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Digital imaging characterisation of a granular hopper flow

Introduction

Granular flows in hoppers have been studied extensively in the past years. One way of approaching the problem is to focus on theoretical investigation of the bulk flow properties at the macroscopic scale: global flow pattern, wall pressure and strains (Brown et al., 2000), optimal design of hopper geometry and outlet size (Gremaud et al., 2000, Shang Jing et al., 1998), etc. Besides, theories have emerged (Drescher et al., 1995) to link the macro-scale behaviour to the micro-scale phenomena acting on the particle level, like arching for example. This can be done by considering the granular matrix as a series of isolated structural members (referring to the so-called Structural Mechanics, SM) or as a continuum (Continuum Mechanics approach, CM). A different approach aims at modelling the inter-particle forces by statistical models (Coppersmith, 1997), or at describing the behaviour of individual particles as well as their interactions during collisions. This leads to computational models referred to as Discrete Elements Simulations (Mattutis et al., 2000) analogous to molecular simulations, which have proved their power but also their limits: due to their complexity, such models are constrained to deal only with simple systems containing a limited number of particles.

Resorting to experimental work is essential in order to compare such theories and models with reality at all levels. Tests on scale models have been carried out for a long time, where quantitative measurements of macroscopic parameters were possible. However, even if phenomena at the particle level were qualitatively observed or suspected, only few quantitative indications could be gained from them.

Recently, new investigation techniques have benefited from the rapid technological innovations. Among them, non-intrusive digital imaging and related image-processing techniques have increased tremendously the potential of traditional photography. Several authors have applied similar techniques for the experimental characterisation of granular flows in hoppers (Langston et al., 1997, Samadani et al., 1999) or in vibrated granular beds (Hsiau et al., 1998). They were initially limited to bulk observations, like deformations of the granular matrix within the silo, e.g. by tracking the shape of initially horizontal layers of coloured particles.

More recently a further step introduced a change of focus from the macroscopic to the microscopic scale, by tracking the movement of individual particles within the matrix. Such techniques, to the knowledge of the author, have always been restricted to the tracking of a small proportion of coloured tracer particles mixed in the dispersion (Hryciw et al., 1997, Losert et al., 1999) or to very large particles. The reason for this limitation is to be found in the characteristics of the particle tracking algorithms, whose robustness is a function of granular concentration and flow velocity: when the interframe particle displacement becomes of the order of magnitude of the particle interdistance (which is close to particle diameter for dense flows in hoppers), the available methods tend to fail quite rapidly, as well the simplest ones relying on minimum displacement matching as the more sophisticated ones, based on trajectory coherence.

In the present work, preliminary results are presented, where a novel particle-tracking method is applied to the characterisation of granular flow in a wedge-shaped plane hopper. Derived from an original pattern-based principle aimed at addressing the above shortcomings, the method (Capart et al., 2001) is able to resolve individual grain motions even for rapid flows of dense, intensively sheared dispersions. Full automation is achieved, allowing the derivation of accurate statistics from large sets of individual measurements, as well as the construction of complete sets of grain trajectories. This set of methods has recently been extended to the third dimension by resorting to stereoscopic imagery (Spinewine et al., 2000), allowing 3D measurements of free surface topography, 3D particle tracking and velocimetry, as well as accurate estimation of volumetric granular concentration.

The remainder of the paper is structured as follows: a first section illustrates the basic principles and potentials of the original Voronoï imaging methods, both for 2D and 3D applications. The experimental set-up is then described, along with the performed tests. Finally, detailed results are presented, including instantaneous and time-averaged 2D velocity fields, granular trajectories, velocity fluctuations, temporal correlations, as well as 3D measurements of the free surface topography. Interesting phenomena were observed, like granular arching near the outlet. Velocity histories along given trajectories clearly exhibit an harmonic evolution, indicating that the flow is characterized by pulsations, not only near the outlet but also within the matrix.

Principles and potentials of the Voronoï imaging techniques

Voronoï construction and properties

Consider a set of feature-points (e.g. particle centres) dispersed in a two-dimensional image plane or in a three-dimensional physical control volume. The Voronoï diagram is a geometrical construction that subdivides the space into a set of non-overlapping polytopes, or cells, surrounding each feature-point (see Figure 1). Each cell encompasses the region that lies closer to a given feature-point than to any other, e.g. with respect to Euclidean distance.

