

Grain Velocity Measurement with Optical Sensors

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ABSTRACT

GRAIN velocity probes were developed and used to measure the velocities of grain on a rotating disk and in a free-fall grain stream. Each probe consisted of two photo-detectors spaced at a fixed distance and four to seven infrared-emitting diodes. By cross-correlating the signals generated by the two detectors, the transit time required for the grain kernels to travel the distance between the detectors was determined. From the values of transit time and the known distance between the detectors, velocities of grain ranging from 2 to 9 m/s, were measured within an accuracy of $\pm 10\%$.

INTRODUCTION

Physical damage to grain during handling is a common problem in the grain industry. With the repeated handling in commercial marketing channels, breakage frequently is sufficient to lower the value of the grain. High velocity impact is one of the major factors contributing to the breakage (Clark et al., 1969; Fiscus et al., 1971b; and Keller et al., 1972a). In addition, grain velocity during handling is an important parameter affecting dust emission and equipment performance. To develop grain handling equipment such as grain flow regulator and retarder for controlling dust emission and reducing impact damage to grain during handling, knowledge of grain velocity in grain handling system is needed. However, no practical apparatus is available for grain velocity measurement at the present time.

Grain velocity can be measured by high speed photography (Fiscus et al., 1971a). Applications of this method are limited to open grain streams or to a grain stream contained in a transparent section.

Heertjes et al. (1970) determined particle velocities in fluid-solid flow by measuring the momentum of the particle using a piezo-electric crystal. Given the mass of the particles, the velocity of the particles can be calculated. Because of the requirements of uniform particle mass, this method is not practical for grain velocity measurement.

Keller et al. (1972b) used a radioactive tracer technique to measure corn kernel velocity in a pneumatic conveyor. Corn kernels treated with radioactive material were mixed in the grain mass. Two scintillation detectors placed at a fixed distance apart along the conveyor were

used to detect the elapsed time for the treated kernels to traverse the distance between the detectors. Because of the hazards of radioactive material and the difficulty in separating treated grain from the grain mass, this technique has limited application.

Mesch and Kipphan (1972) used optical and capacitive sensors to measure the flow velocities of sand and lead shot mixture, granular calcium oxide (1 mm diameter) and polystyrol particles (2 mm diameter) in two sizes of vertical tubes. The sensors were installed at two fixed points along the direction of particle flow. The tube sizes were 10 mm in diameter and 18 mm square, respectively. The heights of particle fall at the measuring point varied from 5 to 6 m. An electronic correlator was used for cross-correlating the signals generated from the sensors to determine the elapsed time for the particles to travel between the two fixed points, which varied from 5 to 37 cm in their experimental setup. With measured particle velocities, they were able to predict the volume flow rate to an accuracy of $\pm 3\%$.

Oki et al. (1977) used fiber optics (0.6 — 1.0 mm diameter) to measure the velocities of glass beads (0.5 mm diameter) on a rotating bed. Individual moving particles were optically detected by fiber optics at two locations aligned in the direction of particle flow. The transit time required for particles to travel between these two points were determined by the cross-correlation function. The particle velocity was calculated from the transit time and the known distance (0.613 mm) between the two detection points. Particle velocities ranging from 20 to 50 cm/s were measured.

In designing a velocity probe, the distance between the two detection points, L , in the probe is a critical feature. The probability that the same particle at the same orientation will pass the two detection points decreases as the distance L increases. Therefore, the correlation between the two measured signals becomes smaller. Oki et al. (1977) stated that the distance L should be close to the diameter of the particles to be measured. They found that when the distance L was greater than five times the diameter of the particle, the correlation coefficient was smaller than 0.2. On the contrary, when the distance L became small, error caused when digitizing the signals to compute the transit time became large. Mesch and Kipphan (1972) reported that the optimal distance L depended upon the particle velocity, detector aperture, and signal scan rate.

The objective of this study was to develop velocity sensors that can be used to measure the velocity of grain in grain handling systems.

