New Methods for Detecting Physical Phenomena in a Silo

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Abstract

To ascertain the stress inside silos we developed several kinds of sensors with specific applications: (1) pressure cells, (2) two-directional stress cells, (3) slipping velocity detectors, (4) surface temperature detectors, and (5) internal temperature and slipping velocity detectors.

The detecting sections of pressure cells and two-directional stress cells comprise a parallel plate structure and strain gauges that can detect pressure, and pressure and frictional stress, respectively.

Measurements of physical phenomena in silos lead to the following conclusions: Pressure cells and two-directional stress cells (1) work as designed, and (2) they are capable of elucidating the fundamental physical phenomena in silos.

1. Introduction

Designing a silo with adequate functions and controlling its processes requires that we conceive the overall phenomena occurring in a silo as physical phenomena.

Those physical phenomena are the deformation, force, heat, sound, and others that arise in silo contents and silo walls, and those translate into content flows and internal stress, the stress acting on walls, the load acting on the silo as a whole, the heat quantity generated by grain slippage, the amount of that heat transmitted to silo walls, the sound generated among granules or between granules and walls, and others. However, research heretofore has not investigated these physical phenomena comprehensively [1-12].

The purpose of this research was to develop an "intelligent silo" that can predict future events and control phenomena themselves by using sensors to ascertain these phenomena and comparing the information obtained with a previously prepared knowledge base [13]. This paper explains the sensors developed in order to perform the essential job of acquiring this information and providing the control for turning it into knowledge, and gives examples of measurements obtained in actual use. This silo research comprises five parts: Sensor development, dynamic silo data, elucidation of physical phenomena in silos, silo analogy, and making silos intelligent.

Ascertaining the phenomena that arise in silo contents generally requires the use of sensors for granular material, which differ from those for liquids. This necessity is particularly evident when measuring stress. To begin with, internal stress in granular material has two components: the force transmitted by contact between granules, and the force transmitted through the liquid or gas filling the interstices among granules (Fig. 1 (a)). Wall stress acting on inside walls of silos consists of both forces, as shown in Fig. 1 (b). For this reason sensors for granular material must accurately measure the sum total of forces from many granules in discontinuous contact with each other.

What is more, as shown in Fig. 1 (c), wall stress is actually measured as the vector sum of the component running parallel to the wall (tangential) and the component running perpendicular to it (normal). Because there is great granule-wall friction in silos holding granular material, the tangential force is much larger than the wall stress generated in containers holding only liquids. Granule sensors therefore

Fig. 1 Granular Stresses

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must be able to measure a total of forces in three directions including the normal and tangential forces. Also, localized contact stress is large owing to the small area of contact between granules and the wall, and because granules roll around, wall stress is measured as a discontinuous value. To measure this large discontinuous value accurately, sensors must have resistance to abrasion and a high natural frequency [14]. Following is a discussion of granule sensors that satisfy these requirements.

2. The Newly Developed Sensors

2.1 Stress Sensor

2.1.1 Parallel Plate Structure in Detector

In order to measure granular stress the authors have developed stress sensors whose detectors have a parallel plate structure (Fig. 2(a)) [13-15]. The structure consists of a square beam with a square hole in the side, i.e., a movable part and fixed part linked by two parallel plates, upper and lower. When subjected to force in a vertical direction, the movable part is displaced selectively in the downward direction alone, and tensile or compressive strain is generated at both ends of the plate. As this strain is proportional to force, the force can be determined by detecting the strain with four strain gauges incorporated into a wheatstone bridge circuit. This structure has the following features: (1) It can detect force in one direction only, making for little component interference from forces in other directions and from moment; (2) assembling this structure makes it possible to configure various kinds of multiple-force component measuring instruments; and (3) this structure provides greater rigidity than the simple beam, diaphragm, and other structures normally used. Fig. 2(b) and (c) show examples of detection blocks using this parallel plate structure. We used (b) in the pressure cell and slipping velocity meter, and (c) in the two-directional stress cell, all of which are described below.

2.1.2 Pressure Cell

Pressure cells are used to detect stress (pressure) acting on the wall vertically. Generally their structure involves the use of flexible, soft diaphragms as detecting sections, so they are susceptible to abrasion and their output characteristics vary. In our research we gave the detecting section and detecting block different functions, and had a hard steel plate as the detecting block (i.e., the part that deforms when exposed to a force). Using this structure allowed us to make sensors capable of obtaining more stable output characteristics.

