High Speed X-ray Imaging of Particulate Flows

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ABSTRACT Understanding complex flows of bulk solids requires three dimensional imaging. Here we will present a new diagnostic and research facility at The University of Sydney for high speed radiography and CT scanning of particulate flows. The facility allows us to image and trace particulate flows in three dimensions, looking inside both prototype and real machinery to allow rapid prototyping of bulk solids transport equipment. The X-ray equipment is complemented by state of the art 3D printing, such that scale models can be rapidly produced in a variety of configurations, and the resultant flow properties can be measured quantitatively. Here, three case studies will be presented.

1. INTRODUCTION

Various tools exist to study the dynamics of bulk solids during motion. Generally, these tools study the bulk behaviour of a large assembly of particles, where the response to an external load is characterised at a set of single points within or on the boundaries of the system, for example by load cells, pressure transducers or strain gauges. With the advent of new experimental techniques and particle-based numerical modelling of such systems, and the ability to peer inside simulations, it has become evident that full-field information is often required to adequately understand the dynamics of many particulate systems. This occurs primarily due to localisation phenomena, where it can no longer be assumed that the material behaves homogeneously [1].

Here we will describe a new facility in the School of Civil Engineering at The University of Sydney where full-field measurements can be made in real time inside operational equipment, using high speed X-ray radiography. X-ray radiography and tomography has been used successfully to reconstruct both continuum deformation fields and even to track individual particles [2]. Dynamically, X-ray radiography has been used to study granular jets, and the path of heavy intruder particles in stationary beds [3].

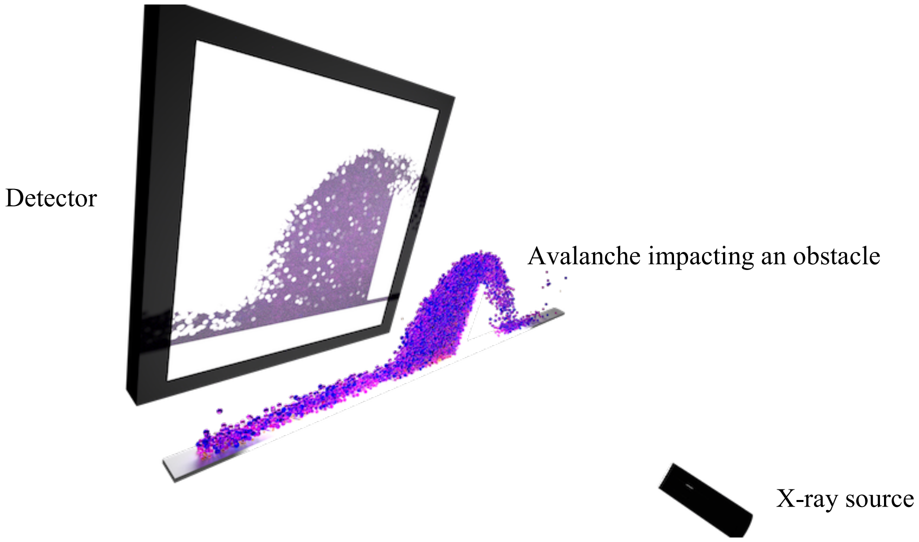

Figure 1 Schematic of X-ray Radiography of an Avalanche

2. THE DYNAMIX FACILITY

The DynamiX facility houses two 225 kV X-ray sources and two Varian PaxScan 2520DX detector panels. This combination allows for radiography, stereoscopic radiography, or partial tomography in real time (up to 30 frames per second per detector). The X-ray equipment is complimented by a rotation table, and a micron-resolution hexapod for precise positioning and motion during recording. This equipment is located within a 4m x 3m x 2m high lead-coated operational room, next to a control room. This allows for imaging of large apparatuses and experiments.

3. FULL FIELD MEASUREMENTS

Granular flows, such as those observed in bulk solids handling, pharmaceutical powder production, landslides, avalanches and bulk conveying, are all heterogeneous media which undergo significant internal deformation due to motion. Many techniques have been developed to quantify these deformations using full-field measurement, i.e. measurements covering a significant proportion of the medium, rather than at one or several discrete points. The use of digital cameras has enabled the tracking of surface deformations using Particle Image Velocimetry [4] and stereo-photogrammetry [5]. These techniques track displacements at the continuum scale, but are restricted to the surface of the medium. The use of transparent soil [6] allows for the tracking of tracers interior to the medium, but requires transparent containers and very little flexibility in the choice of material.