MATERIALS AND METHODS

Apparatus

Three velocity probes (Figs. 1 and 2) constructed at the

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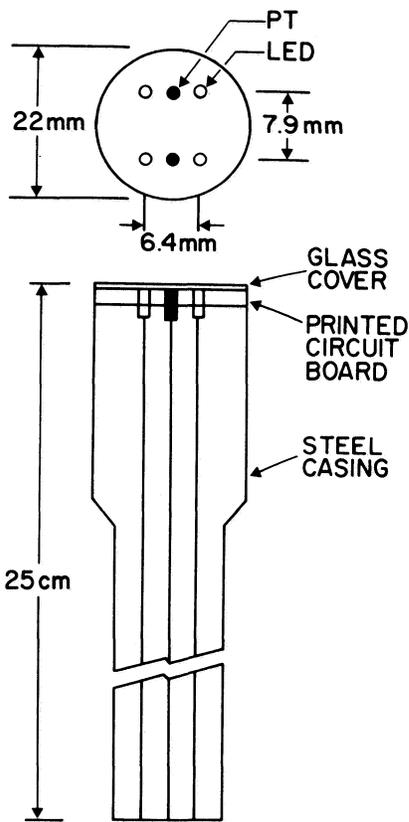


Fig. 1—Schematic of the grain velocity probe.

U. S. Grain Marketing Research Laboratory were used to measure grain velocity. Each probe consisted of two photo-detectors (Type TIL 601, Texas Instruments Inc., Dallas, TX) and four or seven infrared-emitting diodes (Type TIL 24, Texas Instruments). Relative positions of photo-detectors (PT) and infrared-emitting diodes (LED) for each probe are shown in Fig. 2. The LED's were used to illuminate grain kernels and the PT's to detect the radiant intensity reflected by the kernels. Both PT and LED were 2.9 mm high and 1.5 mm in diameter. Response time of the PT was less than 25 ns. For each probe, the LED and PT were installed on a printed circuit board and were enclosed inside a 22 mm or 28 mm diameter steel casing which was 25 cm in length. Physical distances between the two PT's in probes 1, 2, and 3 were 7.9, 9.5, and 12.7 mm, respectively. Optical distances between the two PT's in each probe were obtained by calibration which will be described later. Figure 3 shows the electrical circuit for the LED and PT.

Correlation Method with Photo-Detectors

The correlation method optically detects individual

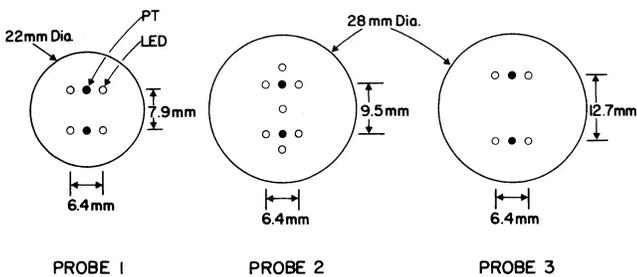


Fig. 2—Schematic showing the relative positions of PT and LED in probes 1, 2, and 3.

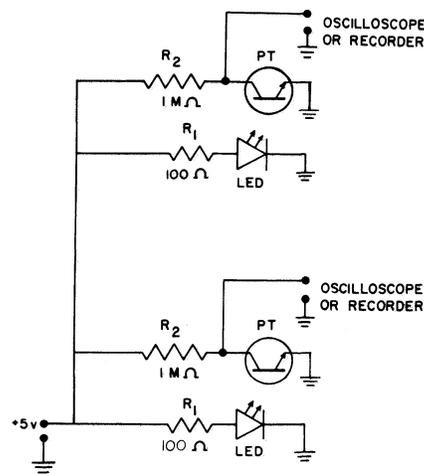


Fig. 3—Electrical circuit for the photo-detectors and infrared-emitting diodes.

moving particles by two photo-detectors at two known locations aligned in the direction of particle flow. The time required for the particles to travel between the two detection points is the transit time (u_m) which can be determined by computing the maximum value of cross-correlation function (Bendat and Piersol, 1980):

$$C(u) = \frac{1}{T-u} \int_0^{T-u} x(t) y(t+u) dt \quad 0 \leq u < T \dots\dots [1]$$

where

- $C(u)$ = cross-correlation function
- $x(t)$ = fluctuating signals generated by detector located upstream
- $y(t)$ = fluctuating signals generated by detector located downstream
- t = time
- T = length of time $x(t)$ and $y(t)$ exist
- u = time displacement