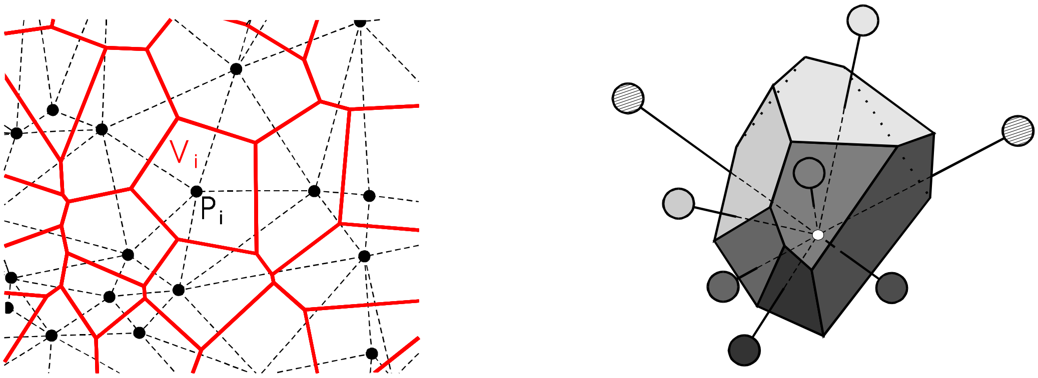


Figure 1: (a): Planar Voronoï diagram (——) and dual Delaunay tessellation (- - -).
(b): A 3D Voronoï cell around feature point ○; to each natural neighbour ● corresponds a particular facet of the Voronoï polyhedron, perpendicular to the segment ●—○.

The construction presents many useful properties that are discussed in a general context in Okabe et al. (1992). For imaging applications, three main properties are of particular interest:

Voronoï cells can be used as patterns encapsulating information about the local arrangement of feature-points. This property can be exploited to construct robust pattern classification and pattern matching methods (Ahuja, 1982) and is applied in the present work to the velocimetric matching of dense granular flows in hoppers.

Secondly, the Voronoï diagram is associated with desirable computational properties. Once constructed, which can be done very efficiently with methods such as Fortune's plane sweep algorithm (Fortune, 1987), the Voronoï construction can first be used to speed-up considerably multiple queries relative to neighbourhood relationships. The number of operations required for a nearest neighbour search, for example, becomes of the order of $n^{1/d}$, where n is the number of feature points and $d = 2$ or 3 is the number of dimensions, rather than of order n which would be obtained with a brute-force algorithm. In the present context, this property is exploited to speed-up the computationally intensive stereoscopic matching step (Spinewine et al., 2000) for 3D reconstruction of the flow free surface.

Thirdly, the Voronoï construction can be used to homogenise quantities relative to individual feature-points, and thus to extend discretely sampled properties to full spatial coverage. Combined with binocular stereo, this property has been used by Spinewine et al. (2000) to develop an imaging estimate for the volumetric granular concentration, which remains robust even in the dense limit. It will not be used in the present work, but it is noted here to highlight the multipurpose usefulness of the Voronoï construction when both granular velocities and concentrations are sought.

The particle tracking algorithm

Consider a sequence of images depicting the flow of an ensemble of grains. Rather than directly correlating windows of pixel values like for standard PIV techniques, the present method deals with grain images by first abstracting them into point-like particles. The granular ensemble is thus reduced to a set of feature-points corresponding to grain centroïds and dispersed in the image plane.

The positions of the particles are first located by filtering the images with a Mexican hat transform, finding the maxima of the convoluted images, then interpolating to subpixel accuracy (Figure 2a). Typically, the error on the position is less than a quarter of a pixel.

The second step aims at matching the position of one and the same particle across successive frames. Therefore, the method resorts to the Voronoï diagram. Qualitatively, the Voronoï match algorithm has the effect of pairing the neighbour feature-points that are characterised by similar Voronoï cells on successive images. The key advantage of the method is its robustness: even for dense, rapid and fluctuating flows, the shape of the Voronoï cells tends to remain relatively stable over a few frames. Once pairing is completed, velocities can be derived from the interframe displacements.

