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Intermittent particle motion on the wall of a model silo during discharge

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ABSTRACT

A novel approach is presented for investigating motion of particles on the wall of a model silo. Measurements are presented for a 1.7 m tall and 0.65 m diameter silo with transparent Lexan walls. The motion of PET particles was recorded visually during discharge using a digital CCD camera and analysed using image processing techniques to give quantitative velocity information. The particles are seen to move with intermittent motion. The particles remained stationary against the silo wall for around 0.1 s and then slip against the wall for a further slightly longer period of time. This pattern of motion is repeated in a regular manner. It was also observed that the particles moved in phase over the entire height of the fill, above the transition level.

1 INTRODUCTION

Wall vibrations in full-scale industrial silos have been investigated recently by a number of authors [1-6]. Two different dynamic phenomena have been observed: silo quaking and silo honking. The first mode, silo quaking, is at a low frequency of a few Hertz, while the second mode, silo honking, is at a much higher frequency of several hundred Hertz. Silo honking has been observed in a range of thin walled metallic silos where the high frequency oscillation of the wall is accompanied by an associated acoustic emission, or honk, with an intensity which is often greater than 100 dB. The excitation mechanism is not fully understood for either quaking or honking, however, it has been suggested that silo honking may be generated by a slip-stick motion of the particulate fill against the silo walls. Indeed, it has been shown that PET particles which induce honking in thin walled metal silos exhibit a slip-stick behaviour against a metal wall sample while other pellets which have not been reported to produce honking do not undergo slip-stick motion under similar circumstances [7]. Further, numerical simulations of particle motion in a small-scale silo using the discrete element modelling (DEM) [8] have also shown intermittent particle motion at the wall. In this paper experimental evidence of intermittent motion on the wall of a model silo is presented for PET particles. The motion of the particles against the wall were recorded digitally and analysed to provide quantitative information on particle motion.

2 EXPERIMENTAL PROCEDURE

The experimental system is shown in Fig. 1. The model silo was 1700 mm high with a diameter of 650 mm and was constructed from 1 mm thick transparent Lexan polycarbonate. The silo had a flat bottom and discharged through a central hole with diameter 65 mm. The silo was filled to a height of approximately 1300 mm from a holding box above the silo, which was filled from the silo discharge by an auger. Both the auger and the refill from the holding box were stopped during the period while the measurements were taken. Images of the particles moving against the model silo wall were obtained using a Sony DCR-TRV340E digital camera. These images were analysed to obtain quantitative information about the velocity of the particles at the wall.

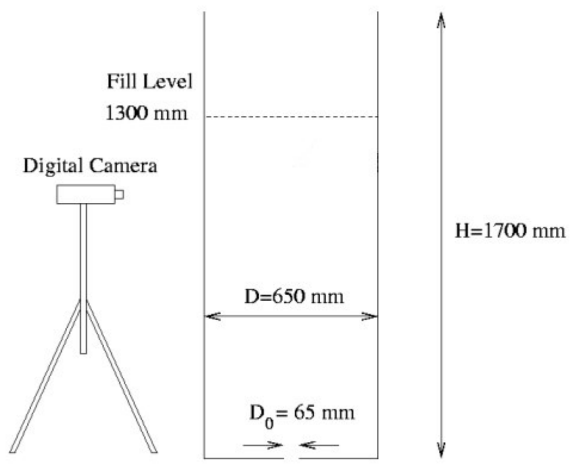

Figure 1: The experimental set-up used to acquire digital images of the PET particles at the silo wall during discharge.

3 ANALYSIS OF IMAGES

The images of the particle motion were analysed to obtain quantitative velocity information about motion of the granular particles. This was done by dividing each image into small regions. The velocity in each region was then obtained using a cross-correlation routine between successive images. Full details of the technique can be found in [9].

4 RESULTS

Six typical consecutive digital images of the PET particles against the silo wall are shown in Fig. 2. The time separation is $\Delta t = 0.12$ s.