Since $C(u)$ is maximum at $u = u_m$, the particle velocity, V , can then be calculated by:

$$V = \frac{L}{u_m} \dots\dots\dots [2]$$

where

- L = distance between the two detectors
- u_m = transit time

Cross-correlation is a measure of the degree to which signals from the two detectors vary together, or a measure of the similarity of signals from two detectors. For the purpose of describing the cross-correlation analysis, a typical plot of signals from the velocity probe is shown in Fig. 4. The dashed-line $x(t)$ and solid-line $y(t)$ are signals from the detectors located upstream and downstream, respectively. The valleys of curves are the indication of kernels passing the detection points. The two curves are similar in shape with one leading the other. The leading time is the time required for particles to travel from the upstream detection point to the downstream detection point. By advancing the curve $y(t)$ or shifting the curve $y(t)$ toward the left, one can see that the correlation between $x(t)$ and $y(t)$ increases. The curve shifting can be achieved by assigning a time displacement u in the curve $y(t+u)$. By trial and error, a value of $u = u_m$, where the correlation between curve $x(t)$ and $y(t+u)$ is the highest or the value $C(u_m)$ in equation

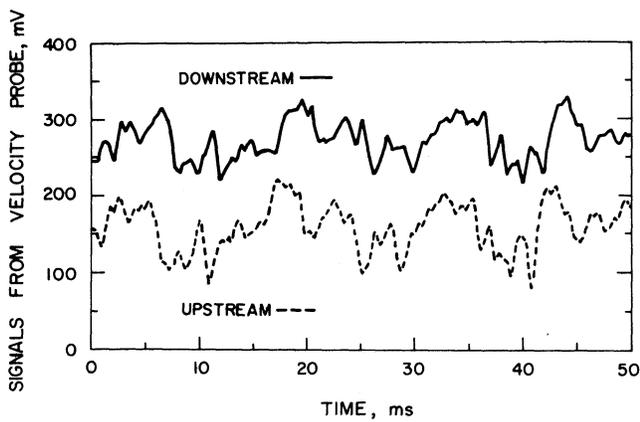


Fig. 4—Output signals from the velocity probe.

[1] is maximum, can be obtained. u_m is the average transit time over the period of scan during which more than one particle passes the detection points.

The curves $x(t)$ and $y(t+u)$ should be identical in shape if particles passing the upstream detecting point also pass the downstream detection point at the same orientation and relative position with respect to the detectors, and the light sources for each PT are identical. Under this condition $x(t)$ will coincide with $y(t+u)$ at $u = u_m$ and $C(u_m)$ reaches a maximum value. This ideal condition does not occur in an actual test due to collisions and rotation of particles in the flow stream.

For numerical calculations of the cross-correlation function $C(u)$, equation (1) is transformed into a finite difference form (Bendat and Piersol, 1971):

$$C(u) = C(ih) = \frac{1}{N-i} \sum_{n=1}^{N-i} (x_n - \bar{x})(y_{n+i} - \bar{y}) \dots \dots \dots [3]$$

where

- i = 0,1,2, . . . m, time displacement numbers
- N = total number of data points collected from each detector during time T
- h = scan rate or time interval per data point
- x_n = $x(t)$ signal at data point n
- y_n = $y(t)$ signal at data point n

$$\bar{x} = \frac{1}{N-i} \sum_{n=1}^{N-i} x_n, \text{ mean value of } x(t)$$

$$\bar{y} = \frac{1}{N-i} \sum_{n=1}^{N-i} y_{n+i}, \text{ mean value of } y(t)$$

In equation [3], deviation from the mean value ($x_n - \bar{x}$) instead of actual value (x_n) was used. Use of the deviation does not alter the shape of the correlation; however, it causes the correlation function to have a zero mean value and eliminates the possibility of numerical overflow in the computations (Bendat and Piersol, 1971). A trial and error method (computing $C(u)$ with various values of i) was used with equation [3] to determine the time displacement number i where the value of $C(ih)$ was maximum. The velocity of grain was then determined from equation [2] using $u_m = ih$.

