A novel magnetic particle tracking technique for dense granular flow

INTRODUCTION

In gas-particle fluid dynamics experimentation without disturbing the flow has often been difficult and numerous techniques have been developed. Among these particle tracking techniques; Positron Emission Particle Tracking (PEPT), (computer aided) Radioactive Particle Tracking (CARPT) and Particle Tracking Velocimetry (PTV) are some of the most well-known. However most of these techniques require safety precautions and are quite expensive. A novel technique has been introduced which is inherently save and much cheaper, Magnetic Particle Tracking (MPT). MPT has first been introduced as a technique for the medical industry to study the motility tract and as a possible tool for use in targeted drug delivery. More recently first studies report the use of MPT as a particle tracking technique in granular flow; rotating drums, spouted- and fluidized beds. One of the main advantages is the possibility to study the effect of rotation of particles in these systems which helps to close the force balance of the particles. This advantage is unique for particle tracking techniques, even though attempts have been made with PEPT.

MPT relies on the strength of the magnetic field originating from a magnetic marker, which acts as a magnetic dipole. This magnetic field is picked up by a set of 72 sensors operating at a 1000 Hz. Back calculation of the position and orientation of the marker is possible by an appropriate algorithm:

$$\overline{H}(\bar{e}_p, \bar{r}_{ps}) = \frac{1}{4\pi}\left[-\frac{\mu_m \bar{e}_p}{\left|\bar{r}_{ps}\right|^3} + \frac{3\mu_m(\bar{e}_p \cdot \bar{r}_{ps})\bar{r}_{ps}}{\left|\bar{r}_{ps}\right|^5}\right] \tag{1.1}$$

By minimization of the so called quality function, which minimizes the difference of the sensor output with the theoretical findings of equation 1, the most probable position and orientation are calculated:

$$Q = \sum_{i=1}^{n} \frac{(H_{\exp} - H_t)^2}{(\Delta H_{\exp})^2} \tag{1.2}$$

Recent advance in the hardware and the software allow for quite accurate results. These optimizations take into account the possible constraints of the positions and orientations using a set of constraints, three for position and 3 for orientation and 1 for the length of the unit vector:

$$-0.15 \le x \le 0.15$$
$$-0.30 \le x \le 0.30$$
$$0.02 \le y \le 0.07$$
$$-1 \le e_{p,x} \le 1$$
$$-1 \le e_{p,y} \le 1$$
$$-1 \le e_{p,z} \le 1$$
$$\left|\bar{e}_p\right| = 1$$

These constraints are the basis for a stable and accurate optimization, previously the Levenberg-Marquardt (LM) algorithm was used which was unable to determine the position of smaller markers. Using the constraints and an appropriate algorithm that can handle constraints, sequential quadratic programming (SQP), smaller markers can be used and accuracy and precision is increased. The increase in performance is best exemplified by a simple and well defined motion. A pendulum swing is proposed and shown in figure 1, which follows a dampened harmonic oscillator:

$$x = e^{-\gamma t} \, a\cos(\omega t - \alpha) \tag{1.3}$$

It can clearly be seen that the LM algorithm seems to loose sight of the marker near the outermost position in the swing. Especially in the beginning of the experiment the position of the marker is estimated at the center rather than at the edge. After a short time the position is estimated at the correct position which is done by an automated re-initialization of the algorithm, which is a multistart method. The difference with the SQP method is just the added constraints and is no longer able to move outside the domain and is thus less influence by the small gradients. The SQP method is thus able to find the correct position of the marker.

