INTRODUCTION

The grain combine and its predecessor, the "separator," use straw walkers or racks to separate the free grain from the straw. "The most important factor in good work by the straw rack is the speed." This quotation is from a 'textbook' (1) used by the first students at the Manitoba Agricultural College. Though speed was known to be critical by 1907, only in the past decade has it been established that the grain losses from the walkers limit the capacity of the combine in many crops (4, 5, 6, 7, 8, 9, 10). Reed et al. (9, 10) list additional references with regard to excessive grain losses from the walkers at high feed rates.

Most investigations of the separating process are factorial experiments because of the variability of the straw and grain. Though such experiments are necessary to assess walker performance, an analysis of thresher particles and walker motion may contribute to the technology of this particular crop-tool interface. The feasibility of analyzing the motion is indicated by the casual observation that the motion of the straw appears to repeat for each revolution of the walker crank. The objective of this study, therefore, was to simulate the motion of thresher particles when subjected to the motion of walkers in a grain combine.

MODEL OF PARTICLE MOTION

The casual observations referred to previously failed to reveal that there are two different motions depending on whether the particles contact the walker or not. Rigorous observation of the outside walker, using slow motion photography, yielded results that are illustrated in Figure 1. The particle that contacted the walker during part of the walker cycle had a reversal of motion, whereas the particle that did not had a motion almost sinusoidal. As will be noted later, there is a zone of transition between the two. The separating process may be enhanced by the different motions. Those particles that do not experience a reversal in motion have a mean horizontal velocity that is nearly double that of the particles that do. The effect of the two velocities is the pulling apart or shearing of the straw mat.

Difficulties in simulating the motion of the noncontacting particle required that it be left for some future study. There is evidence, however, that the ratio of the two horizontal velocities is constant; that is, some observations on the conveying rate for both particles can be made if the motion of the contacting particle can be simulated.

In the study of thresher particles which contact the walker the following assumptions were made:
(i) One particle does not interfere with another;
(ii) There is no sliding of the particle when it is in contact with the walker;
(iii) The air is still.

One effect of particle interactions can be seen in Figure 1. The second cycle of the particle that experiences a reversal is flattened due to the motion of the particle(s) that does not contact the walker. The connecting lines in Figure 1 indicate the relative positions of the two particles, and for that time interval, the motions of the two particles are "out-of-phase." Another interference is likely with particles that straddle two walkers. There will be a transition zone between the motion of one walker and the lead or lag motion of the adjacent walker but the zone cannot be readily observed.

With regard to the second assumption, there is little evidence of any sliding if the particle contacts the walker. As for the third assumption, a test was made indicating that the motion is largely insensitive to the air friction. Though these last two assumptions are not valid in a rigorous analysis, their effect is minimal and the simulated particle motion was found to be reasonably close to the actual.

It was evident from visual observations and the slow motion photography that the particles that contact the walker experience two regimes. While in contact with the walker, they are subjected to the displacement, velocity and acceleration of the walker (rotary) and when not in contact, they are subjected to the air friction and the acceleration of gravity (free fall).

For the rotary regime, the displacement is given by the following:

\[ x = r \cos \theta \quad y = r \sin \theta \quad \ldots (1) \]

where

\[ x = \text{vertical displacement}; \]
\[ y = \text{horizontal displacement}; \]
\[ r = \text{crank throw (radius)}; \]
\[ \theta = \text{crank angle (angular displacement) with respect to the horizontal}. \]

\[ x - \omega r \sin \theta \quad y = \omega r \cos \theta \quad \ldots (2) \]

where \( \omega \) is the angular velocity (radians/
Similarly, the derivative of $\dot{x}$ and $\dot{y}$ with respect to time is acceleration of the particle; that is

$$\ddot{x} = -w^2 r \cos \theta$$
$$\ddot{y} = -w^2 r \sin \theta \quad \ldots \quad (3)$$

The transition from the rotary to the free-fall regime occurs when the vertical acceleration of the walker is equal to the acceleration of gravity ($\ddot{y} = -g$). Substituting $-g$ for $\ddot{y}$ in equation (3) and rearranging the terms provides an equation for calculating the crank angle when the transition occurs, which is

$$\theta = \sin^{-1} \left( \frac{g}{w^2 r} \right)$$

For the crank throw of 2 inches (51 mm) and the walker frequency of 194 rpm of Figure 1, the transition from rotary to free fall occurs at a crank angle of 28°. The initial velocities for the free fall regime are defined by equation (2) and would be:

$$\dot{x} = 1.58 \text{ ft/sec} \quad (483 \text{ mm/sec})$$
$$\dot{y} = 2.99 \text{ ft/sec} \quad (912 \text{ mm/sec})$$

The free fall regime is given by Harrison (2), which is

$$\ddot{x} = -k \dot{x} \left( x^2 + y^2 \right)^{1/2}$$
$$\ddot{y} = k y \left( x^2 + y^2 \right)^{1/2} - g \quad \ldots \quad (4)$$

where $k$ is the particle friction.