Procedure

A rotating disk (59 cm diameter) mounted on a milling

machine was used to hold test grain and provide the desired grain velocity for experiments. One layer of test grain at random orientations was glued to the disk surface. The velocity probe was positioned perpendicular to the disk surface at 27 cm from the disk center and was oriented in such a way that the two detection points were aligned in the direction of grain movement. The probe was kept at 0.6 to 1.0 cm from the grain surface. Preliminary tests indicated that the velocity sensor generated the strongest signals or received the best light reflection from the measuring objects when it was 0.8 cm from the objects. The magnitude of signals were acceptable when the sensor was within the range of 0.3 to 1.5 cm from the objects. The desired velocity of grain at the measuring point could be obtained by adjusting the rotating speed of the disk. Corn and wheat were used as test grains. Grain velocities tested were around 2, 6, and 9 m/s.

A digital oscilloscope (Model 2090-III, Nicolet Instrument Corporation, Madison, WI) with flexible disk recording capacity was used to record signals generated by the two PT's in the velocity probe. The oscilloscope recorded 2048 data points from each of the two PT's in each scan. The scanning speeds, h , ranged from 20 to 100 μ s per data point, depending on the velocity of grain tested. The scanning speed was set as fast as possible but at least a distance of 30 cm was scanned during a scan. The recorded data were transferred to a computer and were used for cross-correlation analysis to determine the transit time u_m , which is the time grain kernels travel from the first to the second PT.

Velocities of shelled corn and wheat in a free fall stream from an 11.1 cm diameter orifice were measured inside a 30 cm square spout at distances of 61, 197, and 386 cm below the orifice. At each measuring point, two holes (5 cm diameter) were made on the spout wall to facilitate velocity measurements and observations. The velocity probe was held in such a way that it was perpendicular to the grain stream and the two detection points were aligned in the direction of grain flow. The probe was kept at about 1 cm from the grain stream. Keeping a constant distance between the probe and the grain stream was impossible because the grain stream moved constantly in all directions during the test.

Velocities measured in the grain stream were compared with the theoretical free-fall velocities. Free-fall velocities at each measuring point were calculated based on the initial velocities of 0.60 m/s for corn and 0.81 m/s for wheat at the orifice. These initial velocities were obtained from the known volume flow rate of grain and the area of the orifice. The volume flow rate was determined by timing the flow of 3600 kg of grain through the orifice and assuming the bulk density of grain while passing through the orifice, was equal to its test weight.

Calibration

The light detection point of a PT may not be exactly at the center of the PT. Therefore, the effective distance between the two detection points in the probe must be determined once. A rotating disk (59 cm diameter) with a white stripe marked near the outer edge was used to calibrate the distance between the two PT detection points. The probe to be calibrated was installed to detect

the white mark while the disk was rotating at known speeds. The signals generated from the two PT while the mark passed the probe was recorded with a digital storage oscilloscope and used for cross-correlation analysis to determine the transit time u_m . The distance between two detection points L was calibrated as:

$$L = 2\pi R W u_m \dots\dots\dots [4]$$

where

R = distance between the disk center and the white mark at the position of PT, m.

W = speed of disk rotation, r/s.

The rotation speed of the disk was determined with a photo-detector detecting the white mark. The time required for the white mark to turn one revolution was recorded on an oscilloscope.

The calibrated effective distances between the two detection points were 7.77, 10.06, and 12.46 mm for probes 1, 2, and 3, respectively. These values were used in equation [2] for velocity calculations.

RESULTS AND DISCUSSION

Velocities of corn and wheat on a rotating disk measured by the velocity probe at various control velocities are given in Table 1 and plotted in Figs. 5 and 6. The control velocities were calculated from the known rotating speeds of the disk. Each value in the table and figure is the average of 6 measurements. The solid-line in the figure represents the coincidence of measured and control velocities. The differences between data points and the solid-line indicated the error which ranged from 0.01 to 0.33 m/s or 1 to 4% of the control velocity for probes 1 and 3 and from 0.05 to 0.51 m/s or 1 to 10% of the control velocity for probe 2. The error is less for probes 1 and 3 than for the probe 2.