The process is illustrated on Figure 2 for the 2D case. However, the technique remains applicable when dealing with three-dimensional dispersions of grains, by comparing the shape of the Voronoï polyhedrons (Figure 1b). An additional procedure is however required, to derive the set of 3D positions of particle centres from their 2D projections on two simultaneous images. An original solution for this stereoscopic matching step, taking advantage of the properties of the Voronoï diagrams, has been presented by Spinewine et al. (2000).

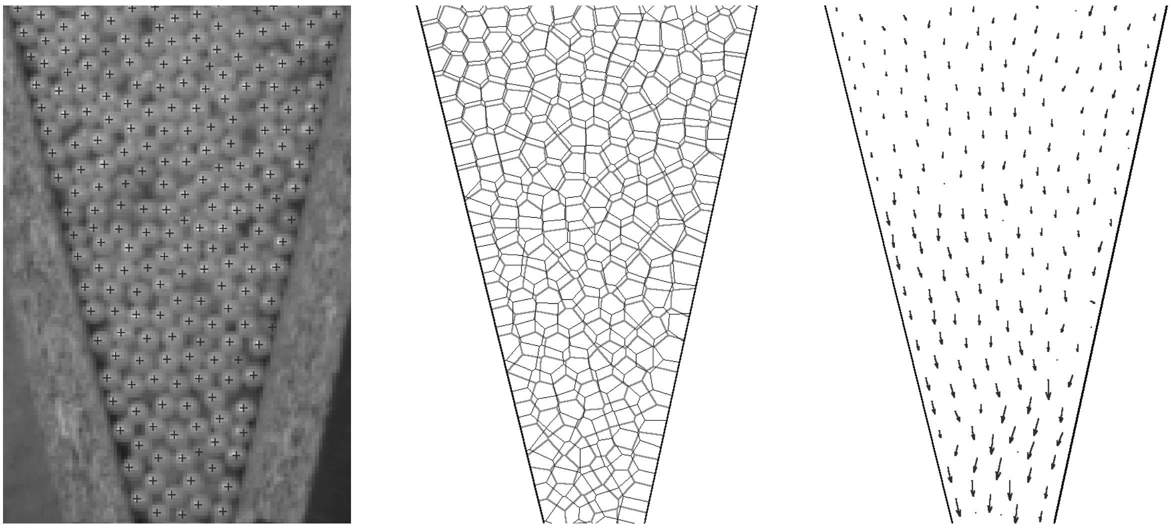


Figure 2: Steps of the image analysis procedure for the 2D case, based on a sequence of images acquired at a reduced frame rate (20 fps): (a) fragment of raw image with particle positions; (b) Voronoï construction and interframe matching; (c) interframe displacements.

<u>Experiments</u>

The experimental set-up is presented on Figure 3. The situation of reference is as follows: a granular phase, consisting of identical spherical particles, flows through a plane hopper with triangular wedge-shaped cross-section and longitudinal outlet. Visualisation of the flow is made possible by imaging either through the transparent sidewall, or from above. Individual grain motions are captured by two synchronised fast digital cameras, used in a monocular or stereoscopic arrangement, and images are processed using the Voronoï imaging algorithms described in the previous section.

The hopper has a height of 55 cm and a depth of 20 cm. The outlet having a width of 15 mm is equipped with a removable gate. The angle between transverse sidewalls is adjustable, but was kept at the constant value of 26° throughout all the tests presented here. Sidewalls and back wall are made of smooth wooden plates, whereas front wall is made of transparent Perspex for visualisation. The particles used are spherical artificial pearls with diameter D = 6.1 mm and density ρ = 1048 kg/m^3.

The flow is imaged by two synchronised Dalsa CCD cameras with a resolution of 256 × 256 pixels × 256 levels of grey, and a maximum acquisition rate of 200 frames per second, ensuring precise measurements even in the fast-flowing outlet region. Precise synchronisation is especially required when resorting to stereoscopic imaging, to avoid position-displacement ambiguities. Two halogen lamps of 500 W provided sufficient lightning.

