PIV Technique applied to granular flows in hoppers

F Ulissi \(^1\), I Ippolito\(^{1,2}\) and A Calvo\(^1\)

\(^1\) Grupo de Medios Porosos, Facultad de Ingeniería, Univ.de Buenos Aires, Paseo Colón 850, 1063, Buenos Aires, Argentina.
\(^2\) CONICET, Av. Rivadavia 1917 – 1033, Buenos Aires, Argentina.

Email: fulissi@gmail.com; iippoli@fi.uba.ar

Abstract. In this work we report a technical method based on PIV, usually used in fluid dynamics, to measure velocity profiles of granular materials in silos and hoppers. The particles inside the hopper were filmed by a digital video camera. Finally, we measure the velocity profile of granular materials inside a quasi-two dimensional hopper and compare the data with some existing models.

1. Introduction
Granular flow in hoppers, silos and similar containers is important in many technologies such as the processing of minerals, grains, chemicals and pharmaceuticals, feeding of furnaces fuelled by solids and mining. In industry, technical solutions to achieve the desired type of flow are empirical, because these materials are difficult to visualize in experimental devices.

The knowledge of the velocity field inside the hopper or silo is important in order to predict the type and flow rate, and for testing the existing models for velocity profiles. Two of the most common flow problems experienced in an improperly designed silo are no-flow and erratic flow. No-flow from a silo can be due to either arching (bridging) or ratholing. Arching occurs when an obstruction in the shape of a bridge forms above the outlet of a hopper and prevents any further material discharge. It can be an interlocking arch, where the particles mechanically lock to form the obstruction, or a cohesive arch. An interlocking arch occurs when the particles are large compared to the outlet size of the hopper. A cohesive arch occurs when particles pack together to form an obstruction \([1][2]\).

In this paper, we will focus on the velocity field measurements in quasi-two dimensional silos applying the Particle Image Velocimetry technique in continuous dry granular flow. As the name suggests, PIV records the position over time of small tracer particles introduced into the flow to extract a discrete velocity field. PIV method knows its origin in the measurement of velocity fields in different fluids. The basic requirements for a PIV system are an optically transparent test-section, an illuminating light source (laser in fluids), a recording medium (CCD camera), and a computer for image processing \([3]\).

\(^1\) Eng. Facundo Ulissi
2. Method of measurement

2.1. PIV Technique: basics
This method allows to obtain the displacement of a group of particles called “markers” that are inserted in the flow. In fluids, the markers are very small non miscible particles (Kerosene or PVC's filings) that join the fluid so that they should not affect the flow.

Figure 1 shows a scheme of the basic general arrangement of devices for applying PIV technique on fluids. The CCD camera only sees the particles in a plane of the fluid that are illuminated by means of a laser sheet that crosses cylindrical lens. In granular materials the images only shows the motion of material against the hopper walls.

![Figure 1. Basic requirements for a PIV system [3].](image)

The basic procedure to apply the PIV method is: a) dividing the obtained images of a movie in basic units called “interrogation area”, typically of 32x32 pixels (figure 2). b) Obtaining the medium displacement for all the markers into this area by identifying the maximum of a function called correlation function, applied between the correlation areas of two successive images of a video.

![Figure 2. Generic image divided into interrogation areas [3].](image)
Basically the correlation function $\phi$ measures the “coincidence” between two images. In this paper we use the cross-correlation algorithm as shown in equation (1), to obtain the displacement field by convolution between portions of two successive images of the experiment.

$$\phi_{fg}(m,n) = \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} f(k,l) g(k+m,l+n)$$  \hspace{1cm} (1)

In equation (1) “$f$” and “$g$” functions indicate the grey level of each interrogation area that corresponds to analogue centered positions of “$t$” and “$t+\Delta t$” images. In our experiments, sizes of 32x32 pixels and 8x8 pixels were used for “$g$” and “$f$” respectively. The displacement of a group of tracers that are confined into an interrogation area is the displacement of “$f$” against “$g$” (starting at centered position) in which the cross correlation function reaches a maximum value. This maximum is commonly called “true correlation”. Physically, the "true correlation" represents the number of coincidences among tracers between “$f$” and "$g$”. Then, the discrete velocity field can be found by dividing the displacement obtained by the time between the two images of a pair (\(\Delta t\)).

