

# KERNEL REBOUND TRAJECTORIES IN A COMBINE SHOE USING ANALOGUE SIMULATION

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## INTRODUCTION

The Saskatchewan Agricultural Machinery Administration in its test work with combines (1) noted difficulty in obtaining a clean sample with no grain loss. With the Gleaner "C" combine, for example, "a setting of the chaffer greater than the optimum resulted in poor separation while one smaller caused excessive loss". With respect to the Massey-Ferguson Super 92 the minimum loss in wheat occurred with a fan speed of 587 rpm and a chaffer opening of 5/8 in. (measured perpendicularly from lip to lip). The loss was approximately double when the chaffer opening was increased or decreased by 1/4 of an inch from the 5/8" opening.

Bilanski and Lal (2) found that the terminal velocity of wheat is in the order of 30 ft. per second. The maximum terminal velocity for threshed particles, other than the kernel, was found to be 16 ft. per second thus indicating no particular difficulty with pneumatic separation. Field observations suggest that the terminal velocities of material to be pneumatically separated from wheat kernels are more likely to range up to a maximum of 10 ft. per second rather than 16. It is apparent, again from field observations, that the difficulty with pneumatic separation is the result of kernels rebounding on the chaffer with sufficient amplitude and number to result in their loss. It is the purpose of this study to ascertain the rebound trajectories and the mechanical parameters of air velocity and the chaffer openings which influence them. For reasons noted below, an analytical approach was adopted.

## PRELIMINARY INVESTIGATION

Slow motion pictures of the kernel rebound were taken while varying

the chaffer opening, air velocity; and oscillation frequency of the shoe. The result of this work suggested the following:

1. The majority of the kernels rebound from the initial and subsequent interceptions with the chaffer. The percentage passing through was equivalent to the chaffer free area which is in the order of 10-15%.
2. The average rebound trajectory is sensitive to the air velocity and chaffer opening and appeared to be independent of the chaffer oscillation.
3. It is virtually impossible, due to the randomness of the rebound particle velocity, to estimate the average rebound trajectories beyond the initial.

## ANALOGUE SIMULATION

In view of the above, and due to the nature of the problem, analytical, rather than experimental, results were obtained. Differential equations were developed following a procedure sug-

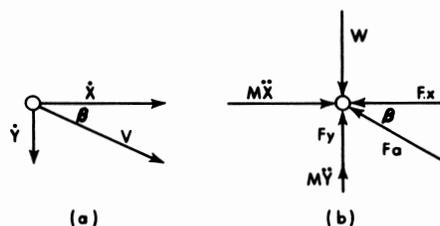


Figure 1. Velocity and Force Vectors

gested by Reints and Yoerger (3) and subsequently were solved with an analog computer. Since it was necessary to develop the model in a slightly different form than that of the authors above, the derivation is outlined below:

From Figure 1a

$$\cos \beta = \dot{x}/V \text{ and } \sin \beta = \dot{y}/V$$

where  $\dot{x} = dx/dt =$  horizontal particle velocity,  
 $\dot{y} = dy/dt =$  vertical particle velocity,  
 $V = (\dot{x}^2 + \dot{y}^2)^{1/2} =$  particle velocity.  
 $\dot{x}$ ,  $\dot{y}$  and  $V$  are with respect to the medium (air).

From Figure 1b

$$F_x = F_d \cos \beta = F_d \dot{x}/V \text{ and}$$

$$F_y = F_d \sin \beta = F_d \dot{y}/V$$

where  $F_d$  is the fluid drag (4) and is equal to:

$$C_d w a \frac{V^2}{2g}$$

where  $C_d =$  drag coefficient,  
 $w =$  density of the fluid (lbs./ft<sup>3</sup>),  
 $a =$  frontal area of the particle (ft<sup>2</sup>),  
 $g =$  acceleration of gravity (32.2 ft./sec<sup>2</sup>).