With the gate closed, the hopper was filled with particles. Upon gate opening, image capture was initiated.

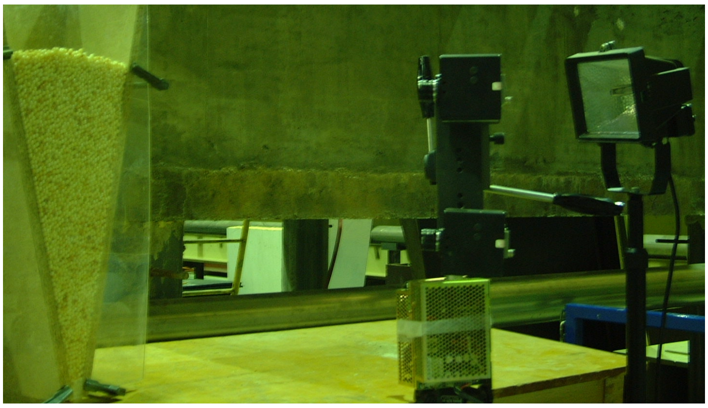


Figure 3: The experimental set-up.

A first series of tests was conducted by monocular imaging through the front-wall at the maximum acquisition rate (200 fps) and at a reduced rate (50 fps) when longer recording sequences were sought. Both cameras were mounted on a common holder, 25 cm apart from each other, and at a distance of 150 cm from the Perspex wall. Upper and lower cameras focused respectively on the upper and lower zone of the hopper, and the interface between the two images was precisely adjusted for perfect superposition. Pixel size is 0.89 mm.

A second series of tests aimed at characterising the evolution of the free surface position during the drainage process. The flow was imaged from above, by positioning the cameras, mounted on separate movable arms, in a stereoscopic arrangement. They were placed at a distance of 100 cm above the original free surface of the granular matrix. The relative angle between the two views was approximately 20°. Before performing the tests, a procedure for camera calibration was needed, using a small dihedron with regular black and white painted squares, in order to be able to associate the two simultaneous views of a given particle on both images with its real 3D position within a global system of coordinates.

Results

The sequences of images were analysed with the Voronoï imaging techniques described above. Some typical results are presented here in graphical form, considering a sequence of 1014 images acquired at a rate of 200 frames per second, for a total duration of 5.07 seconds. The first image of the sequence corresponds to gate opening. Coordinates are expressed in centimetres, with the origin placed at the centre of the outlet.

Tracking of the granular trajectories over a duration of 0.2 second (from 1.0 to 1.2 s after gate opening) is presented on Figure 4, which allows visualising the bulk movements of the granular matrix. Besides the expected progressive increase of the radial velocities towards the outlet, there are some indications of coherent structures (lanes), at a scale of a few particle diameters, especially in the radial direction.

Granular velocities were derived as an outcome of the particle-tracking technique. The mostly radial behaviour of the flow suggests to express velocities in a polar system of coordinates. This system has its origin at the point of convergence of the mean flow lines.

Mean and fluctuating velocities are presented on Figure 5. Mean velocities are averaged over the 1014 images, and fluctuating velocities are obtained by subtracting the mean velocity from the instantaneous velocity. Note that, as expected, the mean-velocity tangential components are zero everywhere. Fluctuations however, both in the radial and tangential directions, tend to increase towards the outlet. This indicates that the granular temperature, a measure of the strength of the particle velocity fluctuations, is much higher in the outlet region.

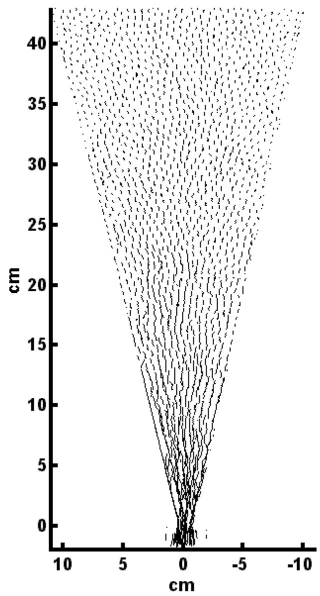


Figure 4: Granular trajectories tracked from 1.0 to 1.2 seconds after gate opening