The transition from the free-fall back to the rotary regime occurs when vertical displacement in the free-fall is equal to the vertical displacement of the walker. The equation required to calculate the crank angle for this transition would have been awkward and was not attempted because its solution was relatively simple using an analogue computer (3).

ANALOGUE SIMULATION

The analogue computer circuit used for the simulation is shown in Figure 2. The computer was equipped with a fixed (sine) diode function generator for $0 - 360°$. The cosine was obtained by using an integrator. The variables in equations (1) to (4) were set with the potentiometers which also scaled the output voltages. A comparator monitored the vertical acceleration and, when it was equal to the acceleration of gravity (negative), the acceleration integrators (V and H, Figure 2) were switched from following equations (3) to integrating for equations (4). The same signal switched comparators so that when the vertical displacement in the free fall equaled the vertical displacement of the walker, the acceleration integrators were switched back.

A track-store amplifier (S, Figure 2) was used to provide for the slope of the walker. The difference between the horizontal displacement of the particle and the walker, when multiplied by the slope, was added to the vertical displacement of the walker (track-mode) before being compared with the vertical displacement of the particle.

It was found to be necessary to extend the store-mode (rotary regime) for a few milliseconds when the transition from rotary to free-fall regime occurred. Because of the complexity of the circuit and the number of potentiometer settings, a calculator with program capabilities was used to determine the potentiometer settings. In order to obtain iterative operation (more than one cycle), the operation of the analogue computer was placed under logic control. With a push button the crank angle was reset to zero without altering the accumulation of the acceleration and the velocity integrators.

RESULTS AND DISCUSSION

A computer solution for particles that contact the walker can be seen in Figure 3. It is evident that the transition from rotary to free-fall regimes occurred near a crank angle of 30° as was calculated previously. The transition back to rotary occurred near 300°. The small loop during the second transition is attributed to the inertia of the plotter and therefore is ignored. The particle friction ($k$) used was 0.5 (equation (4)) which is the particle friction of a straw 4-8 inches (100-200 mm) long (2).

The horizontal displacement of the particle per cycle of the walker is a function of the crank angle when the second transition occurs as illustrated in Figure 4a. These particle motions were obtained using a particle friction ($k$) of zero and 1.0. For the zero particle friction (no air friction), the transition was delayed slightly relative to Figure 3 (less reversal) and for 1.0, it was advanced slightly (more reversal). A particle friction ($k$) of 1.0 is that for a piece of chaff. On the basis that these are extreme values for common threshed particles, it was

In Figures 4-6 and 9-12, the small circles indicate location of the particle when the crank angle of the walker is 360°, 720° etc.
concluded that the particle motion is relatively insensitive to the air friction and that any air movement caused by the walkers will not invalidate the simulation.

Figure 5 (top) is like Figure 3 but with additional walker cycles. It can be compared to the motion of the particle that contacts the walker illustrated in Figure 1. The horizontal displacement of the particle per cycle in Figure 5 (top) is in good agreement with the displacement in Figure 1 even though the particle path is not faithfully reproduced.

Combine manufacturers use a variety of walker slopes but the largest is 0.5. It is evident from Figure 5 (bottom) that increasing the walker slope increases the amount of reversal and reduces the horizontal displacement per cycle, or the conveying rate, but through a small range. This appears to agree with the observation of Reed et al. (10) that with one exception, differences in walker configuration, which include slope variations, do not affect their performance. For a given feed rate the small decrease in the conveying rate, due to an increase in the slope, increases the depth of straw on the walker so little that any reduction in separating efficiency is offset by a greater number of walker cycles or beats. One apparent advantage of a step-type walker is in obtaining steep slopes but, if the observations noted above are valid, it raises a question as to why their use has persisted. Perhaps an analysis of the particle motion "over-the-step" might prove useful.

Increasing the walker frequency from 194 to 215 rpm (Figure 6) increases the horizontal displacement per cycle by eliminating the reversal. The conveying rate is further increased by the ratio of 215:194. Interception of the particle by the walker occurs between 330 and 360° for which there is virtually no horizontal motion of the walker. In this case the particle path is reproduced but the horizontal displacement per cycle differs somewhat from the observed (Figure 7). Reducing the walker frequency to 172 rpm (Figure 6) increases the reversal provided there is no sliding of the particles. If there is any sliding, it will occur at the lower frequency because of the large change in horizontal velocity during the transition from the free-fall to the rotary regimes. This appears to be confirmed when Figure 8 is compared to Figure 6 (bottom). There is the possibility, however, that the particle in Figure 6 (bottom) did not contact the walker but was in the transition zone between those particles that contacted the walker and those that didn't.