Velocities of a free-fall grain stream at various distances below the orifice are given in Table 2 and plotted in Figs. 7 and 8. The differences between measured and free-fall velocities ranged from 0.02 to 0.73 m/s or 1 to 10% of the free-fall velocity. The three probes provided about the same accuracy of measurement in free-fall system. In general, the measured velocities of grain in a free-fall stream were less accurate than that of grain on a rotating disk. The velocity of individual grain kernels at a given measuring point may vary. Grain stream velocity obtained by this method is the average velocity of individual kernels detected by the sensor during a scan.

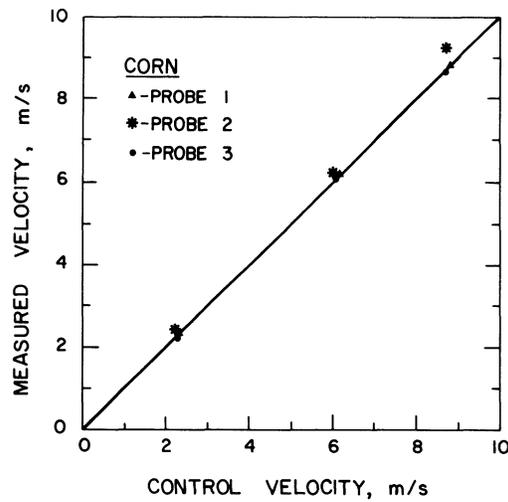


Fig. 5—Comparison of the velocities of corn measured by the probes with control velocities.

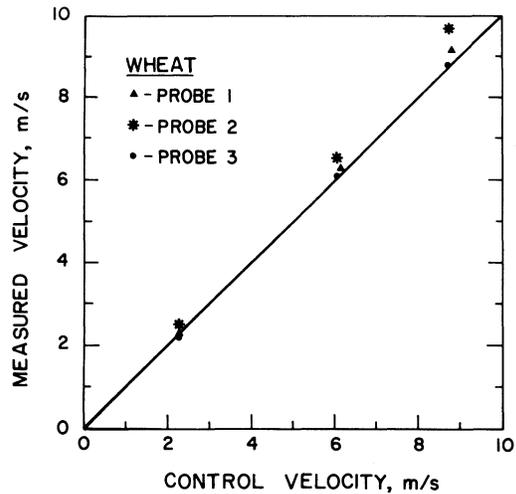


Fig. 6—Comparison of the velocities of wheat measured by the probes with control velocities.

In general, no significant difference in accuracy of velocity measurement was observed among the three probes tested. This implies that within the range of velocity tested, the accuracy of measurement was not affected by the distance between the two detection points in the range of 7.77 to 12.46 mm. Probe 2 consisted of seven LED's which provided about twice the radiant intensity to the grain kernels than did the probes 1 and 3; however, no apparent gain in the accuracy and sensitivity of measurement was observed for the probe 2. This

TABLE 1. VELOCITY OF GRAIN ON A ROTATING DISK

	Control velocity for Probe 1, m/s	Probe 1		Control velocity for Probes 2&3, m/s	Probe 2		Probe 3	
		Measured* velocity, m/s	Deviation, %		Measured* velocity, m/s	Deviation, %	Measured* velocity, m/s	Deviation, %
Corn	2.28	2.29 (0.06)†	1	2.25	2.30 (0.06)	2	2.19 (0.05)	-3
	6.13	6.14 (0.20)	1	6.05	6.11 (0.28)	1	6.06 (0.23)	1
	8.78	8.78 (0.47)	0	8.68	9.19 (0.46)	6	8.62 (0.31)	-1
Wheat	2.28	2.24 (0.03)	-2	2.25	2.42 (0.16)	8	2.19 (0.06)	-1
	6.13	6.22 (0.01)	1	6.05	6.45 (0.46)	7	6.03 (0.12)	-1
	8.78	9.11 (0.17)	4	8.58	9.60 (0.43)	10	8.72 (0.21)	1

