Investigation of silo honking: slip-stick excitation and wall vibration

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The phenomenon of silo honking, a loud, acoustic emission from a silo during discharge is investigated. Simultaneous measurements of the three components of the acceleration of a full scale silo wall and the acoustic emission are presented. The results indicate a fundamental frequency of 330 Hz which characterizes the silo/particle combination. Results of laboratory investigations into the interaction of particulate solids with the silo walls and also internally with other particles are also presented. The observed slip-stick behaviour is a possible excitation mechanism for silo honking and is examined for a range of different particles and wall materials.

1 Introduction

Huge quantities of bulk materials in the form of granular solids are handled each year throughout the world. During emptying from thin-walled metal silos very loud intermittent honking sounds can be generated. This honking noise contains much higher frequencies and differs radically in nature from the periodic thumping or banging which can be heard in some silos during discharge. Honking of silos has been a fairly common industrial problem and has been known to exist in silos with differing dimensions, construction materials and fills in a variety of locations world wide. As noise pollution becomes increasingly unacceptable, silo honking has become an issue that needs to be urgently addressed. Honking with sound pressure levels in excess of 100-110dB can cause long term hearing damage if hearing protection is not worn. In recent years, the dynamic effects during silo discharge have been studied to a limited extent and various descriptive terms such as silo vibration, silo quaking, silo music or silo shocks have been used (Tejchman and Gudehus, 1993; Roberts, 1993). A recent study (Tejchman, 1999) examined the displacement and acceleration response of the walls of a honking silo, but did not consider the causes of honking. Several sources of the dynamic excitations in silos have been proposed (Gudehus and Tejchman, 1992; Roberts, 1993; Schulze, 1998). These include slip-stick behaviour between stored solids and silo walls, internal slip-stick behaviour within the stored solids, alternating flow patterns during flow, collapsing arches and solid dilation during flow.

2 Silo Honking: Field Measurements

Measurements were obtained during honking from a full scale industrial honking silo in Scotland. The cylindrical part of the silo has a diameter of 3 m and is 21 m tall, it is constructed from horizontal aluminium strips which have three thickness of 4.0 mm, 5.2 mm and 6.2 mm from top to bottom. The conical hopper has a half angle to the vertical of 30° and was designed to ensure the PET pellets inside the silo undergo mass flow. The silo was instrumented using a triaxial accelerometer consisting of three PCB 303A02 accelerometers which were calibrated between 1 and 10 kHz. Outwith this range they had a maximum error of ± 10% up to 20 kHz; an Audio-Technica microphone ATM33a which had an approximately flat frequency response between 200 Hz and 2 kHz and a variation of no more than 5dB between 40Hz and 200 Hz and between 2kHz and 20 kHz; and a CEL-254 digital impulse sound level meter with a measurement range of 35-135 dB and a frequency range of 10 Hz to 25 kHz, which was calibrated with a CEL-282 acoustic calibrator. The combination of the triaxial accelerometer and the microphone enabled simultaneous measurements of the acoustic emission and the three components of the silo wall vibration in the axial, z; radial, r; and circumferential, θ, directions.