We call also “mean peaks” to those peak values that are smaller than the “true correlation peak” and the ratio between true correlation and random correlation peaks is the “Signal to Noise Ratio”, or S2NR.

2.2. Control parameters and data validation

We have observed that calibration tips for PIV applied in fluid experiments are also valid for granular materials. In order to calibrate this method, we list the main tips.

The cross correlation algorithm cannot work if the minimum quantity of particle tracers into the interrogation area at image 1 are not into the analogue interrogation area at image 2. To avoid this phenomenon called “loss of pairs” it is necessary to control the interrogation size area (\(d_i\)), the time between images (\(\Delta t\)), and the tracer’s density.

It is necessary to assure that the real displacement will not exceed the interrogation area dimensions. In this case, the measurement is not valid because one of the two positions of a particle is missing. The maximum particle displacement \(\Delta X\) recommended [3] is 0.25 times the size of the interrogation area in pixels (\(d_i\)), as shown in equation (2).

$$\Delta X \leq \frac{1}{4} d_i$$ \hspace{1cm} (2)

In our cases, we have chosen \(\Delta X \approx 8\) pixels in average. The time between images was selected taking into account the following tips:

- To avoid the phenomenon of “loss of pairs” due to excessive time between images.
- To avoid velocity errors due to excessive time between images that causes that the detected velocity is not quasi-instantaneous.
- To avoid reaching the low limit of time interval detectable by the CCD camera.
- To avoid measuring low displacements that can be confused with other correlation values (low Signal to Noise Ratio).

Equation (3) suggests an expression to estimate the time interval between images that considers those tips [3].

$$\Delta t \leq \frac{\Delta X}{MU}$$ \hspace{1cm} (3)
In equation (3) \( M \) is a spatial scale factor in pixels/mm and \( U \) is the average expected flow speed. In our experiments: \( U \approx 20 \) mm/sec and \( M = 5 \) pixels/mm; then, \( \Delta t \approx 0.08 \) sec. Based on equations (2) and (3), by experimental calibration, we finally use \( \Delta t = 0.05 \) sec and \( \Delta t = 0.07 \) sec (each one computed from different estimated velocities \( U \)) depending on the velocity pattern across the flow.

The tracer particle density requires to be also controlled. If the number of tracer particles is increased, the number of real correlations also will be increased and therefore, the relation S2NR and then the reliability of the measurement. The minimum recommended tracer density in an interrogation area is at least 5 particles [4]. Figure 3 shows the effect of seeding density in PIV measurements on fluids.

![Figure 3. Effect of tracer particle density on the measurements [4].](image)

In our case (figure 4), tracer density is bigger than 5, because vacancies can be also taken into account as tracers. Typically, there are 10 or more tracer particles inside each interrogation area.

![Figure 4. Tracer density on granular measurements in a 32x32 pixels interrogation area (4X magnification).](image)

As it has been described, the PIV method provides typically a grid of independent vectors with a density of 32x32 pixels. In our application, the interrogation is performed with an “overlap” between
adjacent interrogation areas of 50%. In this sense, the center of each interrogation area is displaced \(d/2\) respect to its neighbour, in both \(X\) and \(Y\) directions. As a consequence, the total number of vectors increases by a factor of 4 and the detections are not independent [3].

In order to validate the measurement, it is essential to know all the values of the equation (1) in the correlation plane and compare this information to the maximum correlation (position of the measured displacement), according to equation (4).

\[
\frac{h_1}{h_2} \geq k
\]  

(4)

The relation expressed in equation (4) is the mentioned “Signal to Noise Ratio” where \(h_1\) is the maximum of the correlation values and \(h_2\) is the comparison parameter, which can be an average value in the correlation plane (“peak to mean” validation) or a second maximum one (“peak to peak” validation). In this work we will use the first one, and the recommended value for \(k\) is 3 [5]. In our experiments these values are greater, close to 19 in average which satisfies equation (4).

3. Velocity field measurement

3.1. Experimental set up

The experimental quasi-two dimensional hopper consists of two acrylic plates of 400mm side and 5mm of thickness, separated by thickness rods. The width between plates can be adjusted by varying the rods width. The lateral walls are made of two acrylic tilt rods and the angle between the rods and the horizontal can be varied (figure 5).

