

Methods for the physical measurement of collisional particle flows

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Abstract.

Particle image velocimetry (PIV) and particle tracking velocimetry (PTV) are used in this paper to test their ability in measuring kinematic properties of granular flows, such velocity fluctuations and granular temperature. A small inclined chute geometry was used here to reproduce flows encompassing different flow regimes. An experimental investigation of a dry free-surface flow composed of almost spherical monodisperse ceramic beads is presented. The two image velocimetry techniques are directly applied to images captured in a region of the flow where an apparent uniform steady regime was observed. Our results shows that PTV is capable of measuring the movement of individual particles resulting in estimations of granular temperature that can be compared with other studies. In contrast, PIV tends to damp the magnitude of the random component of the velocities, which in turn produces lower values of granular temperature.

1. Introduction

In geophysical contexts, granular flows are encountered in various forms. Examples are granular chute flows, rock avalanches, landslides and debris flows. In general, a granular flow involves one or more flow regimes: a slowly deforming or quasi-static flow governed primarily by inter-particle friction, a dense flow regime where particles interact by long-lived contacts as well as inter-particle collisions, and a strongly agitated regime dominated by particle collisions. This reflects the inherent complexity and the multitude of heterogeneities present in bulk flow that makes these systems very difficult to study as a whole.

Over the last half-century, granular flows have been investigated by means of diverse analytical, experimental and numerical studies. Efforts have been made to formulate mathematical models that try to capture the complex behaviour of granular flows (e.g. [1]). However, a single unified model that includes all the aforementioned regimes is yet not available. The research and development of new models is continuous and there is a strong need for experimental data in order to verify such models. The final goal is to produce theories and models that incorporate notions of the behaviour produced by the relative configuration of the particles which results from complex frictional and also collisional particle interactions.

It is common to treat granular flows, such as debris flows, according to their frictional or viscous behaviour but little is known about the effect induced by collisional interactions to the flow dynamics. Macroscale models that use depth averaging methods are the principle approach



for the dynamic modeling of debris flows [2-3]. However, difficulties arise when accounting for the microscopic behaviour of debris flow materials in terms of transportation kinematics and collision interaction. Consequently, depth averaging methods may result in a unclear picture of the debris flow dynamics. Ultimately, careful consideration to the microscale mechanics should also be considered to achieve a more comprehensive understanding of these granular flows.

From an experimental point of view, non-intrusive techniques such as particle image velocimetry (PIV) and particle tracking velocimetry (PTV) are now widely used for measuring behaviour of granular flows in laboratory experiments. Their development over the past decades has made them practical tools to estimate particle displacement and single particle movements. Such measurements have become useful for checking and refining mathematical theories, especially those based on stresses originated by the collisions of particles such as the kinetic theory of granular flows. This theory relates the random components that generate particle stresses through collisions to the concept of granular temperature. The latter can be used to characterize the flow regimes and infer the ability of a granular medium to flow. However, estimations of granular temperature are rarely found in the literature and in any case are difficult to interpret.

In this paper PIV and PTV are applied to dry free-surface flows of almost spherical monodisperse ceramic beads down an inclined chute geometry. We use the two image velocimetry techniques and compare their ability to estimate kinematic properties of the granular flows, e.g., velocity fluctuations and granular temperature. The flows are relatively less complex than natural debris flows, although the primary motivations for this work are to test PIV and PTV and to provide new experimental evidence that may help in the formulation of unified models that encompass the whole range of flow regimes. After a brief introduction on the two image analysis techniques, apparatus, and experimental procedure we present our results and discuss their significance.

2. PIV and PTV for granular flows

Two main methods can be distinguished for the measurement of instantaneous velocity fields from a set of recorded images, namely, particle image velocimetry (PIV) and particle tracking velocimetry (PTV). Each technique presents strengths and weaknesses; which method one decides to use strongly depends on the experimental set-up and flow conditions [4].

PIV is a well-established techniques that uses statistical cross-correlation to determine the spatial shift of particles from subimages. PIV provides exhaustive analyses although some limitations exist. One of the problem encountered is gradient biasing caused by the development of velocity gradients in the flow. Faster moving particles leave the subimage region and the remaining slower particles act to bias the displacement estimate [5]. A further limitation regards the size of the interrogation region. It plays an important role in determining the achievable spatial resolution of the flow. There is a limit on how large or small this interrogation region can be for adequate measurements. Subimages smaller than the particle diameter do not produce sufficient textural information and increment the level of noise. Conversely, larger interrogation area implies that the measure will refer to an ensemble of particles.

