig. 1(b)[4].

In a fluid PIV method, a marker or a tracking particle should be additionally inserted in the experimental fluid to measure the flow of the fluid. The size and density of the marker should be carefully determined, so as to accurately identify the characteristics of the flow. In contrast, a granular PIV method does not require the insertion of an additional marker, as each particle serves as a direct tracking particle. Thus, the granular PIV method can be used more conveniently than the fluid PIV method[5].

As the fluid PIV method determines the mean velocity in the interrogation area based on a correlation between images, it can generate errors related to the number of tracking particles, size of the samples, and image resolution. Errors can also have other causes, such as overlapped particles or a correlation between a pair of particles inconsistent with the movements of particles located outside of a boundary[6]. These errors are mainly related to excessive velocities, the density of particles, and the sizes of samples, and numerous studies have been conducted to reduce such errors.

Keane and Adrian found that a lower number of particles in the interrogation area led to a higher number of false vectors observed in the PIV data, and that a higher number density of particles in the interrogation area led to a rapid decrease in the number of false vectors. Based on these findings, they verified that a higher number density of particles could increase the probability of accurately measuring the displacements of particles based on correlations[7].

However, when the number density of particles is significantly high, it changes the flow characteristics

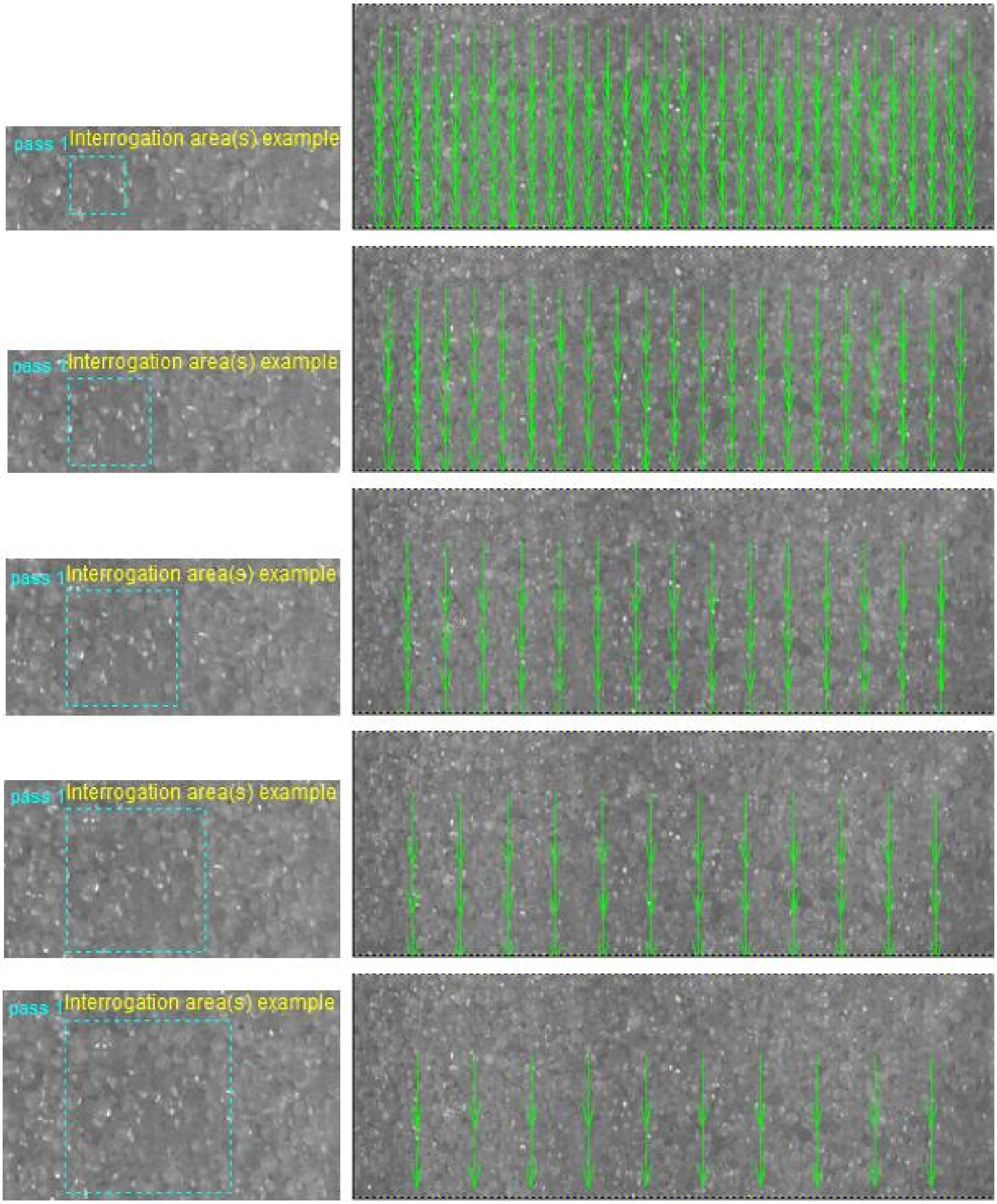
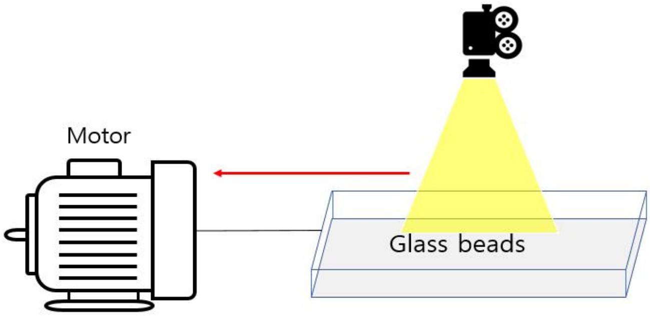