To quantify the behaviour of arbitrary materials, radiography has been used in a variety of configurations [7]. In a geotechnical context, X-ray radiography was used famously to validate the discovery of shear localisation [8]. Radiography is the technique of measuring the mean density along a path between the X-ray source and each pixel on the detector array. X-rays are attenuated by material in such a way that intensity, I, scales as

$$I = I_0 \exp(-\alpha\rho l), \tag{1}$$

where I_0 is a reference intensity, α is the X-ray attenuation coefficient (a material property, which varies with wavelength), ρ is the density and l is the path length. For time varying phenomena, we can decompose the density into a time averaged ($\bar{\rho}$) and fluctuating (ρ') part as

$$\rho = \bar{\rho} + \rho', \tag{2}$$

$$\bar{\rho} = \frac{1}{T}\int_{-T/2}^{T/2} \rho \, dt, \tag{3}$$

for some time window T. By similarly defining the time averaged intensity $\bar{I} = \frac{1}{T}\int_{-T/2}^{T/2} I \, dt,$ we can relate the intensity to the density fluctuations as

$$\frac{I}{\bar{I}} = \exp(-\alpha\rho' l), \tag{4}$$

or

$$\rho' = \frac{\ln({}^{I}/_{\bar{I}})}{-\alpha l}. \tag{5}$$

By measuring the intensity over time, and knowing the geometry of our problem (which defines l) and the materials (which define α), we can then calculate our density fluctuations directly. During deformation the internal structure of bulk solids change, and the resultant density fluctuations that occur can be readily observed using X-ray radiography and tomography.

4. CASE STUDY I: SINGLE BLADE MIXERS

To illustrate the power of dynamic X-ray investigation of bulk solids, we look at the case of a single rectangular blade rotating in a drum of glass beads. Observed from the surface, it is evident that material near the blade is being stirred, and that the motion of the grains extends far from the edges of the blade. To quantify what is happening below the surface, we show in Figure 2 the average of the absolute value of the density fluctuations,

$\overline{|\rho'|}$. Four cases are shown; for each case, the height of the blade is 50mm and the depth 3mm, while the blade width varies from 10 to 40 mm. The blades are 3D printed from PLA using an Ultimaker 2 FDM printer. This construction technique allows us to generate multiple geometries in a rapid manner, allowing for iterative design.

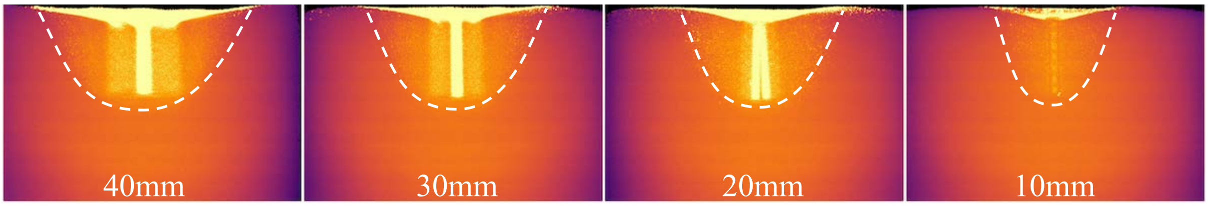

Figure 2 Zone of Mixing in Single Bladed Mixers

For each case, a clear zone of disturbance is delineated, where the material is not significantly perturbed beyond this point. The line marking this region is shown dashed in white. As the blade narrows, it is evident that the zone of effect also narrows. The shape of the disturbed zone indicates that the observations at the free surface are in general not representative of the behaviour below, and that near the bottom of the mixing blade, very little occurs beyond the width of the blade.

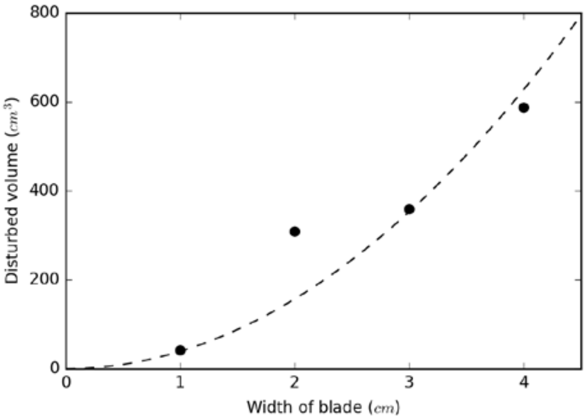

Figure 3 Volume Disturbed by Single Blade Mixer

By assuming that the observed behaviour is axisymmetric, and taking slice integrals around the centre of the image, the total volume that is disturbed can be calculated for each blade by assuming that the material is disturbed if $\overline{|\rho'|}$ passes the threshold indicated by the dashed lines in Figure 2. This volume is shown in Figure 3, where we observe that the increase in volume occurs quadratically with blade width, as expected. The dashed line in Figure 3 represents a quadratic best fit to this data, passing through the origin. From Figure 2, it is evident that the blade with width 20mm has a significant wobble, due to manufacturing errors, which has significantly increased its displaced volume.