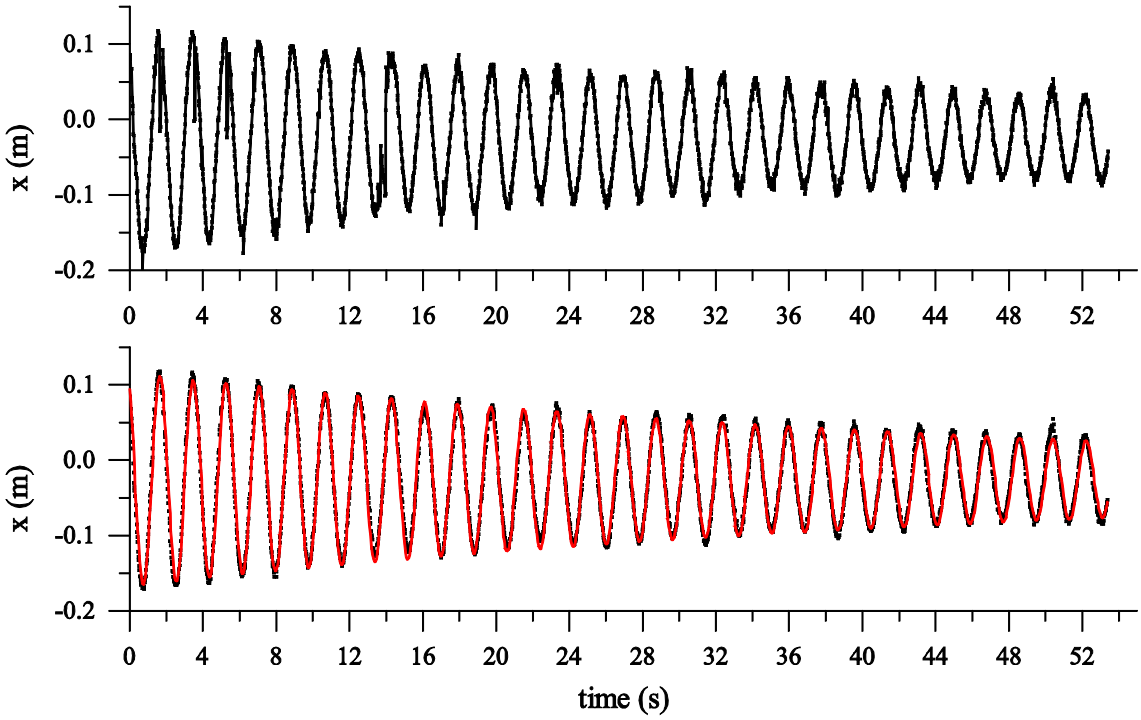


Figure 1: Results of the pendulum swing with a marker with a magnetic moment of 0.003 Am^2, using LM analysis; top, and SQP analysis bottom, fitted with a dampened harmonic oscillator, equation 3, with R2=98.5 %.

As a true performance test the MPT was compared to PIV-DIA, a well-established measurement technique. A magnetic marker was fluidized in a pseudo 2D fluidized bed for 1 hour for the MPT and a mere 25 seconds at 200 Hz for the PIV-DIA. This results in an average of 5000 data points per interrogation area for PIV-DIA and 230 for MPT. The magnetic marker was a 3mm neodymium magnet with a magnetic moment of μ=0.0125 Am^2 coated with a polymer shell to 4.5 mm with a composite density of 2100 kg/m^3. The bed material was glass beads of 2.8-3.2 mm with a density of 2600 kg/m^3. The minimum fluidization velocity of the bed material is 1.7 m/s, determined with standard pressure drop analysis. The estimated minimum fluidization velocity of the magnetic marker is 1.82 m/s using the Beetstra correlation. To avoid segregation of the magnetic marker, background velocities u_{bg} of 2.5 and 3.5 m/s have been used.