The pressure cell we developed in this research (Fig. 3) is structured so that pressure is transmitted from the detecting surface to the interior quadrangular pyramid, which is supported, through an upper and a lower plate, by the suspending block surrounding it. Pressure is ultimately detected as changes in electrical resistance by the strain gauges attached to the bottom plate. This pressure cell's pressure detection performance has good linearity, nonhysteresis, and sensitivity (Fig. 4(a)). It is thought that grains come in contact with the pressure cell's detecting surface at random locations, where a concentrated
load acts. The graphs show the cell's corresponding performance (i.e., eccentric load characteristics; Fig. 4(b)). It is evident that no matter where grains contact the detecting surface, strain gauges get about the same output.

2.1.3 Two-Directional Stress Cell

Because the measurement of frictional stress was important to achieving the objective of this research, we developed a sensor for that purpose as there were none up to that time, the mid-size model silo treated herein releases granules from its bottom. Because grains flow downward, the wall is subjected to mainly vertical and perpendicular (tangential and normal) force components. But as a later report notes, because in large silos large rotational movements are generated around vertical axes, one should take note of the horizontal frictional stress. For the sake of simplification, this paper ignores horizontal frictional stress and focuses exclusively on that in the vertical direction. The stress cell we developed uses two parallel plate assemblies in the detecting block: one for detecting frictional stress and one for detecting pressure. These allow the cell to detect the principal two of the three stress components acting on the wall.

It is the two-directional stress cell that simultaneously detects both stress acting vertically on the wall (i.e., pressure) and stress acting horizontally on the wall (which we shall call either frictional stress or shearing stress) with a single instrument. It detects the two force components: the single-component frictional stress and the pressure created by the granular material inside a silo (Fig. 5) [16]. Pressure and frictional stress are transmitted through the detecting section to the cruciform detecting block, which is in contact with the underside of the detecting section's outer edge, pass through the cruciform block from one side and are transmitted to another side intersecting at a 90° angle. At this point pressure and frictional stress are detected separately by two parallel plate structures inside the cruciform detecting block. Just as in the pressure cell, pressure and frictional stress are detected as changes in electrical resistance from the strain gauges attached to the plates.

Performance graphs for this two-directional stress cell (Fig. 6) show pressure detection performance (a) and frictional stress detection performance (b). All show good linearity, nonhysteresis, and sensitivity. They also indicate that pressure interference in frictional stress output and frictional stress interference...
in pressure output are very small. The graph for eccentric load (c) shows that there is only a small 8% effect on the output at the point on the 84 mm diameter detecting surface upon which the load concentrates. This figure can be ignored in actual use because the largest granule size of our experimental sample was small at under 3 mm, making it impossible for a concentrated granule load to be imposed on that part. The graph for the effect of temperature on output (d) was plotted with data that had not been corrected for resistance variation among the four strain gauges, so with correction it would be possible to further reduce the effect of temperature to under 3 μst/°C.

In measuring stress on walls, the material and surface state of the sensor's pressure detecting section must be the same as those of the wall that is being observed, or it is impossible to correctly measure stress because of changes in the frictional state of the granules. This makes it necessary to have a structure capable of changing the material and surface state of the detecting surface at will. An example of this structure (Fig. 7) shows how the desired detecting section can be affixed by means of screws.

2.2 Deformation Sensor [17]

2.2.1 Determining Structural Deformation from Overall Information

Generally the supporting structure for a working part deforms in response to the working part's force. Measuring the deformation of the supporting structure therefore makes it possible to estimate the magnitude of the working part's force. This holds for a silo as well, for measuring the deformation of supports makes it possible to find the weight and eccentric load of grains in a silo.

2.2.2 Deformation Sensor

Let us examine the principle by which displacement-caused structural deformation is measured (Fig. 8). Affixed to two points on the structure and parallel to it is an assembly connected with a deformation detector having a high-rigidity rod and a parallel plate structure. The parallel plate structure and notch in the rod's center allow this detector to measure deformation of the structure in the x direction alone. Using a deformation sensor to directly detect the amount of change over the distance between two points far apart provides a significantly larger S/N ratio and guarantees sensor protection from changes in the immediate environment, making this method superior to installing direct strain gauges that detect localized strain. The advantage of this method is that it allows stable, accurate detection of force phenomena in a silo.