The other technique (PTV) uses matching algorithms to recognize the trajectory of particles from a prior identification of their centroid coordinates. The first step of the PTV analysis is the detection of the particle centres. It has a strong influence on the quality of the recovered information and can result in a clear limitation of this method. Indeed, PTV contains individual errors which are mostly related to the estimate of the particle centroids which may induce physically unrealistic disturbances to the velocity vectors. PTV has been historically classified as suitable for images of low particle density. However, the combination of current algorithms for particle detection [6-8] with algorithms used to solve the temporal matching problem [9], have also provided good performance for images with a moderately high particle density. In

any case, intrinsic centroiding errors may occur and a trade-off between particle concentration and imaging delay has to be found. An appropriate choice of the temporal resolution (i.e., the frame speeds) is important. Long term steps between successive frames damps high-frequency fluctuations, whereas short time steps lead to large displacement errors [10].

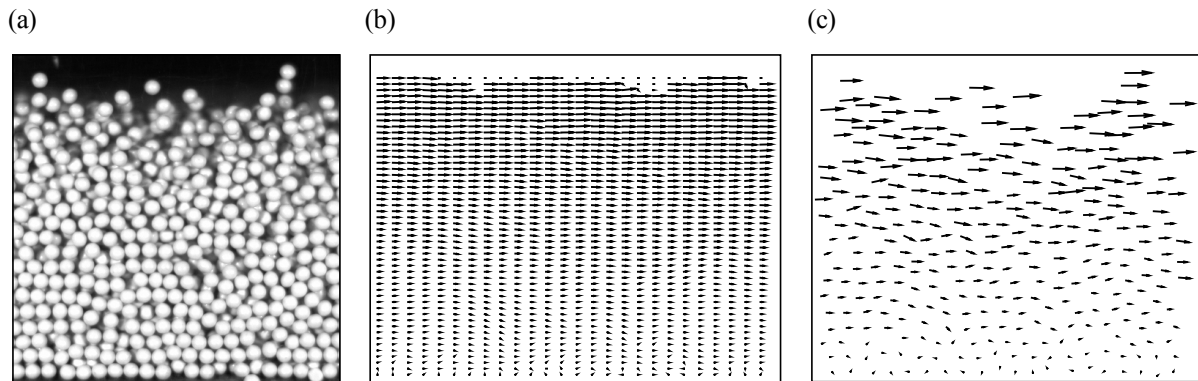


Figure 1. Pattern-based particle velocimetry methods: (a) Example of image extracted from the bead flows; (b) PIV velocity vector output produce by the cross-correlation routine between to frame images; (c) PTV displacement vectors (up-scaled) obtain by resolving the matching algorithm.

For the present work we selected two imaging algorithms that we deemed appropriate for the study of granular flows. A modified version of the PIV algorithm [11] used by [12] was employed directly to the captured images and was found sufficient to determine the velocity fields. This PIV method is adequate to determine the vector field via the cross-correlation analysis between interrogation areas in the first and second images (Fig. 1(b)). The software allows a static mesh to be kept in the same location while the granular mass is flowing. Within the mesh, columns of patches are drawn. User-defined slope-normal and slope-parallel spacing of the patches determine the amount of overlap and the number of patches within the mesh. The number of columns is dependent on the size of the patches chosen and the user-defined width of the mesh. The instantaneous velocity between two frames is finally obtained as the spatial average of the patches belonging to the same row.

For the PTV analysis we used a cross-correlation-based algorithm for PTV, coupled with a relaxation method proposed by Brevis et al. [9]. This integrated system has the ability to ease the matching problem by applying a relaxation algorithm where the cross-correlation method shows low reliability. An example of processed velocity vectors is shown in Fig. 1(c). To detect the particle centres, the particle-positioning approach [8] was found to yield good results. More specifically, the accuracy of this method was tested in a series of bench-scale experiments consisting of a container sliding unidirectionally along a track in a supporting base plate. Known increment translations were applied by a manual micrometer. By collating the displacement vectors and calculating the standard deviation, the error magnitude in the direction parallel to the plane of sliding can be seen. The estimated standard deviation error was found of the order of 0.05 pixel. Particle detection was also implemented with a Circular Hough Transform (CHT) algorithm (e.g. [13]) in order to remove the background particles from the analysis. Use of the Circular Hough Transform (CHT) is a robust technique mainly used to detect spherical/elliptical-shaped particles from noisy images. However, this implementation resulted in sporadic detection of background particles although these occasional outliers were removed by the matching algorithm. Finally, binning was used to extract velocity profiles. The

flow was subdivided into non-overlapping horizontal slices, typically of thickness one particle diameter. The mean velocity was then constructed by taking the ensemble-average streamwise and transverse velocities in each bin.