Fig. 2 Examples of interrogation area: 64×64, 96×96, 128×128, 160×160 and 192×192 pixels from top to bottom



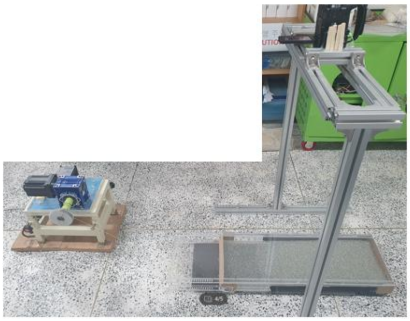


Fig. 3 Experiments using Motor

considerably, leading to difficulty in accurately measuring the displacements of particles. For this reason, the scale of the number density is generally limited. Moreover, as a correlation in an area distant from the interrogation area can be found when a tracking particle moves at high velocity, owing to the restricted size of the interrogation area. In this case, the correlation distribution shows peaks which are comparatively low and widely spread, instead of a remarkable peak at a certain location. As a result, accurate data cannot be obtained. With regard to this phenomenon, F Ulissi argued that the maximum displacement of particles in an interrogation area must not exceed 0.25 times the size of the interrogation area[8].

The aforementioned studies mainly focused on analyzing errors under the conditions of an applied fluid. These studies are relatable to this study if the markers are assumed as individual granular particles. However, appropriate PIV settings for powder flows should be made owing to the differences between the fluid and granular PIV methods. Nevertheless, the number of existing studies conducting granular PIV experiments and analyzing the measurement errors in these experiments is significantly lower than that of existing studies on fluid PIV experiments. Therefore, this study analyzed the optimal experimental settings for a reliable granular PIV analysis by considering the relationships among the velocity of the flow, size of the interrogation area, frames per second (FPS), and image resolution.