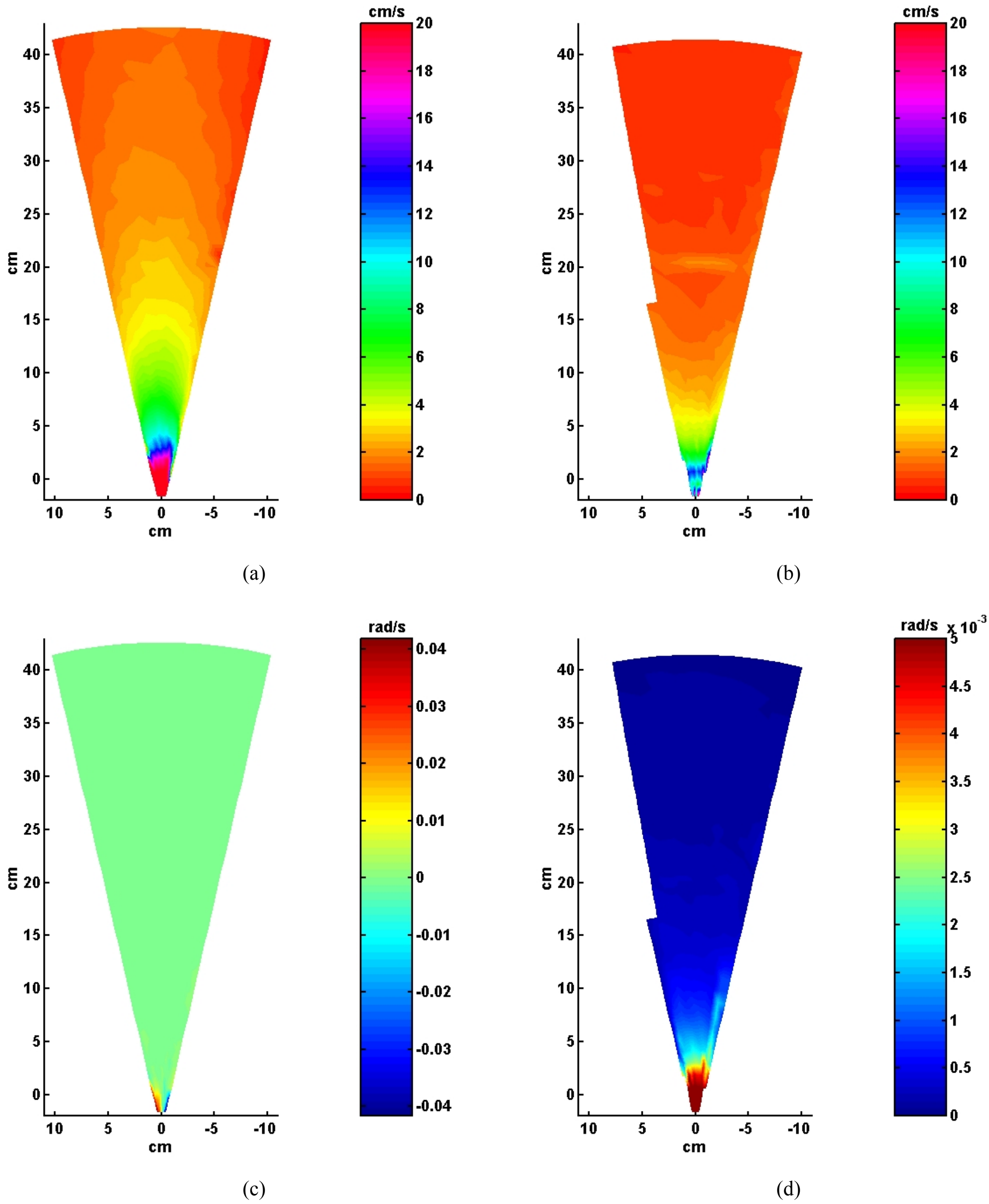


Figure 5: Mean and fluctuating velocities: (a) Mean-velocity radial component; (b) Fluctuating-velocity radial component; (c) Mean-velocity tangential component; (d) Fluctuating-velocity tangential component.