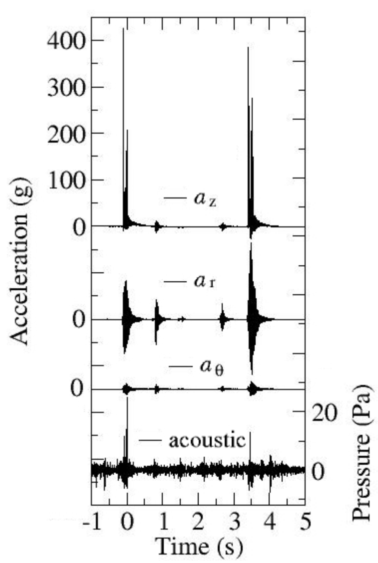

Figure 1: Accelerometer and microphone measurements

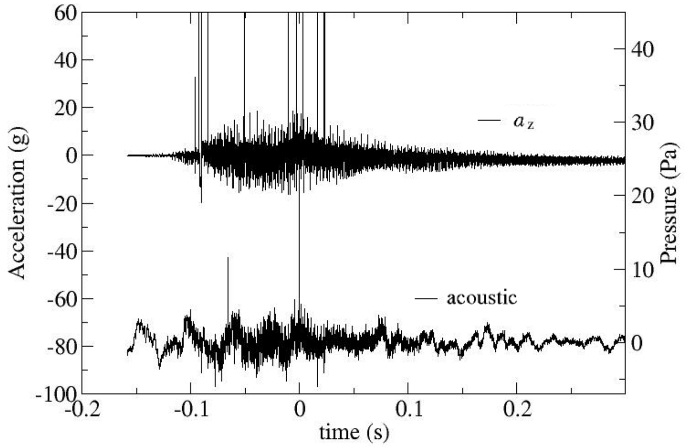

Figure 2: The axial acceleration and the acoustic signal

Figure 1 shows the acceleration measurements obtained from the triaxial accelerometer attached to the silo wall at a height z = 17.7m above the hopper transition. Also shown in figure 1 is the acoustical emission measured by the microphone at the base of the silo. The measurements presented in figure 1 correspond to one discharge cycle of the silo during which the silo was heard to honk 5 times, Honk1 at $t \sim 0.0$, Honk2 at $t \sim 0.8$, Honk3 at $t \sim 1.5$, Honk4 at $t \sim 2.6$ and Honk5 at $t \sim 3.5$ s. At these times the acceleration plots in figure 1 show corresponding wall accelerations of varying magnitudes which can be associated with the acoustic emissions. It is not, however, possible to detect the individual honks from a visual display of the pressure readings obtained from the microphone, however these can be observed if the low frequency noise is removed from the signal using a digital filter. Figure 2 shows a magnification of the axial acceleration and the acoustic signal around Honk1. The axial component of the acceleration, a_z, shows accelerations of over 400 g, which is comparable with the magnitude of acceleration measured elsewhere (Tejchman 1999), however figure 2 indicates that these high accelerations are intermittent impulses and are not oscillatory. Figure 2 shows that the typical acceleration amplitude of oscillatory response is up to 20 g.

Frequency analysis of the acceleration and pressure measurements was also performed and is shown in figure 3. The spectrum for each acceleration component shows the same harmonic series as was obtained for the acoustic signal indicating a direct correlation between the two. The figure indicates that there were significant acceleration at frequencies up to 10 kHz for the radial and circumferential components, at frequencies up to 20 kHz for the axial acceleration and up to 6 kHz for the acoustic signal. Each spectrum shows a harmonic series of peaks at a fundamental acoustic frequency of approximately 330 Hz and further peaks at frequencies corresponding to integer multiples of the fundamental acoustic frequency. This behaviour was observed in all measurements and the fundamental acoustic frequency was found to be independent of fill height and position of the accelerometers in further measurements.

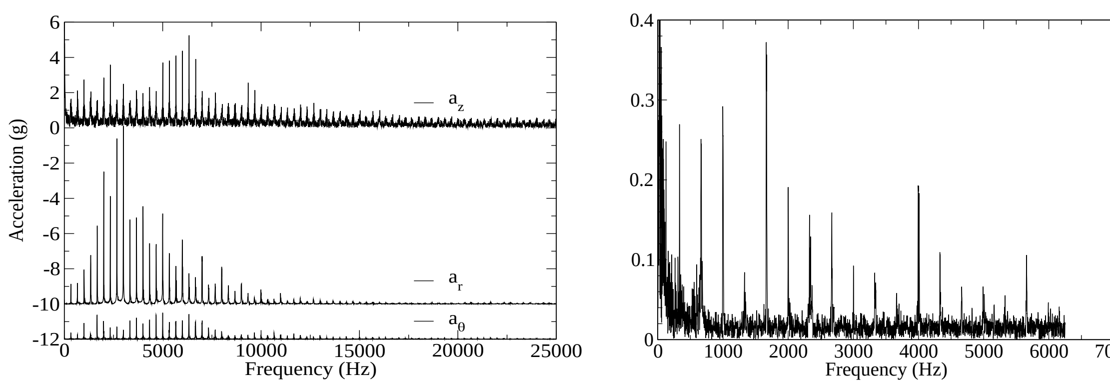

Figure 3: Frequency spectrum for the three components of the wall acceleration and the acoustic signal.