2. Determination of Particle Image Velocimetry (PIV) Parameters

Commercial PIV software programs or PIV freeware programs provide various adjustable parameters. For example, PIV algorithms are classified as those based on fast Fourier transformation (FFT) and those based on direct cross-correlation. This study applied an FFT-based PIV algorithm, as Oliver verified that FFT-based PIV algorithms could derive more accurate results [9]. In general, in this software, the interrogation area can be input according to the sizes of the particles and flow fields. When the interrogation area is input as 64, the size of the interrogation is established as 64 × 64 pixels. Thus, the size of the interrogation area can differ, although the same values as those of the practical images are input. Furthermore, an increase in the size of the interrogation area can enhance a signal-to-noise ratio and derive a clearer correlation, but reduces the vector resolution. In other words, an increase in the

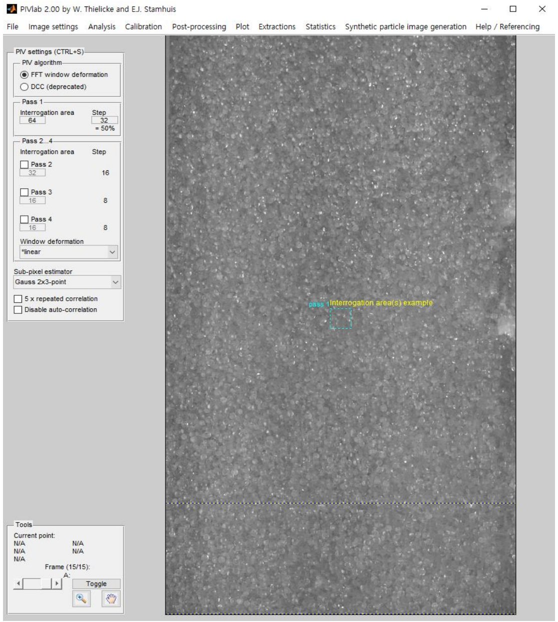


Fig. 4 An example of PIV analysis using PIVlab

size of the interrogation area leads to a rapid decrease in the number of vectors measured in a flow field. Consequently, rapid changes in the flow of particles in the flow field cannot be completely represented. In this study, five types of interrogation areas were used, i.e., 64 × 64, 96 × 96, 128 × 128, 160 × 160, and 192 × 192 pixels. Fig. 2 shows the examples of these interrogation areas as applied to images. As for the number of analyses ("passes") performed, the result from a single analysis was not significantly different from those derived from four analyses. Thus, a single pass was applied in the experiments for this study.

3. Experimental Equipment and Methods

3.1 Experimental equipment

In this study, the equipment included a low and long rectangular acrylic container, glass beads with a mean diameter of 4 mm, a motor (NMRV-050,

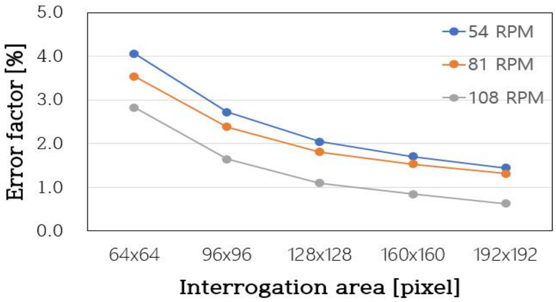


Fig. 5 Relation between Interrogation area and Error rate at 120 FPS and HD resolution

TS tech), and a camcorder (FDR-AX700, SONY), as shown in Fig. 3[1]. The container comprised acryl of 10 mm in thickness, and a transparent acrylic cover was placed on the container including the glass beads inside to make the experimental conditions consistent to those of a hopper experiment. In terms of the camcorder, the Sony FDR-AX700 product, which supports both UHD (3840 × 2160) and HD (1920 × 1080) resolution, was used. Although this camcorder could support 960 FPS (SD resolution) at maximum, this study applied 120 frames (HD resolution) as the maximum FPS, in consideration of the resolution.

The PIVlab v.2.3 PIV freeware program was utilized for the PIV analysis, as shown in Fig. 4[10].

