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Cross-validation of 3D particle tracking velocimetry for the study of granular flows down rotating chutes

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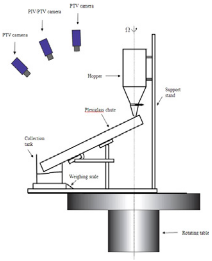
HIGHLIGHTS

- A 3D particle tracking technique is cross-validated against independent methods.
- Granular particles are flowing down a rotating chute.
- Surface particle velocities and particle bed height are obtained simultaneously.
- Discrete Element Model simulations are validated.

GRAPHICAL ABSTRACT



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ABSTRACT

Three-dimensional particle tracking velocimetry (3D-PTV) is a promising technique to study the behavior of granular flows. The aim of this paper is to cross-validate 3D-PTV against independent or more established techniques, such as particle image velocimetry (PIV), electronic ultrasonic sensor measurements for bed height, and the discrete element model (DEM), for the complicating circumstance in which granular particles are flowing down a rotating chute. 3D-PTV was used to gain access to Lagrangian trajectory data of surface particles in such flows, from which independent measurements of both the surface velocity and the bed height in the chute were derived. The 3D-PTV method was based on imaging and tracking colored tracer particles that were introduced in the granular material, which are viewed from three directions. The three cameras collected consecutive frames a known time interval apart and the PTV algorithm for locating and tracking particles was used to determine particle trajectories and velocities. We found that the 3D-PTV results are in good agreement with PIV results with regard to the streamwise and spanwise surface velocity of particles in the rotating chute. The particle bed height obtained from 3D-PTV was also found to be in good agreement with data from an ultrasonic bed-height sensor. The experimental findings from PTV for the non-rotating case were used to tune the friction coefficient in our DEM simulations. The simulation method was validated by the good agreement between experimental findings and simulations at all rotation rates studied.

1. Introduction

Experimental studies of granular flows are difficult to perform due to the opaque nature of such materials. Nevertheless, insight has been generated through use of magnetic resonance imaging

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(Kawaguchi, 2010; Hill et al., 1997), digital imaging (Guler et al., 1999; Capart et al., 2002; Bonamy et al., 2002), particle image velocimetry (PIV) applied to 2D granular flows (Bokkers et al., 2004; Laverman et al., 2008; Zeilstra et al., 2008) and particle tracking velocimetry (PTV) (Chou and Lee, 2009; Yang and Hsiau, 2006; Liao and Hsiau, 2009; Jasti and Higgs, 2008; Veje et al., 1999; Jain et al., 2002). In the past a large amount of experimental work has been performed on granular flows through inclined channels, see e.g. Augenstein and Hogg (1978), Brennen et al. (1983), Campbell and Brennen (1985), Johnson et al. (1990), Holyoake (2011), Ottino and Khakhar (2000), Khakhar et al. (1999), Savage and Lun (1988), Pouliquen and Renaut (1996), Silbert (2001), Ancey (2001), Barbolini et al. (2005), and Baran et al. (2006).

Most of the above experimental studies are focused on fixed chutes. However, in some applications such as in the operation of blast furnaces in the metallurgical industry, the chutes are rotating. The chutes may even rotate at such high rates that Coriolis and centrifugal forces start to play a significant role, leading to flows and particle distributions deviating considerably from those in non-rotating chutes. Reliable measurements are essential to obtain a detailed understanding of such granular flows in rotating chutes. Three-dimensional particle tracking velocimetry is a promising technique, because it can potentially deliver with high spatial and temporal resolution the particle bed height and 3D velocity profile. The bed height can also be obtained by using ultrasonic height sensors, but the resolution of such sensors is lower, while the experimental procedure is much more labour intensive or expensive (a new experiment needs to be performed for each measurement position, or a large number of sensors needs to be used). The velocity profile can also be obtained by using particle image velocimetry, but usually only in two dimensions.

In this paper we will focus on cross-validation of the 3D-PTV technique, for applications of granular flows in chutes rotating at significant rotation rates. Note that by ‘cross-validation’ we do not mean the statistical technique of estimating the performance of a predictive model. Rather we mean the practice of confirming experimental findings from one technique by repeating the experiments using independent other techniques.