The deformation sensor we made (Fig. 9) is 900 mm long, has a parallel plate detecting section measuring 45×80×20 mm, and a connecting rod 10 mm
Deformation of a structure is determined from the strain gauges attached to the parallel plates on the deformation detecting section. Sensor material is steel or invar. The latter has small thermal expansion of $1 \times 10^{-6}$/°C, and can be suitably applied to the thermal deformation of steel structures.

We have graphically represented deformation sensor performance (Fig. 10). In order to investigate sensor rigidity, one end of a sensor was left free and a weight placed on the bottom. Fig. 10(a) shows the relationship between load and load direction displacement. Using this to determine rigidity shows that when the detecting section is made of steel it is 0.83 N/μm, and when invar it is 0.24 N/μm, far smaller than the rigidity of the structure. This sensor's natural frequency is 400 Hz even when using invar.

Investigating interference on deformation in other directions showed that while output in the main direction ($X$) was 24 μst/μm, that in the $y$ and $z$ directions was 0.001 μst/μm, with 2 μst/deg for $θ$, small values showing there is very little interference.

2.3 Slipping Velocity Meter

2.3.1 Principle of Detecting Slipping Velocity with the Spectrum Method

Grains produce sound when they slip against a silo wall. As shown in the diagram (Fig. 11(a)), the waveform of that sound changes in accordance with slipping velocity magnitude. Frequency analysis of that waveform shows that the height of two representative peaks change relative to one another (Fig. 11(b)). For example, when slipping velocity is small ($V_1$), the higher frequency with the 1,000 Hz peak value ($P_b$) is lower, while the frequency with the lower 100 Hz peak ($P_a$) is higher. But when the slipping velocity is large ($V_2$), it is the opposite: the peak with the higher frequency is high, while that with the lower frequency is low. In view of these findings, our research proposes a method, called the spectrum method, of finding slipping velocity from the ratio between the two peak values by using the correlation between that ratio and slipping velocity. A possible reason for that correlation is inter-granular collisions. Specifically, the larger the slipping velocity, the greater the frequency of inter-granular collisions, and the greater generation of pressure with a high-frequency component.

The development of such a sensor would produce a detector that would detect a totally new physical quantity.

2.3.2 Slipping Velocity Meter Types

The authors used the principle described in 2.3.1 to devise several ways of measuring slipping velocity in granular material. First we tried a way of directly measuring sound pressure. One structural type is the slipping velocity meter using a microphone (Fig. 12) [18], which has a condenser microphone connected
through an ultra-thin pressure plate. Sound pressure is detected as a voltage that is proportional to change in static electricity capacity. But despite the excellent sensitivity of this microphone type, its drawback is that the thinness of the plate over the pressure detecting section makes for poor abrasion resistance and results in varying detection performance owing to abrasion by granules.

To eliminate this shortcoming we devised a method that detects wall acceleration. The slipping velocity meter using an accelerometer (Fig. 13) consists of an accelerometer installed in the bottom of the detecting block of the pressure cell described in section 2, and works by using the accelerometer to detect vibration impinging vertically on the detecting surface due to pressure. The spectral distribution obtained in actual use was the same as that obtained with the microphone meter in Fig. 12.

Because the structure of the pressure detecting section in Fig. 13 is the same as that of pressure cells, we next conceived a method of using direct spectral analysis on the output of strain gauges attached to a pressure cell. Using this method yielded the same spectral distribution as the two methods described above. It is therefore possible to determine slipping velocity by analyzing pressure cell output, thereby eliminating the need for making and using separate slipping velocity meters. In future related research we shall adopt this method of determining slipping velocity by spectral analysis of pressure cell output.

2.4 Surface Temperature Sensors

2.4.1 Surface Temperature Detection Principle

Using the principle of finding surface temperature and thermal flux from the temperature difference between two points at different depths (Fig. 14(a)), it is possible to find surface temperature $T_s$ from temperatures $T_1$ and $T_2$ at two points $X_1$ and $X_2$ located at different depths using an inverse Laplace transformation when temperature distribution at a certain time $t=t_2$ is given [19].

This transformation's linear approximation entails finding surface temperature by a linear extrapolation from temperature change in a micro-area. Surface temperature is found as $T'_s$ in this case. Temperature changes for $T_1$, $T_2$, and $T'_s$ as found in this manner are represented in a graph (Fig. 14(b)). As temperature change in a silo is not rapid, there is no problem with using the linear approximation value of $T'_s$ for surface temperature even if a precise inverse Laplace transformation is not used. It is possible to calculate thermal flux using the same principle. If such a sensor were developed it would detect totally new physical quantities.