From Newton's second law,  $\Sigma F = ma$  (5)

$$\text{or } \Sigma F_x = m\ddot{x} \text{ and } \Sigma F_y = m\ddot{y}$$

for planes at 90° to each other where  $\ddot{x} = d^2x/dt^2 =$  horizontal particle acceleration,

$$\ddot{y} = d^2y/dt^2 = \text{vertical particle acceleration,}$$

and  $m =$  mass of the particle  
 $= W/g$  where  $W =$  weight of the particle (lbs.).

Considering dynamic equilibrium in Figure 1b,

$$\Sigma F_x - (m\ddot{x}) = 0$$

$$-F_x - m\ddot{x} = 0$$

or  $\ddot{x} = -F_x/m$  and substituting  
in for  $m$  and  $F_x$

$$\ddot{x} = -gF_{c0}x/VW$$

and substituting for  $F_d$ ,

$$\ddot{x} = -C_d w a \dot{x} V / 2W = -K \dot{x} V$$

$$= -K \dot{x} (\dot{x}^2 + \dot{y}^2)^{1/2} \dots\dots\dots 1$$

where  $K = C_d w a / 2W$  and is referred to as the "particle friction".

Similarly in the vertical plane:

$$\ddot{y} = K \dot{y} V - g = K \dot{y} (\dot{x}^2 + \dot{y}^2)^{1/2} - g \dots\dots\dots 2$$

The sign for term  $K \dot{x} V$  and  $K \dot{y} V$  depends on the sign convention adopted and the direction of the particle.

In a free fall where  $\dot{x}$  and  $\ddot{x} = 0$  and after a period of time when  $\dot{y} = 0$ ,  $\dot{y}$  is constant and is equal to the terminal velocity,  $V_t$ . Equation 2 then becomes:

$$0 = K V_t^2 - g$$

$$\text{or } K = g/V_t^2$$

Bilanski and Lal defined a similar term to the particle friction and called it resistance coefficient,  $k$  where  $k = W/V_t^2$ .

The analog flow diagram is shown in Figure 2. Multipliers were used to generate values of  $\dot{x}^2$  and  $\dot{y}^2$ . Fixed diode function generators could be used instead, provided opposite directions of velocity (signs) do not occur.

Values of  $K$  (or  $k_d$ ) were introduced in the upper and lower loops so that the second set of multipliers could operate at a reasonable percentage of their maximum voltage.

Rumble and Lee (6) in their analog solution assumed  $C_d$  to be constant. For spherical bodies,  $C_d$  is essentially constant (4) for Reynolds numbers of 1000-20,000.

The Reynolds number,  $N_R$  for a wheat kernel at its terminal velocity is:

$$N_R = V l / \nu \text{ where } V = V_t \text{ (28.4 ft/sec)}$$

$l$  = particle dimension ( $1.60 \times 10^{-2}$  ft),

$\nu$  = kinematic viscosity ( $1.6 \times 10^{-4}$  ft<sup>2</sup>/sec) or

$$= 28.4 \times 1.6 \times 10^2 / 1.6 = 2.84 \times 10^3.$$

The  $N_R$  for straw and chaff at their respective terminal velocities would be larger and, therefore, the assumption that  $C_d$  is constant is reasonable. For rebounding kernels, however,  $V$  may approach zero at times and, therefore, the following was considered.

A graph of  $C_d$  versus  $N_R$  was plotted using rectangular coordinates (see Figure 3) where  $C_d$  is for a

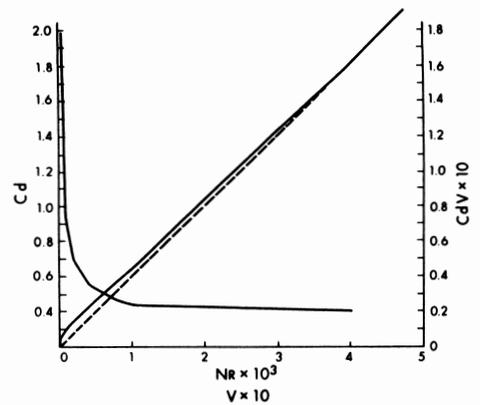


Figure 3. Relationship between  $C_d$ ,  $N_R$ ,  $C_d v$  and  $V$  for wheat

sphere. For a particular particle in a particular medium it represents the relationship between  $C_d$  and  $V$ . For the specific wheat kernel ( $V = 28.4$ /sec),