*Each value is the average of 6 measurements.
†Standard deviation

TABLE 2. VELOCITY OF FREE-FALL GRAIN STREAM FROM AN ORIFICE

Grain	Distance from orifice, cm	Free-fall velocity, † m/s	Probe 1		Probe 2		Probe 3	
			Measured* velocity, ms	Deviation %	Measured* velocity, m/s	Deviation %	Measured* velocity, m/s	Deviation %
Corn	61	3.51	3.29 (0.27) ‡	-6	3.73 (0.63)	6		
	197	6.24	6.48 (0.24)	4	6.86 (0.54)	10	5.80 (0.45)	-7
	386	8.72	9.45 (0.60)	8	9.15 (0.26)	5	8.61 (0.36)	-1
Wheat	61	3.55	3.51 (0.25)	-1	3.46 (0.20)	-3	3.27 (0.15)	-8
	197	6.27	6.61 (0.62)	5	6.64 (0.34)	6	6.24 (0.50)	-1
	386	8.74	8.34 (0.39)	-5	8.76 (0.43)	1	8.33 (0.51)	5

*Each value is the average of 6 measurements.

†Based on the initial velocities of 0.60 m/s for corn and 0.81 m/s for wheat at the orifice.

‡Standard deviation

indicated that four LED's for each probe or two LED's for each PT provided adequate radiant intensity to the grain kernels for PT to detect.

SUMMARY AND CONCLUSIONS

Three grain velocity probes were designed and constructed and were used to measure the velocities of grain on a rotating disk and in a free-fall grain stream. Each probe consisted of two photo-detectors (PT) at a fixed distance apart and four or seven infrared emitting diodes (LED). The LED's were used to illuminate grain kernels and the PT's to detect the radiant intensity reflected by the kernels. By cross-correlating the signals generated by the two detectors in the velocity probe, the transit time required for the kernels to travel the fixed distance between the detectors was determined. From the values of transit time and the calibrated distance between the detectors, velocities of grain ranging from 2 to 9 m/s, were measured to an accuracy of ±10%. Results indicate that the probes are applicable for grain velocity measurement. Two LED's provided adequate radiant intensity to the grain kernels for each PT to detect. The three tested effective distances (7.77, 10.06, and 12.46 mm) between the two detectors in the probe provided about the same accuracy and sensitivity of velocity measurements.

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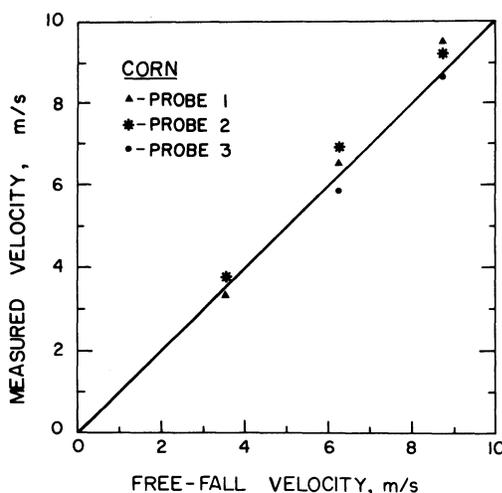


Fig. 7—Comparison of the stream velocities of corn measured by the probes with free-fall velocities.

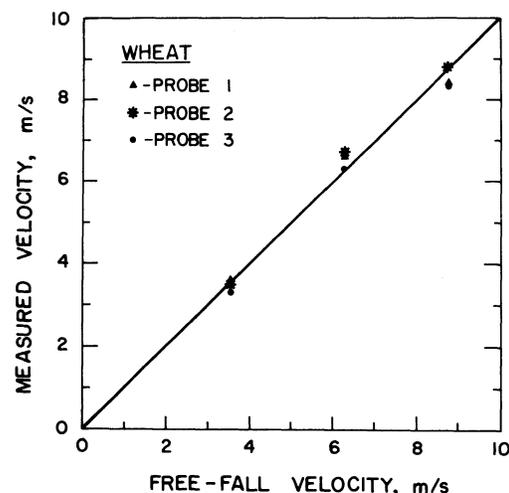


Fig. 8—Comparison of the stream velocities of wheat measured by the probes with free-fall velocities.