3.2 Experimental methods

Fig. 3 shows the process of the experiments conducted in this study. First, the glass beads were placed in the acrylic container to completely fill it. Subsequently, the motor was used to pull the container. At this time, the velocity of the motor was set as 54, 81, and 108 RPM, respectively. Accordingly, the practical velocities of glass beads were calculated as approximately 0.084816, 0.127224, and 0.169632 m/s, respectively. The velocity of the motor was set according to the conditions indicated above, given that the velocity distribution was within the aforementioned velocity

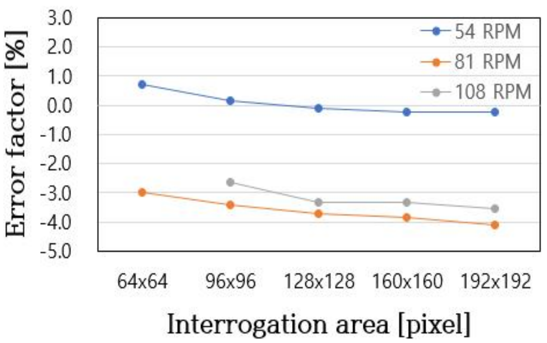


Fig. 6 Relation between Interrogation area and Error rate at 30 FPS and HD resolution

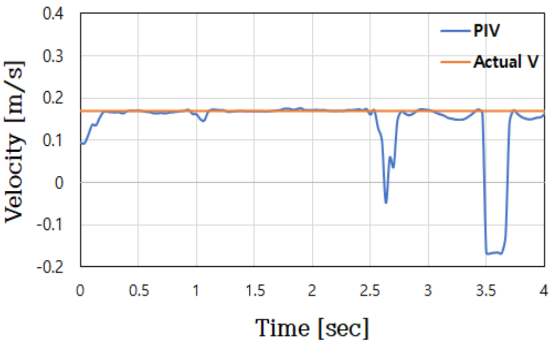


Fig. 7 Velocity and time curve measured with 30 FPS and 108 RPM

range in the process of performing a granular PIV analysis based on a hopper. The camcorder was used to record a video of the container being pulled by the motor, and the video was uploaded to the PIVlab program to perform calibration and parameter adjustment for the PIV analysis. The video of the container was recorded under different resolutions and FPS values to identify the tendencies of errors related to the interrogation area, resolution, and FPS. The size of the interrogation area was increased from 64 × 64 pixels to 192 × 192 pixels at an interval of 32 pixels, and five types of interrogation areas were analyzed in the experiment. The entire experiment was conducted for three times or more, and the mean of the experimental values was applied for analysis.

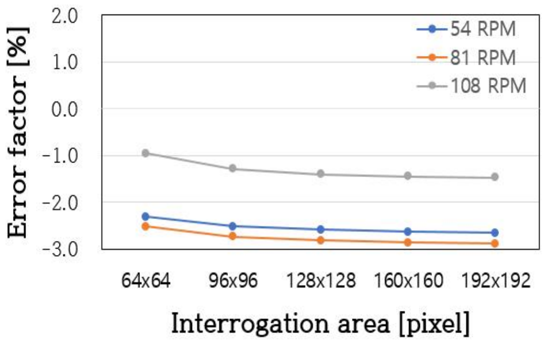


Fig. 8 Relation between Interrogation area and Error rate at 30 FPS and UHD resolution

4. Error Analysis

4.1 Flow velocity

First, the change of the error rate based on the following equation was measured according to different sizes of interrogation areas under the same conditions of 120 FPS and HD (1920 × 1080) resolution.

$$Error = \frac{Motor\ Velocity - PIV\ Velocity}{Motor\ Velocity} \qquad (1)$$

Fig. 5 shows that the error rate converges to 0 as the size of the interrogation area increases, regardless of velocity. However, as mentioned above, an increase in the size of the interrogation area reduces the number of vectors that can be measured in the flow field, and makes it impossible to represent a rapid velocity change in the flow field. Nevertheless, it is found that the measurement values will not have significant problems when the conditions of 120 FPS and HD resolution are applied to measure the flow of powder in a hopper, as the measurement values have error rates of 5% or lower under these conditions. In addition, the accuracy of the analysis increases as flow velocity increases. However, the reason for such a phenomenon was not clearly identified.