$$V = N_R \nu / l = 1.6 N_R \times 10^{-2} / 1.6 = N_R \times 10^{-2}$$

From this, a graph of  $C_d V$  versus  $V$  was plotted (also shown in Figure 3). An arbitrary diode function generator was set up to provide the values of  $C_d V$  for values of  $V$  expected. In the upper and lower loops of the program a term  $k_d$  was introduced where

$$K = k_d C_d \text{ from } K \dot{x} V =$$

$$k_d C_d \dot{x} V,$$

$$\text{and } K \dot{y} V = k_d C_d \dot{y} V$$

or  $k_d = K/C_d$  where  $C_d = .41$  for spheres at  $N_R = 2.84 \times 10^3$  or  $k_d = .040/.41 = .096$  for wheat kernels of  $V_t = 28.4$  ft/sec.

### CONDITIONS FOR PNEUMATIC SEPARATION

Location and dimensions of the chaffer, fan, etc., were determined for the larger models of three leading manufacturers of combines. The various physical arrangements may be noted in figures 4a, b, and c. From this, and prior considerations, the following was assumed for pneumatic separation:

1. The particles were released 3" above the leading edge of the chaffer without any initial velocity.

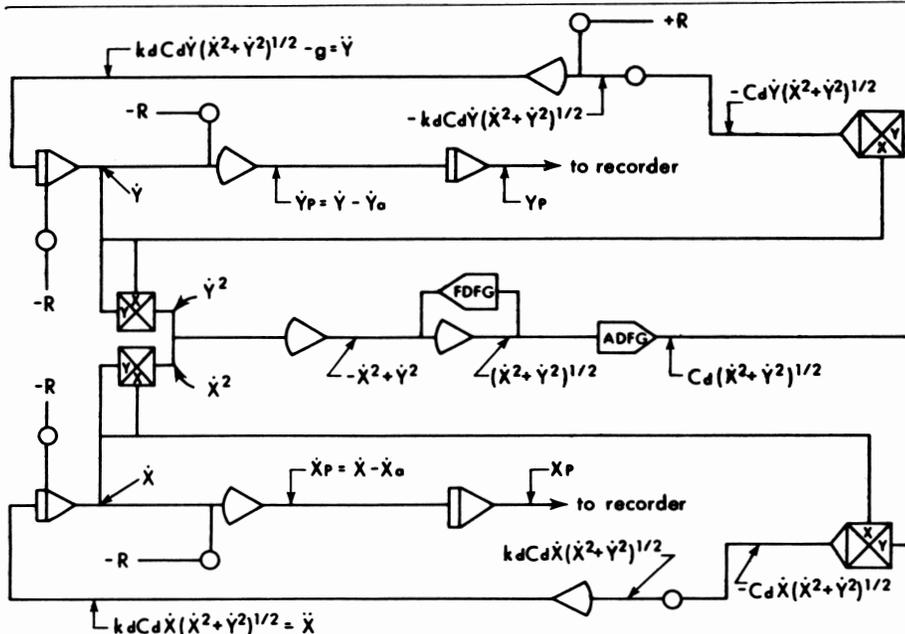


Figure 2. Analog Flow Diagram

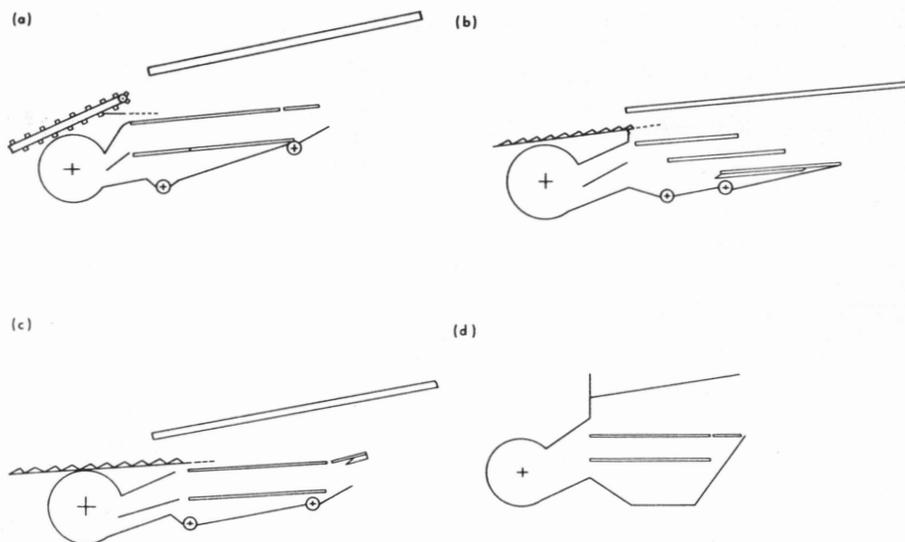


Figure 4. Schematic of combine shoes: (a) J.D. 95, (b) M.F. 410, (c) I.H.C. 403, (d) shoe made up of composite dimensions

2. The length of the chaffer was 3 ft.
3. The pneumatically separated particles were to clear the rear edge of the chaffer without touching it.
4. The critical particle for separation had a terminal velocity of 10.5' / sec. ( $K = .300/\text{ft}$ ).