The 3D-PTV technique is a flexible non intrusive image analysis technique for flow measurements. It was first introduced by Chang et al. (1984) and was further developed by Racca and Dewey (1988). This technique has a history of development for more than a decade at the Institute of Geodesy and Photogrammetry (IGP) and at the Institute for Hydrodynamics and Water Resources Management (IHW) both at the Swiss Federal Institute (ETH) Zurich (Maas, 1991; Malik et al., 1993; Maas, 1995; Maas et al., 2002). In a previous paper we used the PIV technique to measure the surface particle velocity and an electronic ultrasonic sensor to measure the bed height in a rotating chute (Shirsath, 2013). In contrast to PIV, PTV is able to track individual particles in the flow and provides both the Lagrangian and the Eulerian representation of the flow field (Willneff, 2002). To be able to track individual particles instead of providing a global (Eulerian) flow field, PTV requires three cameras to detect the position of the particle in the three dimensional domain. The cameras capture images of the flow from different angles. From these images, it is possible to determine the position of an individual particle and compute its trajectory. In PTV it is necessary to make a clear distinction between the particles which are actually tracked and all other particles. Therefore, tracer particles are introduced in the granular flow. Obviously, the concentration of tracer particles may not be too high, otherwise it becomes difficult to distinguish individual tracer particles, and the method becomes less accurate (Prasad, 2000).

We perform our analysis on a system of monodisperse 3 mm spherical glass particles, flowing down a rectangular plexiglass chute inclined at 30° and rotating at various rotation rates. The mass rate used is 3.2 kg/s. In our previous paper (Shirsath, 2014), we published a discrete element method (DEM) validation using experimental results of surface velocity obtained by PIV and bed height from an ultrasonic sensor, using a lower mass rate of 1.6 kg/s.

Besides the primary goal of assessing the ability of the 3D-PTV technique to provide surface information such as surface velocity of particle and particle bed height, as a secondary goal we will use the results of this work to further validate our DEM simulations (Shirsath, 2014). Recently, a number of papers focusing on DEM simulations of granular flows in the blast furnace charging process have appeared (Mio et al., 2008, 2009, 2010, 2012; Ho et al., 2009; Zhou et al., 2011; Yu and Saxén, 2010, 2011; Yu, 2013; Yu and Saxén, 2013; Wu et al., 2013; Bhattacharya and McCarthy, 2014; Akashi et al., 2008; Zhang et al., 2014). Given its popularity, it is crucial that the DEM method is properly validated against precise experiments, including cases in which the process equipment is rotating.

The paper is organized as follows. In Section 2 we present the experimental set-up and its procedure. In Section 3, the measurement techniques using PIV, PTV and the electronic ultrasonic sensor are presented. In Section 4, the numerical model is explained briefly. In Section 5, we present our post-processing methods to obtain data from the numerical model which are similar in spirit to the experimental measurements. In Section 6, we present the experimental results, including a repeatability study of the PTV experiments for bed height and streamwise surface particle velocity. We compare the bed height from PTV with independent measurements using an ultrasonic height sensor, and compare the surface velocity from PTV with independent measurements using PIV. In Section 7, we validate our DEM simulations by comparing with the experimental findings of bed height, streamwise velocity and spanwise velocity for different rotation rates of the chute. We end with our conclusions.

2. Experimental setup and procedure

In this section we describe the hardware of the 3D-PTV system, consisting of the rotating table facility, camera system and illumination facility.

2.1. Experimental setup

The experimental equipment includes a plexiglass chute, a hopper for storage of particles, and a collection tank. A dynamic weighing scale was used to measure the mass rate, and PTV, PIV and an electronic ultrasonic sensor were used to measure surface information such as particle bed height and the surface particle velocity field.

The granular particles were deposited onto a rectangular plexiglas chute straight from the hopper mouth. The bottom wall of the chute was white to achieve a better contrast in the photographs for detecting tracer particles. The whole chute was fixed at its bottom to a strong metal plate of 1 cm thickness to minimize vibrations caused by the particles poured from the hopper mouth to the chute surface at the inlet. The inclination angle of the chute was adjustable between 0 and 70° with respect to the horizontal. At the end of the chute, a collection tank received the granular particles. This tank was placed on a dynamic weighing scale to measure the exit mass flow rate.

The whole setup was mounted on a rotating table, so that the flow was measured in the non-inertial frame of reference. All the hardware, constituting the focusing system and the measurement system, was located on the top of the table or surface below it as