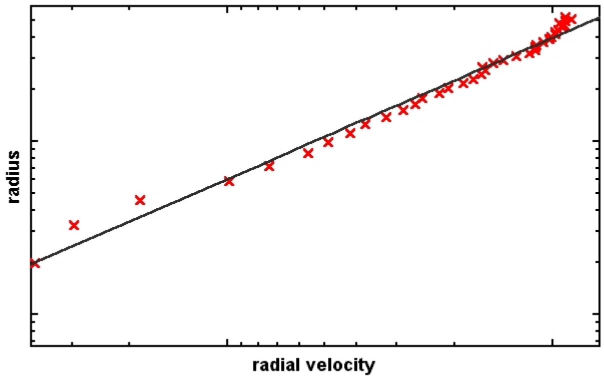
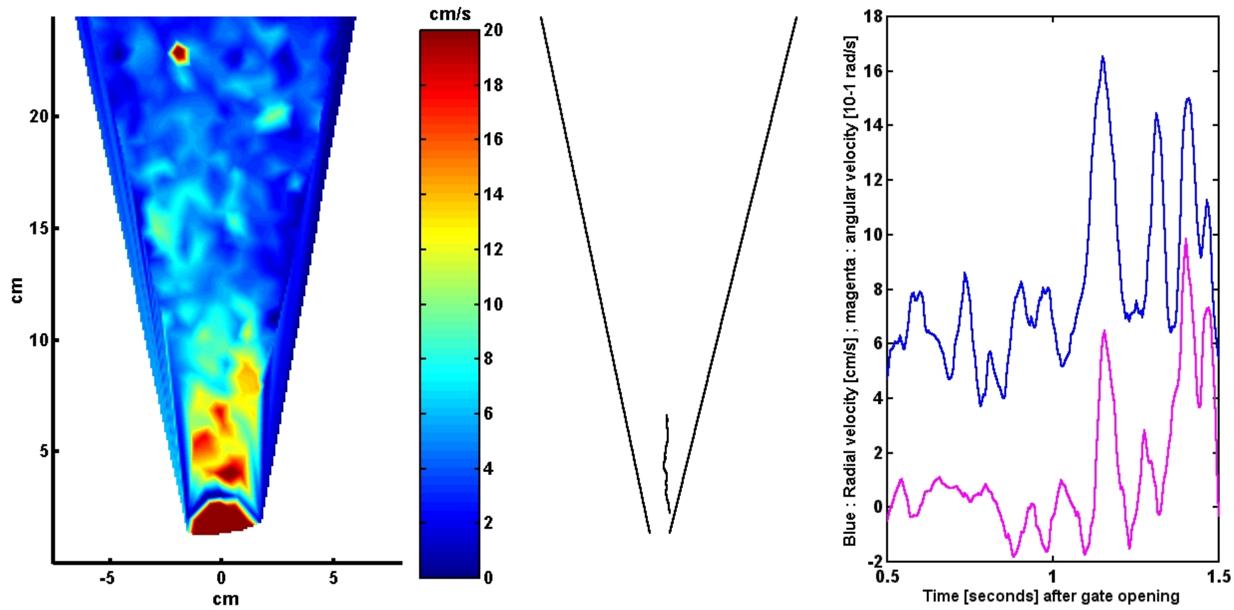


Figure 6: Mean radial velocity along the vertical; data points and best linear fit in a log-log plot.

Mean velocities were found to be independent of the volume of particles in the hopper, which confirms the idea that the hopper discharge is governed by local features in the vicinity of the outlet, and is not function of the degree of filling of the silo. Figure 6 indicates the evolution of the radial velocities along the vertical.

If we look at the particle level, interesting phenomena are observed. Figure 7(a) shows the instantaneous velocity field for a particular time. In contrast with the average velocity field, the flow discontinuities are now revealed. Above the outlet in particular, a granular arch is clearly visible: static contacts between neighbouring grains enables the transfer of stresses along the arch to the sidewalls, and the flow is temporarily stopped (see the blue concentric region near the outlet), until the pressure induced by the upper grains exceeds the resistance of the arch. This arching phenomena is well known, but the present method permits to investigate experimentally the dynamic process leading to the formation and subsequent rupture of arches.