![Figure 5. Basic scheme of experimental hopper.](image)

The thickness of the hopper was fixed in 10 mm and the discharge hole in 5 mm in order to optimize the calibration of PIV method. The lighting system consists of four 18W fluorescent tubes placed in front of vertical planes. A scheme of the set-up is shown in figure 6. Special care was taken to horizontal and vertical align the different parts of the general arrangement.
3.2. Experimental procedure

The characteristics of grains used in the experiments are listed in Table 1, where $\Phi_m$ is the mean size of the grains, $s$ is the standard deviation of sizes and $C_v$ is the relative dispersion of sizes to the mean size.

Table 1. General characteristics of granular materials.

| Grains          | Mean Size $\Phi_m$ [mm] | Standard Deviation $s$ [mm] | Relative Dispersion $C_v$ [%] |
|-----------------|-------------------------|-----------------------------|-------------------------------|
| 0.5 mm Glass Beads | 0.5                     | 0.0                         | 8.60%                         |
| 1 mm Glass Beads | 1.1                     | 0.1                         | 7.80%                         |
| Type S Quartz   | 1.0                     | 0.2                         | 23%                           |
| Type B Quartz   | 1.4                     | 0.3                         | 23.90%                        |
| Type S Sand     | 0.6                     | 0.2                         | 27.20%                        |

Depending on the illumination, the grains can be seen as translucent or opaque to prevent from carrying out the PIV method as usually described for fluids. So, we replace the laser plane by conventional light illuminating the frontal plane of the hopper. The markers are some dyed grains, but the interstitial vacancies between grains make up markers too. Typically, we achieve good results by dying 15% of the total mass of the grains in the hopper. The lighting system serves to enhance the contrast between the markers (vacancies and grains) and the granular matrix.

A filling procedure was developed and controlled to achieve a regular charge that is kept constant in all the experiments. The exit orifice is suddenly opened and steady state flow is established before acquiring the images for PIV technique.

We focus the attention on a rectangular region of the hopper of 200mm x 100mm above the orifice with a resolution of 1000 x 500 pixels approximately. The CCD camera acquires 20 frames per second using an external trigger and the exposure time is 5 msec which corresponds to a 10% of the time between images. This exposure time provides a displacement error within 0.1 mm.
The experimental recorded videos are composed of 1200 images approximately and therefore, the maximum discharge time is about 60 seconds. To enhance the contrast and to distinguish boundaries of particle tracers, we apply two convolution filters. For smoothing the image noise, we first apply a Gaussian filter with $\sigma = 0.5$ and a kernel size equal to a half grain size for each image (typically 5x5 pixels). After that, we apply an average filter with the same kernel size. The resulting image is less noisy and the boundary of grains more clear to apply then the velocimetry technique (Figure 7).

![Figure 7. Images after applying Gaussian and Average filters.](image)

3.3. Preliminary results
By applying the PIV technique controlling the mentioned parameters, we achieve satisfactory results. As said before, we achieve a 32x32 pixels resolution in the velocity field. Figure 8 shows the vertical velocity field on a hopper image.

![Figure 8. Experimental vertical velocity field.](image)

Figure 9 shows the same results in chromatic scale. The graphic was obtained plotting the vertical velocity values for each spatial position in the hopper. Black regions represent stagnant zones and
white regions represent high velocity zones in the hopper. Note that the maximum velocity value is located in the middle of hopper and increases near to discharge.

**Figure 9.** Vertical velocity field, represented by a chromatic scale.

## 4. Conclusions

In summary, we have used a PIV technique to achieve good resolution in measuring a velocity field on granular materials confined in silos or hoppers. We show that PIV method is reliable and allows us to measure in a good precision velocity profiles. In that sense, we describe a simple, cheap and versatile experimental device that allows to obtain several results in the granular material studies. Furthermore, we describe the principal characteristics of the method and its control parameters, and we obtained its regulation values to achieve reliable results with granular materials.

## 5. References

[1] Duran J 1997 *Sables poudres et grains*, (Eyrolles) ISBN 2-212-05831-4.

[2] Nedderman R 1992 *Statics and kinematics of granular materials* ed. (Cambridge University Press) ISBN 0-521-40435-5.

[3] Prasad A 2000 Particle image velocimetry *Current Science* 79 51–60.

[4] Keane R and Adrian R 1992 Theory of cross-correlation analysis of PIV images *Applied Scientific Research* 49 191–215.

[5] Westerweel J 1993 Digital particle image velocimetry *Ph.D. Thesis Delft University Press*. 