Within PIV and PTV analyses a transformation from camera to real world coordinates is required. Before each test a calibration grid was located at the wall surface exactly where the images were captured. With this information an approach based on Brevis and Garcia-Villalba [14] was used. Using a binarized grid image, the calibration marks were detected with subpixel accuracy and the image coordinates were subsequently associated with its real x and y coordinates by means of an interpolation technique that uses a Delaunay triangulation approach.

3. Apparatus and experimental procedure

A small inclined chute has been developed in order to study dry granular flows (Fig.2). The flume is a sloping rectangular 10 cm wide and 150 cm long channel that can tilt from horizontal up to 45° . At one end, the material is held inside a hopper which can contain approximately 10 kg of material. A double-slider gate mechanism enables control of the releasing flow height which in turns determines the thickness of the descending mass. The thickness is well controlled although it is unlikely to be equal to the opening. The basal roughness is made by covering the flume bottom with the same material used to reproduce the granular flows. The walls are made of transparent material allowing observation to be taken throughout the entire length of the chute.

The material used is almost spherical ceramic beads. It was selected because of its spherical shape which is typically assumed in the majority of the granular flow theories. Ceramic beads are nominally 1.4 – 1.6 mm in diameter with a bulk density of 2.43 g cm^{-3} . The static friction angle, determined from a tilt test, was 24° .

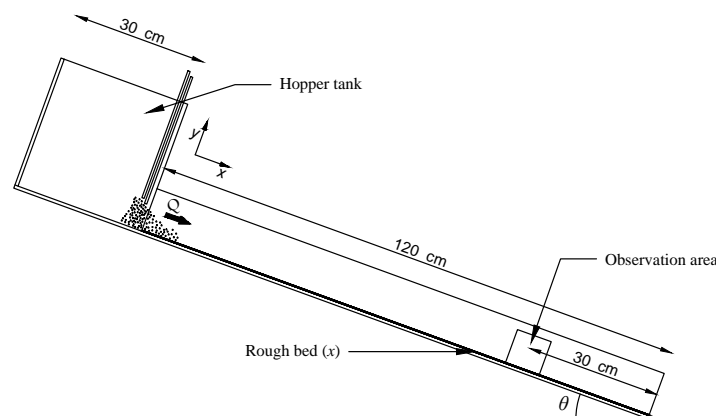


Figure 2. Sketch of the inclined chute geometry used to study dry granular flows (side view).

A high-speed camera (Phantom Miro 310) supplemented with two light sources was positioned 30 cm before the outlet. In this region the flows are more likely to reach an apparent steady regime. A steady state is needed as the analyses performed here are fully valid only if the flows are uniform in the direction parallel to the main plain of sliding. The uniformity was checked by visual inspection. We selected temporal regions where flow exhibited no detectable variations in the depth profile. Typical nominal flow depths are approximately 20 particle diameters. Video were recorded at a frame rate of 4000 fps with a camera resolution of 448×448 pixels. The frame rate was selected in order to minimize the gradient biasing in PIV and at the same time to avoid losing low-frequency fluctuations in PTV. However, further verifications and testing are

required to identify which temporal resolution is the most suitable for the image velocimetry analyses described here.

From the image information, the instantaneous velocities were computed by the PIV and PTV algorithms and the following granular flow field properties calculated: mean velocities, velocity fluctuations and granular temperature. Using PIV, Reynolds et al. [15] showed that granular temperature may be measured by statistical analysis. The standard deviation of the velocities can be used as a good indicator of the velocity fluctuations. Moreover, if the mean velocity of all particles is constant, the variance of the velocity may characterise the particle granular temperature. Notably, a patch size of the order of the particles should generate the most accurate values of granular temperature [15]. As the material is almost uniform in size, we deemed accurate to use a patch size that covers the entire pixel surface of a particle. Specifically, a patch 32×32 pixel patch was chosen to analyse the flows of ceramic beads. Similarly, for the PTV analysis, granular temperature is given by the variance of the fluctuation velocity calculated by subtracting the mean velocity from the velocities between two image frames.