What is new, the discontinuous and 'pulsated' behaviour of the flow is found to occur not only in the outlet region, but also in local zones within the granular matrix, quite distant from the outlet. The spots (in red and bright blue) on figure 7(a) are, to the knowledge of the author, the first experimental evidence of this phenomenon. This is confirmed by Figures 7(b) and (c): the velocity history is plotted for a given trajectory. Both radial and tangential profiles clearly have an harmonic component, characteristic of the flow pulsations. The period of the oscillations seems to indicate a typical time-scale of approximately 0.1-0.2 second for the flow pulsations.



(a) (b) (c)

Figure 7: (a) Instantaneous radial velocities; (b) and (c): A chosen trajectory, and its velocity history, (*Blue*: radial velocity , in cm/s; *Magenta*: Tangential velocity, in 10^{-1} rad/s).

Finally, three-dimensional tracking of the free-surface position (figure 8) was obtained through stereoscopic imaging. The noticeable depression in the free surface topography above the outlet gives some indication about the near-wall effects and non-uniformity of the flow profile.

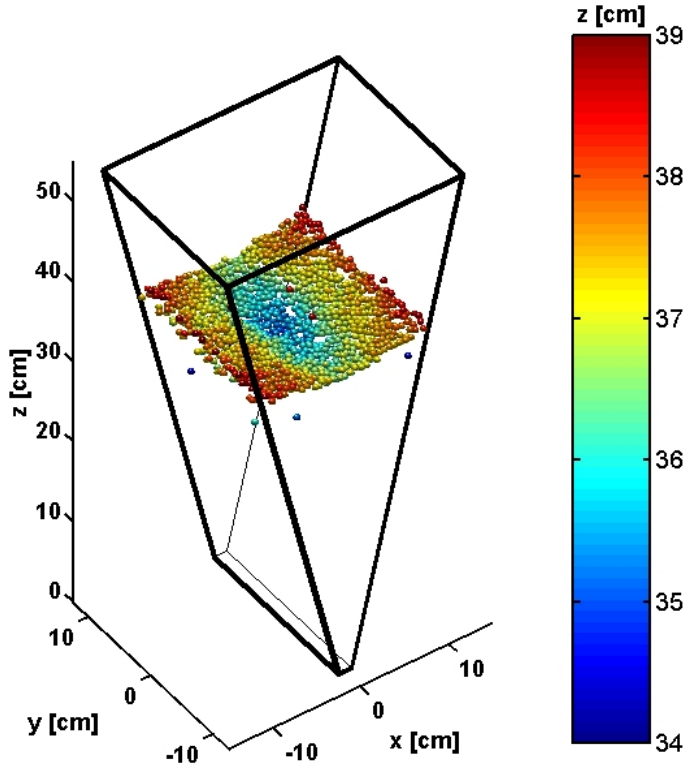


Figure 8: Example of reconstruction of the 3D free surface topography from binocular stereo.

Conclusions

The paper introduces the potentials of original imaging methods recently developed for the experimental characterisation of fluid-granular flows. Those novel techniques are able to provide a powerful tool in a wide variety of applications, and are at a stage of possible implementations in an industrial environment. In the present study those techniques have been applied to the characterisation of the flow in a plane hopper, resulting in an unprecedented degree of detail with respect to the flow behaviour at the particle level. The flow was observed both through a transparent sidewall and from above. Localisation and tracking of individual particles has been achieved, using both monocular and stereoscopic techniques for obtaining respectively 2D and 3D information. Presented results include granular velocities and trajectories, time-averaged velocity fields, estimation of the velocity fluctuations, and 3D topography of the flow free surface. Observation of instantaneous velocity fields and Lagrangian velocity histories have put interesting phenomena to the fore, showing clearly the discontinuous and discrete character of the flow. This has been observed predominantly near the outlet, with the formation and subsequent rupture of granular micro-arches, able to temporarily stop the flow by static contacts between the grains and transfer of stresses inside the granular matrix. What is new, this pulsated behaviour is found to occur not only near the outlet, but also in local zones in the granular matrix quite distant from the outlet, which is, to the knowledge of the author, the first experimental evidence of this phenomenon.

Acknowledgments

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