5. The terminal velocity for the wheat kernel was 28.4 ft/sec ( $K = .040/\text{ft}$ ).
6. There was no particle interaction.
7. The air velocity for the first 6 inches of the plenum was double that for the remaining.

The basis for the last condition was obtained by making up a shoe of composite dimensions (Figure 4d) and measuring the air velocity for various chaffer openings. The results of this investigation are shown in Figure 5. With the use of an oscillograph, the particle velocity was determined at the point of transition from higher to lower velocity regimes. Using equations 3 and 4 as listed below, new velocities of the particles with respect to the medium were calculated ( $\dot{x}'$  and  $\dot{y}'$ ) and the analog solution reinitiated at this point.

$$\dot{x}' = \dot{x}_p - \dot{x}_a/2 \dots\dots\dots 3$$

$$\dot{y}' = \dot{y}_p - \dot{y}_a/2 \dots\dots\dots 4$$

where  $\dot{x}_p$  and  $\dot{y}_p$  are the particle

velocities and  $\dot{x}_a$  and  $\dot{y}_a$  are the initial air velocities.

The procedure to determine the required air velocity was to arbitrarily select values of  $\dot{x}_a$  in increments of 5 ft. per second and, by trial and error, determine a value of  $\dot{y}_a$  (and  $\dot{y}_a/2$ ) which would satisfy con-

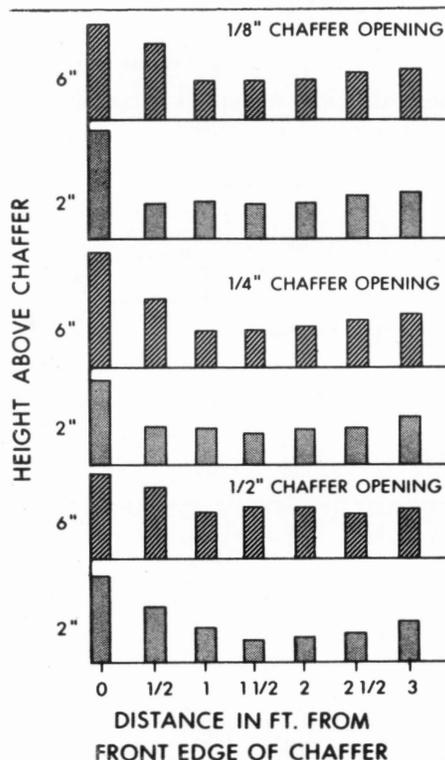


Figure 5. Relative air velocities in combine plenum

ditions 3 and 4 above. Reproductions of the resulting trajectory plots, identified as the critical particle, are shown in Figure 8 for each of four values of  $\phi$ .  $\phi$  is the angle between the velocity vector and the horizontal plane.