2.4.2 Surface Temperature Sensors

The surface temperature meter used to measure internal silo wall temperature (Fig. 15) [20] has two sheathed thermocouples set at different depths from the detecting surface. As the casing material's heat transfer characteristics and thermocouples' positions are known, one can calculate silo wall surface temperature from the temperatures at the thermocouple positions.
This detector can also detect the thermal flux passing vertically through its own surface (i.e., the heat quantity passing through per unit time per unit area), but owing to the differences between the materials and shapes of the silo and the detector's detecting section, problems remain with regard to the differences between detector readings and actual temperatures in other locations. For this reason we decided not to deal with thermal flux in our research.

2.5 Internal Temperature/Velocity Meter

The authors made a new internal temperature/velocity meter to measure the internal temperature and the velocity of granular material in silos (Fig. 16) [21]. This sword-shaped sensor is inserted into the side of a silo at the height where measurements are desired. There it measures the temperature of granular material with thermocouples, and its slipping velocity relative to a beam with a microphone.

2.6 Window for Observing Internal Flow

We made an observation window for directly observing the flow of granular material near a silo wall (Fig. 17) [21]. It has the same shape as sensors so as to be interchangeable with them. The window has these features: (1) The combination of the push and pull bolts in the outer frame allow one to adjust the glass flush with the silo wall to eliminate indentations or protrusions that would interfere with granule flow, and (2) the use of reinforced glass provides excellent resistance to abrasion.

3. Measurement Examples

To check the performance of the detectors we developed, we gave each a performance test and also verified their practicality by installing them in model silos or real silos.

3.1 Measurement of Stress on Wall

We measured silo wall stress by installing the two-directional stress cells described previously in a medium-sized silo having a cylindrical section 1 m in diameter and 3 m high, and a conical section 0.9 m high with an angle of 60°. These two sections are supported by separate piers and load cells. We installed a total of seven two-directional stress cells, five on the cylindrical section and two on the conical section (Fig. 18).
Readings for changes in pressure and frictional stress in the mid-size model silo have been graphically represented (Fig. 19). The experimental granular material was silica sand with an average granule size of 0.38 mm. The graphs show that when the sand is put in the silo beginning at -5 min, stress rises beginning with the lowest cell and proceeding in order to the highest. As the valve opens and begins releasing the sand at 0 min, the two cells in the conical section register decreases in pressure and frictional stress, while the fourth and fifth cells near the cylinder's bottom show that pressure starts to gradually build, then subsequently decreases. These measurements reveal a phenomenon in which, as granular material begins to exit the silo bottom, the conical section is no longer able to support the silo contents, and the cylindrical section takes over the job of supporting the weight of the material above.

3.2 Measurements of Slipping Velocity at the Wall

We have plotted, as a sound pressure spectrum for each slipping velocity, the output from pressure cells arising when granules slip in a mid-size silo 1 m in diameter and 4 m high (Fig. 20(a)). The silo was filled with coal, and the graphs show the spectral analysis results when slipping velocity relative to the wall (i.e., flow velocity) is 6, 12, and 24 cm/s. In all cases peak readings appeared at around 100 Hz and 1,000 Hz (correctly, 150 Hz and 1150 Hz).

Fig. 20(b) shows the relationship between the ratio \((Pa/Pb)\) of the peak values \((Pa, Pb)\) and flow velocity. There were three measured points, and the results show it is possible to measure slipping velocity at the wall from the slipping sound at the wall.

3.3 Measurements of Wall Temperature

We have plotted the temperature changes measured at two points inside a temperature sensor and 1 mm and 4 mm from the silo wall surface, and the changes in inside wall temperature as determined by
linear approximation calculations from the readings at those two points (Fig. 21). After beginning to release silo contents at 0 min, surface temperature immediately rises, and then gradually climbs about 0.4°C while fluctuating.

3.4 Measurements of Internal Flow Velocity and Internal Temperature

The internal temperature/velocity meter shown in Fig. 16 was used to measure the temperature and flow velocity inside a silo (Fig. 22). Temperature increase was very small at a maximum of 1°C, and the peak appears closer to the wall than to the center. This shows that more heat is generated by wall-granule friction than by inter-granule friction.