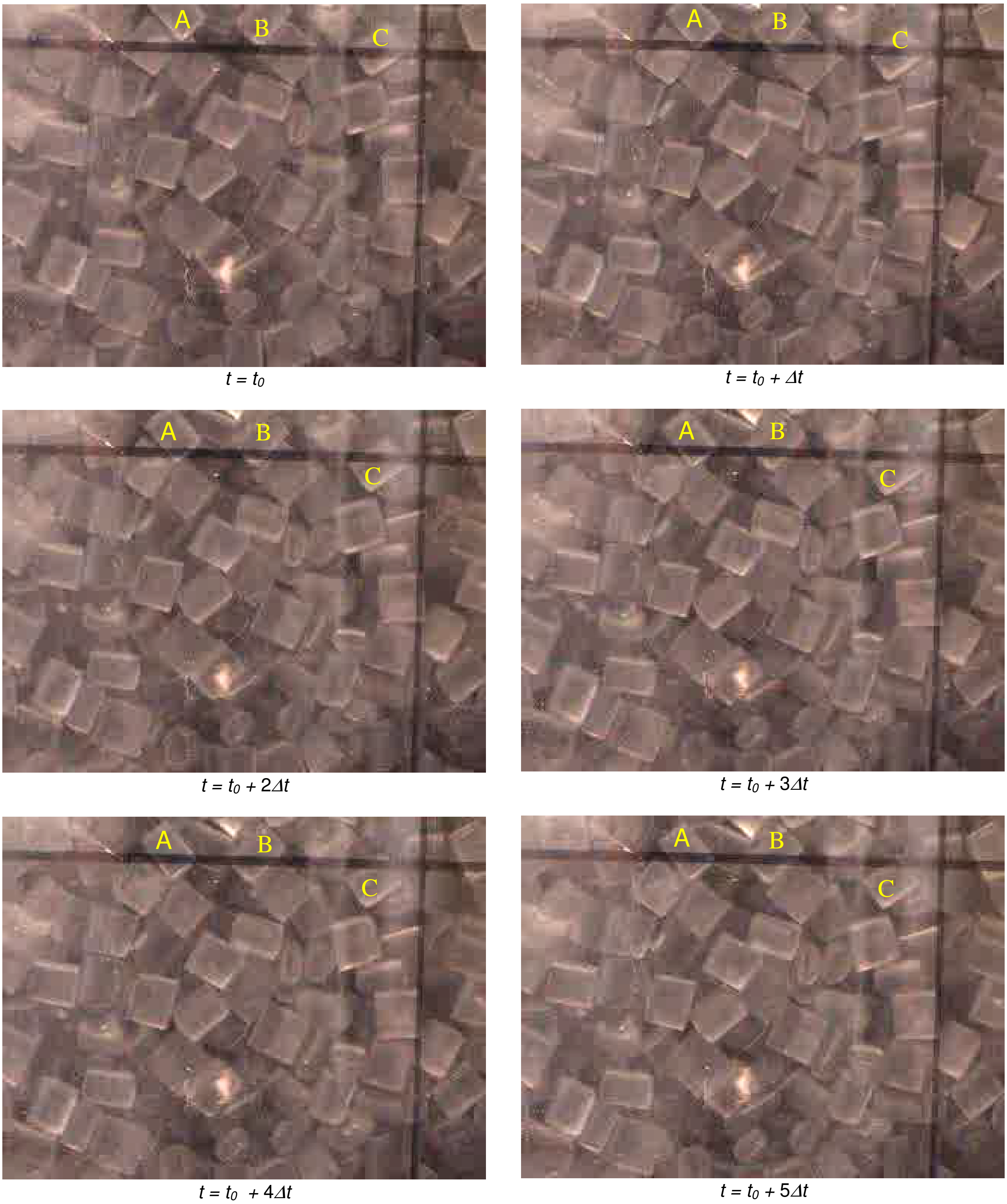

Figure 2: The position of the PET particles in the model silo at successive times. The motion of the particles is best observed in relation to the solid horizontal line which was marked on the outside of the silo wall.

The dimensions of the rectangular region shown in Fig. 2 are approximately 37 mm by 28 mm. The black horizontal line in the images is drawn on the outside wall of the silo and is 1000 mm above the base of the silo which is well above the transition region (between 600 and 700 mm above the base) and significantly below the top of the fill level which was approximately 1300 mm above the base. The motion of the particles can be observed between the six images which are shown. This is best done by comparing particles which are adjacent to, or bisected by, the 1000 mm line on the silo wall. For example, consider particles A, B and C which are marked on the initial picture at $t = t_0$. Both particles A and B are initially sitting just above the horizontal line. During the first four time intervals, Δt, these two particles (A and B) move down steadily. At $t = t_0 + 4\Delta t$ both of the particles are approximately a third of the way past the line. Similarly, it can also be seen that particle C, and any other particle which can be identified, has also moved down the wall by roughly the same distance. Comparing the particles between $t = t_0 + 4\Delta t$ and $t_0 + 5\Delta t$, the motion of the particles can be seen to have stopped. It is also possible to estimate the particle velocity between $t = t_0$ and $t_0 + 4\Delta t$, the particles have moved two to three mm in about half a second.

Clearly direct observation of the particle images can give some qualitative information about the motion of the particles, in particular it is clear that the particles are moving in an irregular manner: sometimes stationary and at other times slipping against the silo wall. However, in order to obtain a more quantitative description of the motion it is necessary to analyze the images further. This was done using the technique outlined in Section 3 [9]. A time series of velocity vector maps was obtained over the region of the silo wall which was imaged. Given the small dimensions of the region it can be assumed to be approximately flat with minimal distortion of the results due to the curved nature of the silo wall. At any time, the value of the velocity over the region considered in Fig. 2 was found to be constant. For this reason the average velocity in each special region was considered at each time interval.