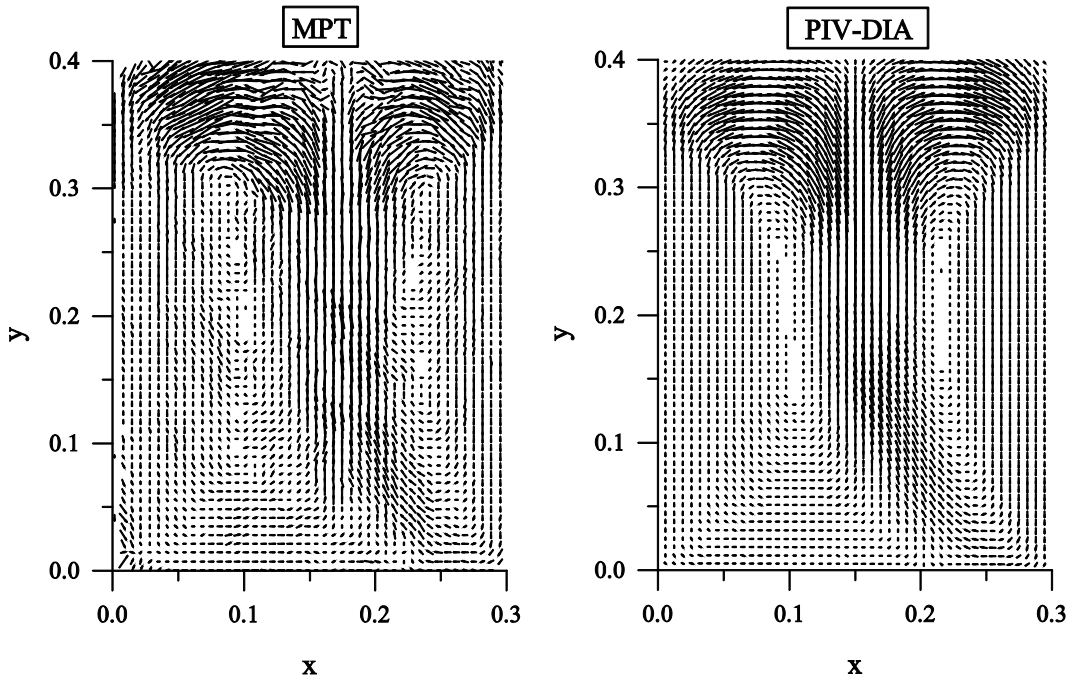


Figure 2: Vectorplots of the particle velocity in the pseudo 2D fluidized bed, left; PIV-DIA, right; MPT, u_{bg}=2.5 m/s.

The time-averaged velocity fields of the fluidized beds obtained with the two techniques are shown in figure 2, fluidized with a background velocity of 2.5 m/s. High particle velocities can be found in the center of the bed, where the bubbles predominately rise. The particle velocities in the annulus are very low. A larger part of the flow seems to come from the right side of the bed, which can be attributed to (minor) maldistribution of the distributor plate. Still the typical circulation patterns for bubbling fluidization are clearly obtained. Overall the results of the MPT and PIV-DIA compare very well.

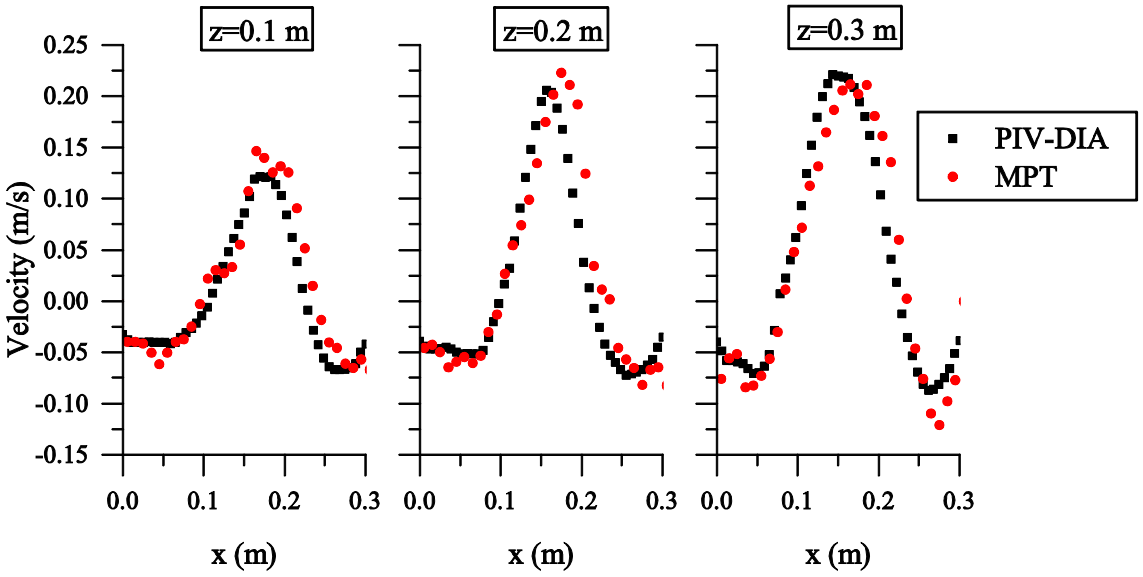


Figure 3: Vectorplots of the particle velocity in the pseudo 2D fluidized bed, left; PIV-DIA, right; MPT, u_{bg}=2.5 m/s.