3 Wall Excitations: A Laboratory Study

In this section possible excitation mechanisms for the silo walls during discharge are considered. There are a number of possible excitation mechanisms which could potentially be responsible for exciting the silo

walls: a) Slip-stick behaviour between pellets and silo walls; b) Internal slip-stick behaviour within the pellets; c) Changing pattern of flow during discharge; and d) Dilation of the bulk solid during flow.
Three different particles were used in the laboratory measurements. Results are presented for PET pellets which were know to produce honking and blue polypropylene pellets which have not been reported to exhibiting honking. Aluminium plates were used with the same grade and thickness as used in silo constructions. Stainless steel plates were also used for comparison.

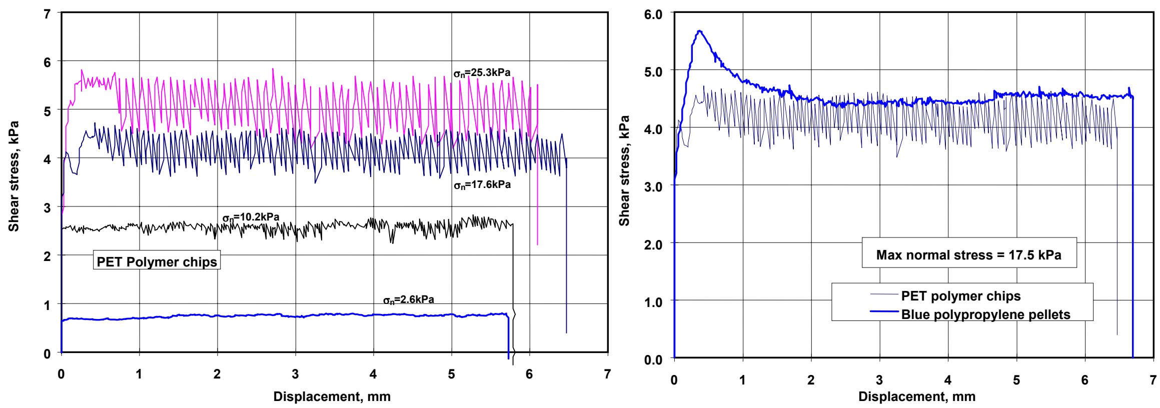

Figure 4: Shearing response of PET and blue polypropylene pellets on an aluminium wall for a nominal shear rate of 1mm/min.

Using Janssen theory (Janssen, 1895), it is possible to calculate the normal wall pressure on a silo wall. For the silo from which the acceleration measurements were obtained this was found to increase to just over 30 kPa near the transition. The testing of the mechanical behaviour of the pellets was therefore conducted with the stress level between 0-30 kPa. Wall friction tests were conducted using a Jenike shear tester (IChE, 1989) with a non-standard, large shear cell of 143 mm in diameter. In each test, the shear ring was positioned on top of the plate and then carefully filled with the pellets. After levelling the surface of the pellets, a shear lid was placed on top and a normal load was applied before the shearing was initiated. The results are presented in figure 4 for the PET pellets at four different normal stress levels and for both the PET and blue polypropylene particles for a normal stress level of 17.5 kPa.