Flow velocity is higher in the silo center than at the wall. Additionally, velocity immediately after discharge begins is generally greater than that during a steady flow, something that is especially evident in the silo center. These results indicate that immediately after discharge begins, granules at the center start flowing before those near the silo wall.

3.5 Measurements of Silo Structural Deformation

To measure structural deformation we used a silo 1.5 m in diameter and 4 m high (cylindrical section 1.6 m), with a wall thickness of 1.6 mm and central outlet (Fig. 23). Deformation sensors were installed at four equidistant points – N, S, E, and W – around
the silo skirt. Before making measurements we placed two horizontal bars in a plus shape on the silo’s top in the N-S and E-W directions so that an eccentric load would be imposed. First we measured the output of all deformation sensors with equal loads in all four directions (Fig. 24(a)), and found that W and S deformation was greater than E and N deformation. This was because of the door on the silo skirt in the SW position, which lowered the rigidity of that area. We then read sensor output with an eccentric load at N alone (Fig. 24(b)), and found that as a result the north side of the skirt shrank, while the south side was extended. Totaling these load outputs showed that they are equal to the eccentric load at N within 5%.

These data indicate that if silo deformation is measured with a suitable method it may very well be possible to directly measure, with considerable accuracy, the weight of silo contents without the use of a load cell.

4. Discussion

We used the sensors developed in this research to perform measurements for three to four months. While the detecting sections were slightly rusted and abraded, there was hardly any change in their detection performance, results which show they have adequate long-term stability, durability, abrasion resistance, and other qualities.

In stress detection we compared the integral of frictional stress in the entire silo cylinder with the total of the load outputs measured at the three piers supporting the cylinder, and found they were nearly equal. From this we know that the detector correctly detected frictional stress. And because the flow velocity measured with the slipping velocity meter was nearly equal to the velocity as measured visually while granules flowed by observation windows, we know that the slipping velocity meters using pressure cells are correctly measuring the slipping velocity.

As little heat is generated by slipping between granules and the silo wall or among granules, temperature changes found by measurements were very small. Thus, we found that to correctly measure transitional temperature changes it is necessary to place the temperature sensor’s internal temperature measurement points closer to the surface than we did in our research (for example, 0.5 mm and 1 mm). Also, when using the internal temperature/velocity meter it is possible that the beam inserted into the silo will disrupt the measuring system itself, but we found that nevertheless it is useful in finding the approximate values for a silo’s internal temperature and flow velocity. We also discovered that finding the deformation in a silo’s structure makes it possible to measure things such as the total quantity it holds and the eccentric volume, which indicates the need to further develop the methods used here and devise a method using deformation sensors that are easier to install.

5. Conclusion

This paper describes the use of several sensors we developed for granular materials in order to detect physical phenomena in silos. In particular, the use of a parallel plate structure in stress sensors made it possible to develop stress sensors for granular materials that can simultaneously detect the pressure and frictional stress acting on a single pressure-sensitive part, and that have excellent non-interference, eccentric load qualities, and abrasion resistance.

We also developed slipping velocity and temperature sensors that can measure flow velocity and temperature, which could not be checked until now, as well as a deformation sensor that measures the structural deformation of silos. We used these sensors three to four months in experiments on actual silos and found that they have good qualities including long-term stability, durability, and abrasion resistance. Experiments showed that the surface tempera-
The development of these sensors was necessary to create intelligent silos, and the development of the sensors described here has made it possible to directly obtain data on the physical phenomena occurring inside silos. Building on this will allow development of technologies for intelligent silos. Further papers will report on the analysis of the data obtained, their application to intelligent silos, and other matters.

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Nomenclature

| Symbol | Description                                    | Unit |
|--------|------------------------------------------------|------|
| X_i    | distance between measuring points              | m    |
| ∆X_i  | displacement of X_i                           | µm   |
| V      | velocity of slipping grains                   | m/s  |
| P_a    | power spectrum at 100 Hz                      | dB   |
| P_b    | power spectrum at 1000 Hz                     | dB   |
| t      | time                                          | s    |
| T      | temperature                                   | °C   |
| X     | distance from surface of silo                 | m    |
| X_1   | 1.0 mm under the surface                      | m    |
| X_2   | 4.0 mm under the surface                      | m    |
| T_1   | temperature at X_1                            | °C   |
| T_2   | temperature at X_2                            | °C   |
| T_c   | calculated surface temperature                | °C   |
| T_s   | calculated surface temperature using an inverse Laplace transformation | °C   |
| D     | outlet diameter                                | m    |

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