Reed et al. (10) reported that they obtained a reduction in the conveying rate when the frequency for a 2-inch (51-mm) throw was reduced from 200 to 150 rpm. According to Figure 9 (top) the rate would indeed be slow because at this frequency the horizontal displacement per cycle is small. Also pertinent is their observation that for a 2-inch (51-mm) throw the frequency for optimum walker efficiency is about 200 rpm. Applying this observation to Figure 5 (top) and 8, this combination of throw and frequency provides either the optimum conveying rate or the optimum reversal of motion or both. The frequency of 194 rpm is specified by two combine manufacturers using a 2-inch (51-mm) throw. Other manufacturers specify 217, 225 and 226 rpm for the same throw.

Reed et al. (10) included a frequency of 250 rpm in their investigations and found little difference in walker efficiency between that frequency and one at 200 rpm. They asserted that "the higher walker speed conveyed the straw much faster and maintained a much thinner layer which assisted in separation." The simulation (Figure 9, bottom) suggests that the horizontal displacement per cycle is somewhat less for a walker frequency of 250 rpm than for 194 rpm; that is, the conveying rate would be increased for an increase in the walker frequency from 194 to 250 but somewhat less than the ratio of 250:194. For those particles that contact the walker, the horizontal displacement per cycle is defined largely by the different initial velocities of the free-fall regime. At 250 rpm (Figure 9, bottom) the transition occurs at a crank angle of 17°. The initial velocities for this frequency are:
Though the initial vertical velocity is larger than at 194 rpm, as noted previously, the horizontal velocity is somewhat smaller.

For a 3-inch (76-mm) crank throw, Reed et al. (10) found the optimum walker frequency to be 150 rpm. This frequency coincides with one manufacturer's specification for a 3-inch (76-mm) throw. Another manufacturer specifies 157 rpm for the same throw. There is a similarity between the simulation for the 3-inch (76-mm) throw and 150 rpm (Figure 10), and the 2-inch (51-mm) throw and 194 rpm (Figure 5) but the horizontal displacement per cycle of the former is only slightly larger than the latter. The conveying rate, therefore, would be less by a ratio that is nearly equal to 150:194. In other words, for equal walker lengths the number of beats would be the same for both combinations of throw and frequency but the depth of material would be different for equal feed rates.

When the frequency for the 3-inch (76-mm) throw was increased from 150 to 170 rpm (Figure 11, bottom), the horizontal displacement per cycle was increased by 30% and because of the ratio 170:150, the increase in the conveying rate would be somewhat higher than this. This increase would diminish the depth of material but would also reduce the number of beats by 30%. This observation appears to correlate with that of Reed et al. (10) who stated that for the 3-inch (76-mm) throw the straw was conveyed out too quickly for walker frequencies greater than normal.

For Figure 12 the walker frequencies were one and one-half times the commonly specified frequencies for the 2- and 3-inch (51- and 76-mm) throws. The particle motions are different and differ substantially from any of those noted previously. The differences result from the particle contacting the walker when the acceleration of the walker is less than the acceleration of gravity \( y < -g \). Depending on the inertia of the particle and the amount of sliding (switching time in the case of the computer), the rotary regime would be brief. The initial velocities of the succeeding free-fall regime would depend on the crank angle during the brief rotary regime and, therefore, would vary widely.

Increasing the walker frequency near the manufacturer's specified values increases the conveying rate by increasing the horizontal displacement per cycle and the number of cycles per unit time.

Increasing the frequencies above the specified values increases the conveying rate but to a lesser extent because the horizontal displacement per cycle may decrease. For example, the horizontal displacement for the 2-inch (51-mm) throw in Figure 12 (300 rpm) is about 75% of that in Figure 6 (194 rpm) with the result that the conveying rate may be increased by only 15%.

SUMMARY AND CONCLUSIONS

An attempt was made to simulate the motion of particles for the straw walker-crop interface of a grain combine. Two different motions were identified depending on whether the particle contacted the walker or not. Only the former was simulated.

The simulation suggests that the relationship between the horizontal displacement per cycle of the walker and the walker frequency is complex for those particles that contact the walker. In general it increases and then decreases with frequency. Because the conveying rate is a function of the displacement and the frequency, the rate will not increase indefinitely. At some frequency, greater than that specified by any manufacturer, the conveying rate and number of beats may equal that at the specified frequencies but with greater agitation.

REFERENCES