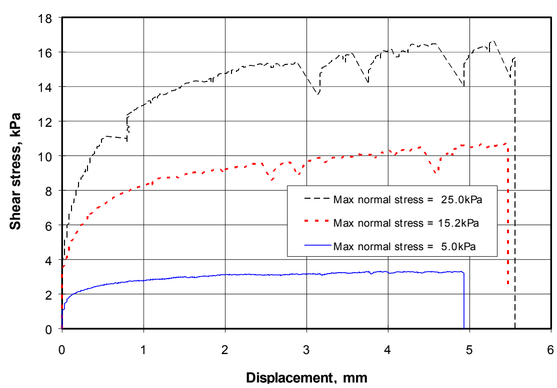

Figure 5: Inter-particle shearing response for the PET pellets.

The results show the shearing response of the PET pellets on the aluminium plate for the four normal stress levels and a shear rate of 1 mm/min. After the initial period when the shear stress increased towards shear failure, there was considerable slip-stick response. The pellets appeared to stick against the aluminium plate until the shear stress reached a certain magnitude, and then a sudden slip occurred, bringing the shear stress down to a lower value before building up again. The shear stress fluctuated between the peaks and the troughs as the pellets slip-stick continually during shearing against the aluminium plate. The slip-stick response is also noted to be very much stress level dependent, with considerably larger fluctuations at larger normal stress, and very little fluctuations at very low stress levels. Since the stress level in the real silo is partly governed by the height of fill, this indicates that the slip-stick phenomena at the walls may become significant only when the horizontal stress reaches around 10-15 kPa, which equates to z = 11-13 m in the instrumented silo. Similar results were also obtained for a second type of PET pellets, however, the blue polypropylene did not exhibit this slip-stick behaviour. Slip-stick motion was also observed between the PET pellets and a stainless steel wall sample but with a reduced magnitude.

Jenike direct shear tests were conducted to explore the internal stress-strain response of the honking PET pellets. The testing procedure involved setting up a sample of the pellets within two split rings, which were then sheared relative to one another under a certain normal stress. Figure 5 shows the results of three tests under normal stresses of 5.0, 15.2 and 25.0 kPa respectively. At higher stress levels, say above 10-15 kPa, the pellets exhibit some slip-stick phenomena, but these do not take place on a regular basis. The results indicate that internal slip-stick is probably not significant in this bulk solid and is certainly less than the wall slip-stick.

4 Conclusions

The phenomenon of silo honking has been investigated using a two-pronged approach. Full scale measurements have been obtained from a honking silo to evaluate the honking process and laboratory measurements were performed to investigate the excitation mechanism which is responsible for generating the honks. The full scale measurements provided simultaneous measurements of the three components of the wall acceleration during honking as well an acoustic recording of the honk. The most striking feature of the measurements was the constant value of the fundamental frequency of both the acoustic and wall acceleration measurements. This was found to be approximately 330 Hz and was totally repeatable and appeared to be independent of the position of the accelerometer, the fill level and other external factors such as temperature and humidity and acts as a signature of the silo/particle combination. Higher harmonics of 330 Hz were also observed. The laboratory measurements concentrated on investigating the slip-stick behaviour which can occur between the fill particles and the silo wall and internally between particles. The measurements were performed at wall pressures typical of those found at different height in a realistic silo. The two pellets which were known to exhibit honking in an aluminium silo displayed a slip-stick motion against a aluminium wall plate, while the third pellet which was thought not to exhibit honking showed no slip-stick behaviour. The amplitude of the fluctuations in the slip-stick motion was seen to increase with increased normal wall pressure. Internal slip-stick between the pellets in the silo was also considered. These showed some slip-stick properties but this was not considered significant when compared to the particle-wall slip-stick motion.

5 Acknowledgements

We would like to thank Mark Astin, Tim Bell, John Carson, Ron Dailey, Paul Dean, Paul, Michael Duerr, Karl Jacob, Paul Mayer, Colin Milton, Peter Moon, and John Thorman for many useful discussions throughout the course of the work. The authors would like to acknowledge the financial and practical assistance of Braby silos; Dow Chemical Company; DuPont; DuPont Teijin Films; Eastman Chemical Company; Jansens & Dieperink; Jenike & Johanson Inc.; and Waeschle and the financial support of EPSRC UK (grant no. GR/R44263) and an ORS Award (Chavez-Sagarnaga).

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