The value of the spatially averaged velocity was, however, found to vary with time as was expected from the visual observations of the particle motion. Figure 3 shows the measured particle velocity as a function of time over a time period of approximately 15 s. There are two distinct modes to the motion: a period where the particles are sliding on the silo wall with a velocity between about 4 ms^{-1} and 6 ms^{-1}; and a shorter period where the particles are stationary against the wall. It is important to realize that the velocities shown in Fig. 3 represent the temporal average of the velocity of the PET particles over the time between images. This may partially account for the range in the measured velocities of the moving particles.

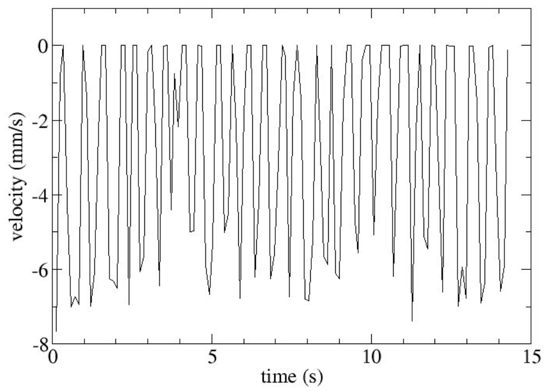

Figure 3: The velocity of the PET particle against the silo wall as a function of time.

Only a small region of the silo wall is shown in Fig. 2, however, other measurements taken over considerably larger areas suggest that the particle motion is in phase over the whole of the silo (from the transition level to the top of the fill).

It is also evident from fig. 3 that the intermittent motion of the particles is relatively regular. To further investigate this the velocity time-series in Fig. 3 was Fourier transformed and the spectrum is shown in Fig. 4.

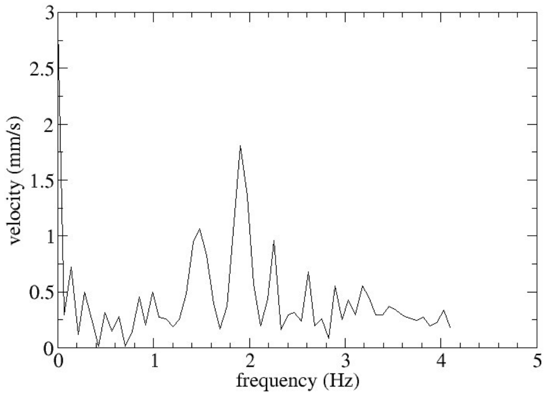

Figure 4: The frequency spectrum of the particle velocity from the results in Fig. 3.

The intermittent nature of the motion is not completely regular; it repeats with a frequency between 1.5 and 2.5 Hz. It is interesting to note that the frequency spectrum is not a smooth Gaussian like distribution; rather there are a number of distinct peaks in the spectrum.

5 DISCUSSION AND CONCLUSIONS

The motion of PET particles against the transparent wall of a model silo has been investigated. This was done by taking digital images of the particles to obtain a qualitative description of the particle motion. The particles were seen to move in an intermittent manner. They remained stationary against the silo wall for a period of time of the order of 0.1 s. The particles then fall abruptly before coming to rest and the cycle is repeated. The images were further analyzed to provide quantitative information about the particle velocity. It was found that the all particles moved in phase. That is, all the particles, over the entire wall of the silo, were either stationary or sliding against the wall at the same time.

This intermittent motion is consistent with DEM simulations [8] on a silo with similar dimensions where similar motion was observed with a higher frequency of around 7 Hz. The motion of the particles is also similar to slip-stick response which has been observed between the same PET particles and aluminum and stainless steel plates with the same grade and thickness as those used in silo construction [7]. This slip-stick motion was observed using a Jenike shear tester and was only observed when a normal stress was applied with a level typical of that found in a full-scale silo. The normal stress level in the model silo considered here is considerable less than the minimum level in [7] at which slip-stick was observed. There are clearly a number of differences between the polycarbonate walls of the model silo and the metal plates used in [7], not least the increased flexibility of the model silo and the different frictional properties of the wall. The results, however, indicate that the particles are moving against the wall with intermittent motion in the model silo which has a lower normal stress level.

Given the significant differences in normal stress between the model silo and those used in [7], it is not evident that the same mechanism is responsible for both motions, although friction apparently plays an important role in both. Before the particulate solid can flow through the silo it is necessary for it to dilate and loosen. In doing this a pressure wave can be set up which can propagate through the fill. The presence of such a pressure wave could account for the intermittent motion which has been observed in the model silo.

It is also interesting to consider that horizontal wall vibrations have also been observed in the model silo during discharge [9]. These have a frequency of around 3 Hz, corresponding to the natural frequency of free vibration of the silo wall. This indicates that vertical motion of the particles is coupled with radial vibrations of the silo wall. Such a coupling is required in a full-scale silo if the slip-stick motion of the particulate fill against the wall is the driving mechanism for silo honking and/or quaking.

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