4.2 Frames per second (FPS)

An additional experiment based on 30 FPS was conducted to examine the changes in error rates according to 30 FPS and 120 FPS. As indicated in Fig. 5, the error rates form a downward curve with a certain amount of reduction regardless of the velocity under 120 FPS. Moreover, all of the error rates are positive. In contrast, the error rates calculated under a condition of 30 FPS applied show different results, as shown in Fig. 6. Although the error rates under the condition of 30 FPS also form a downward curve, the error rates at 81 RPM and 108 RPM are negative. An error rate at 54 RPM is partially negative as well. Based on these results, it is confirmed that measurement can be performed without a significant problem at 54 RPM, and that minor errors (with an overall error rate of 5% or lower) occur at 81 RPM and 108 RPM. Thus, it can be evaluated that the data reliability is potentially reduced when the powder velocity in a hopper is measured under the conditions of 30 FPS and HD resolution. Particularly, Fig. 6 shows that an error rate is not displayed when an interrogation area of 64 × 64 pixels is applied at 108 RPM. That is because the error rate is calculated as approximately 20%, considerably exceeding the allowable error range. As a result, this error rate is excluded from the graph. Such a significant error rate occurs owing to the displacement of particles, i.e., those in the interrogation area having left the corresponding area when the following time step image is analyzed, particularly under an interrogation area of 64 × 64 pixels (the smallest in size) and 108 RPM (the highest velocity). Fig. 7 shows that the practical velocities of most particles is nearly consistent with those of the particles calculated in the PIV analysis. Nevertheless, the velocities of certain particles are significantly different from their practical velocities. These significant error values are observed at points where particles are lost owing to considerably great displacements of the particles in the interrogation area measured in the PIV analysis.

4.3 Resolution

This study analyzed the measurement results from UHD (3840 × 2160) and HD (1920 × 1080) resolution, under the same condition of 30 FPS. Notably, the size of the interrogation area of 64 × 64 pixels in HD resolution is practically consistent with that of 128 × 128 pixels in UHD resolution, as the interrogation area is input based on pixel units. The HD images are analyzed in Fig. 6, and the UHD images are shown in Fig. 8 . The analysis results indicate that error rates are distributed in a range from -1% and -3% under UHD resolution, and that these rates constantly converge to a certain value. In addition, the scale of errors increases as the size of the interrogation area increases, as shown in Fig. 6. However, the errors calculated under UHD resolution can be ignored, as they are 3% or lower. Therefore, a PIV analysis of the flow of powder particles in a hopper can be performed without a significant problem when the video is recorded under the conditions of 30 FPS and UHD resolution.

4. Conclusions

When the conditions of 120 FPS and HD resolution were applied within a velocity range generally measured in a hopper, ignorable error rates of 5% or lower were generated in interrogation areas of 64 × 64 pixels or greater in size. At 30 FPS, i.e., the level applied in general cameras, the entire error rates were calculated to be approximately 5% as well. However, the errors increased as the size of the interrogation area increased, thereby causing a problem related to reliability of the measured values. It was analyzed that this problem occurred because the high velocities of certain particles were not measured. To solve this problem, the resolution was increased to UHD resolution (four times higher than

HD resolution) under the condition of 30 FPS. Through this process, the accuracy of the measured values could be ensured, with error rates of 3% or lower. In conclusion, it was verified that the flow velocity of powder particles in a hopper could be measured with error rates of 5% or lower under the combined conditions of HD resolution and 120 FPS or higher, or under the combined conditions of UHD resolution and 30 FPS or higher.

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