4. Results

In this section our intention is to demonstrate the results that can be obtained from these types of dry granular flows. For clarity we present only one flow which was released down the inclined at an inclination of 32° . It serves well to represent the flow properties attainable by using PIV and PTV techniques. Furthermore, the results reported here correspond to measurements and ensemble-averages based on a sampling period of 0.5 s.

Distributions of the mean and velocity fluctuations for PIV and PTV are given in Fig. 3. In the figure the transverse (U) (normal to the plain of sliding) and streamwise (V) velocity components are shown separately. The mean velocities reach their maximum at the free-surface (approximately 28 mm) while decaying almost linearly to 0 at the base. A small dissimilitude arises at the free-surface of Fig. 3(b). This is explainable by the fact that PTV analysis discards the particles in the background resulting in slower velocities than PIV. Fluctuation

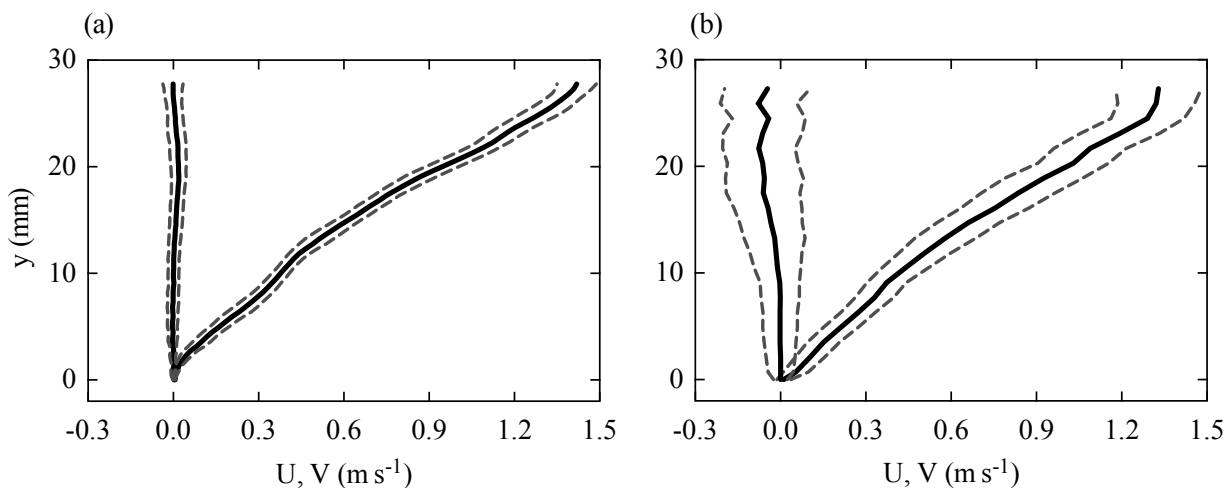


Figure 3. Ensemble-averaged raw velocity data over a sampling period of 0.5 s for (a) PIV and (b) PTV. U and V are the transverse and streamwise velocity components, respectively. Mean velocities (solid line) and fluctuation velocities (dashed line) plotted on both sides of the corresponding means.

velocities progressively increase towards the free-surface where the flow becomes more diluted. Interestingly, PTV gives rise to a much larger velocity fluctuation magnitude whereas PIV tends to damp the fluctuations in both directions. It seems that the average procedure followed by the PIV algorithm used here is unable to capture the random component of the velocities producing values that are very close to the mean profiles.

Granular temperature was extracted as the second-order statistics, i.e. the square of the velocity fluctuation; temperature was then taken as the non-stationary component of the local mean velocity. The fluctuation velocity gradient perpendicular to the flow direction (U) showed non-negligible effects. Thus, in the calculation we have taken both U and V components into account. For the PIV and PTV analyses, profiles of granular temperature are shown in Fig. 4. Temperature is zero at the flume bottom while reaching its maximum at the free-surface indicating that flow changes from a slowly deforming flow, mainly dominated by friction, to a more diluted collisional regime.