5. CASE STUDY II: COMMERICAL GRINDERS

Radiography is limited in general by the 'equivalent path length', $\alpha\rho l$, which controls how much of the signal is attenuated by the medium. This is difficult to overcome in many high stress conditions, where the material of interest is normally shrouded in thick layers of steel. One common operation that occurs at high rate, and usually surrounded by metal is grinding. In Figure 4, we show an example of the intensity field observed in a coffee grinder during operation (Krups GVX2). Individual coffee beans can be resolved clearly whilst residing in the hopper before they are ground. While inside the conical grinder, the beans are obscured from view at this X-ray frequency, however increasing the frequency (or intensity) of the X-ray source can make this region accessible, whilst oversaturating the detector in the region of the hopper. By running multiple tests at different frequencies, a composite image can be constructed.

Figure 4 X-ray Radiograph of a Krups GVX2 Coffee Grinder During Operation

6. CASE STUDY III: RECIRCULATING FLOWS

Granular flows can be readily studied by the techniques outlined above. In this case, an additional technique is presented, wherein a perpetual avalanche is created when a conveyor belt carries material towards a rigid obstacle, such that the material forms a pile that continually flows towards the obstacle near the belt, and falls back at the free surface, at the dynamic angle of repose. In Figure 5, we show this effect in a set of polystyrene balls contained within a rectangular container, 300 mm x 150 mm, and 200 mm tall, placed directly above a rough-top conveyor belt, such that the container does not touch the belt, but the particles cannot escape. The conveyor is not pictured, and is just out of frame below the shown data. Similarly, the obstacle is not shown, and is out of frame to the right. The belt moves at 2 cm/s from left to right. Colours indicate the magnitude of the time averaged magnitude of the density fluctuations, $\overline{|\rho'|}$. The velocity field is calculated by running a Particle Image Velocimetry algorithm [9] directly on the density fluctuations. Further details are shown in this issue, please see [10].

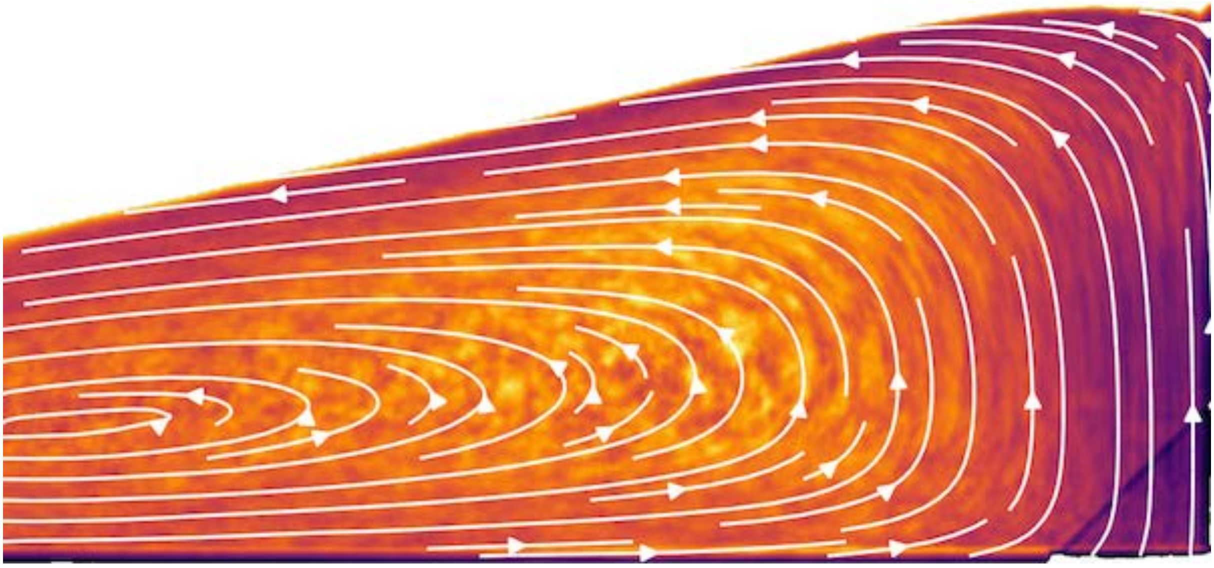

Figure 4 Streamlines of Flow in a Perpetual Avalanche

In this case, due to the steady nature of the flow, we can over a long period of time (in principle indefinitely) aggregate enough data to have arbitrarily smooth fields, allowing us to reconstruct not only the velocity fields and their fluctuating components, but also spatial gradients.

7. CONCLUSIONS

We have here shown that dynamic X-ray imaging of bulk solids provides a wealth of internal information about their kinematics. Firstly, by defining properly the density fluctuations, we showed that it is possible to capture internal motions. Secondly, an example was shown that illustrates the use of such methods in production equipment. Finally, a steady state example was provided, where arbitrarily smooth fields could be obtained. Together these findings show that dynamic X-ray imaging, such as that done at DynamiX, can be an instructive and quantitative tool for measuring the internal deformation of bulk solids.

8. ACKNOWLEDGEMENTS

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