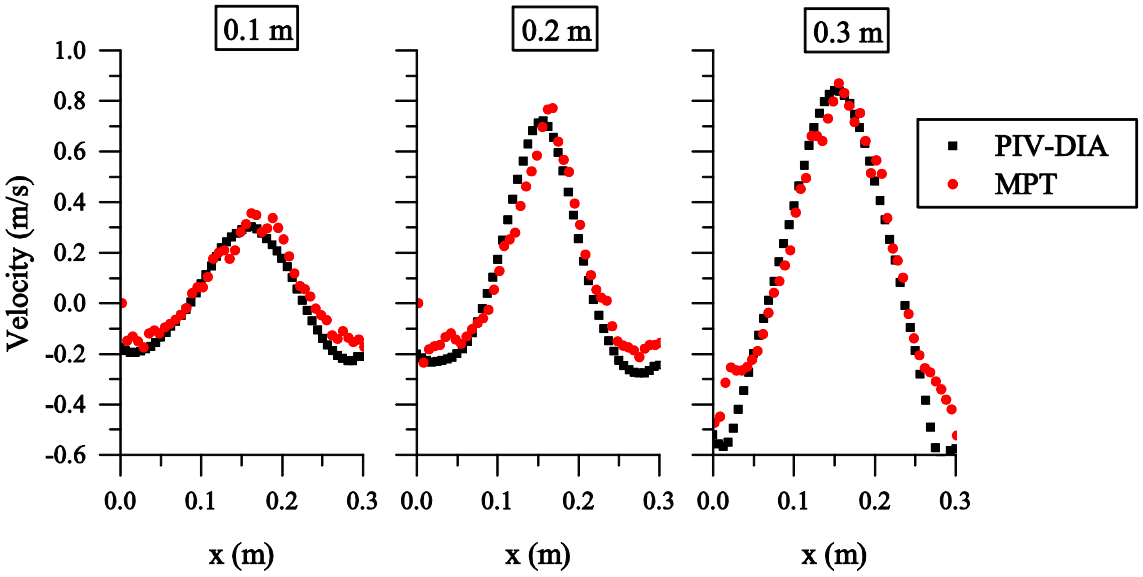


Figure 4: Comparison of averaged particle velocity for PIV and MPT in vertical direction at three cross-sections of the bed. u_{bg}=3.5 $ m/s

Figure 3 and 4 show the vertical velocity components obtained from the two techniques with horizontal slices at three different heights in the pseudo 2D bed, starting from 10 cm above the distributor plate and increasing by 10 cm increments. These results reveal a very good agreement between the two techniques. However at low velocities some deviations for the MPT can be seen which can be attributed to the larger error margins, which can be expected from the magnetic marker position determination and the lower number of data points per interrogation area. the velocities at the center of the bed are upwards and high resulting from large bubbles passing through the center. The velocities in the annulus are downwards and much smaller which is

attributed to dense particle packets moving downwards. Especially in the center of the bed the comparison of the two techniques is very good. The maldistribution of the flow is less predominant in these parts of the bed because the bubbles and particles are drawn to the center of the bed and at sufficient height from the distributor plate the circulation pattern is almost symmetrical.

CONCLUSIONS

This study shows MPT to be a very promising particle tracking technique that can be used to study particle velocity. Accuracy and precision of the technique have been improved by using physical constraints to the orientation and the physical domain of the setup. Comparison between a well-established technique, PIV-DIA and the novel Magnetic Particle Tracking technique show a good comparison.

This technique also allows for study of the orientation of the markers and the rotational velocity of the markers, this has not been done in this study but will be done in the future. Especially the rotational velocity will help close the force balance for the particle behavior and gives extra insight when compared to discrete particle simulation studies. The orientation of the marker makes it possible to study non-spherical particles. All in all the use of the Magnetic Particle Tracking technique is a cost effective, save and promising alternative to conventional particle tracking techniques.

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