The most striking result concerns the magnitude of the granular temperature. When compared, values of temperature measured by the two methodologies differ almost by a factor of 9. PTV exhibits a granular temperature that is comparable to values found in the literature. For instance, Hanes and Walton [16] estimated granular temperature at the sidewall of up to 0.01. In saturated granular flows for material sliding over a dense layer of particles Armanini et al. [17] measured granular temperature of 0.05 at the surface. The PIV analysis damps the velocity fluctuation which in turn produces lower values of granular temperature. On the other hand, by measuring the movement of single particle, PTV appears to be the method of choice able to capture the collisional nature of the flow.

Differences can also be seen in the shape of the temperature profiles. While PIV produces different uncorrelated peaks with no clear trend (Fig. 4(a)), PTV shows a linear profile up to nearly 20 mm (Fig. 4(b)). Towards the free-surface, peaks arise but they are most probably related to the generation of granular temperature (e.g. the streaming mechanism [18]) and the removal of information due to the routine followed by the PTV algorithm. By removing the background information, fewer particles are found and if a longer sampling period is analysed, a smoother more linear profile might be generated in this part of the flow.

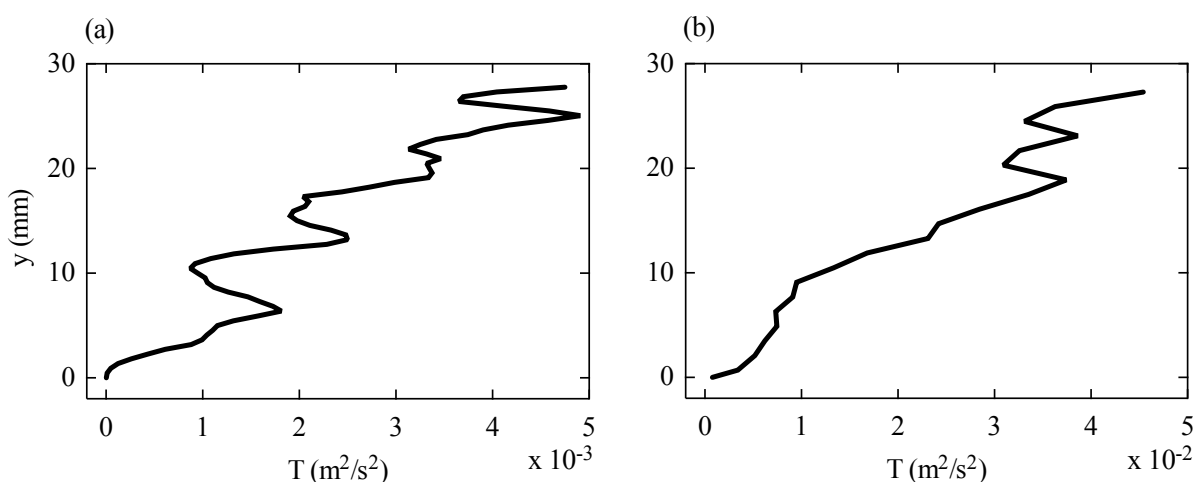


Figure 4. Granular temperature profiles. Comparison between experimental measurements obtained by (a) PIV and (b) PTV.

5. Concluding remarks

Experimental dry granular flows were reproduced in a small inclined chute geometry. Two non-invasive techniques, namely particle image velocimetry (PIV) and particle tracking velocimetry (PTV) were tested to verify their validity in estimating kinematic property of granular flows, such as velocity fluctuation and granular temperature. We found that PTV analysis is a more reliable method to extract such measurements. Indeed, by detecting the movement of individual particles, PTV is able to provide higher-accuracy measurements as shown by our results. Conversely, PIV yields averaged vectors resulting in underestimations of the random component of velocity and granular temperature. However, further investigations have to be done. We need to determine the adequate temporal resolution useful to minimize centroiding errors. If we are able to ascertain the accuracy of the PTV method, it might be possible, by comparison, to identify the appropriate configuration (e.g., in terms of spatial resolution of the interrogation region) to achieve the same results using PIV. Additionally, flows were recorded at the boundary conditions where the sidewalls are known to damp the generation of fluctuating motion. It would be interesting to study the motion at different cross-sections by using a non-intrusive technique that allows the visualization of the three-dimensional movement of particles. Ultimately, the measurements provided here may be processed to obtain results that could be useful for checking and refining mathematical models of granular flow.

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