### CONDITIONS FOR KERNEL REBOUND

Dimensions of the adjustable lip of the chaffer (1") were obtained and from these the angle of the vanes for different chaffer openings was calculated. These may be noted in Figure 6. For the rebound trajectories, the following conditions were selected:

1. A coefficient of restitution of 1/2 was taken as representative. The value was arrived at by observing the amplitude of rebound for free-falling kernels.
2. The inclined surface of the chaffer vanes was flat.
3. The kernel behaved as a sphere during the period of deformation and restitution.
4. The air velocity was not affected by adjustment of the chaffer.

These assumptions, particularly number 3, preclude the possibility of determining an absolute quantity of grain that would be lost. On the other hand, if the spherical shape was not assumed then an infinite variety of trajectories would occur obscuring the average trajectory and how it is influenced by air velocity and chaffer openings. This was the problem that was noted with the slow motion pictures.

The procedure to determine the

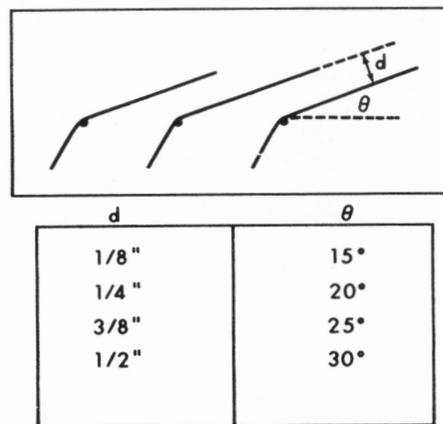


Figure 6. Chaffer openings at various vane angles

rebound trajectories was to find (with the aid of an oscillograph) the particle velocity at the time of its interception with the chaffer surface. Using equations 5 and 6 below, the rebound particle velocities were calculated. New values of  $x'$  and  $y'$  were calculated using equations 3 and 4. In all cases the rebound occurred in the lower air regime of the plenum. The analog solution was reinitiated at this point with new values and allowed to proceed until the kernel intercepted the chaffer surface again.

$$\begin{aligned} \dot{x}'_p &= (\dot{x}_p \cos 2\theta - \dot{y}_p \sin 2\theta)/2 \dots\dots\dots 5 \\ \dot{y}'_p &= (\dot{x}_p \sin 2\theta + \dot{y}_p \cos 2\theta)/2 \dots\dots\dots 6 \end{aligned}$$

### RESULTS

Four air velocities were determined. Because one or the other dimension of the vector is fixed by conditions for pneumatic separation, (critical particle does not make contact with the chaffer) the air velocity may be referred to by its direction ( $\phi$ ) only. As Figure 9 suggests, there are an infinite number of velocities with  $\phi$  ranging from zero to  $90^\circ$  which would satisfy the separation requirements. It is obvious at  $90^\circ$  that the magnitude of the velocity must be equal to the terminal velocity. As can be seen in Figure 8, Parts a, there is little to distinguish between the trajectories of the critical particle (K = .300/ft) for the dif-

ferent values of  $\phi$ . On the other hand, the trajectory of the kernel (K = .040/ft) is altered. The horizontal displacement from release to initial interception with the chaffer is inversely related to  $\phi$ .

The rebound trajectories are also sensitive to changes in the air velocity. In fact, because of the small range of  $\phi$  ( $3\ 1/2$  to  $9\ 1/2^\circ$ ), the rebound trajectories are very sensitive to  $\phi$ . In addition, it is quite evident in Figure 8, when  $\phi = 4\ 3/4^\circ$  and  $\theta = 15^\circ$ , that a large grain loss would occur. Considering the randomness of a rebound trajectory of an ellipsoid shaped kernel, significant losses would occur when  $\theta$  is  $20^\circ$  and even when it is  $25^\circ$ .

In adjusting the combine shoe, the operator can adjust the magnitude of the velocity and the chaffer opening, but can do little with regard to the direction of the air flow  $\phi$ . The latter is largely defined by the shape of the

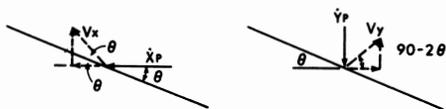


Figure 7. Kernel intercept and rebound velocities

Equations 5 and 6 were derived from observation of Figure 7 and considering condition 1 above. They are:

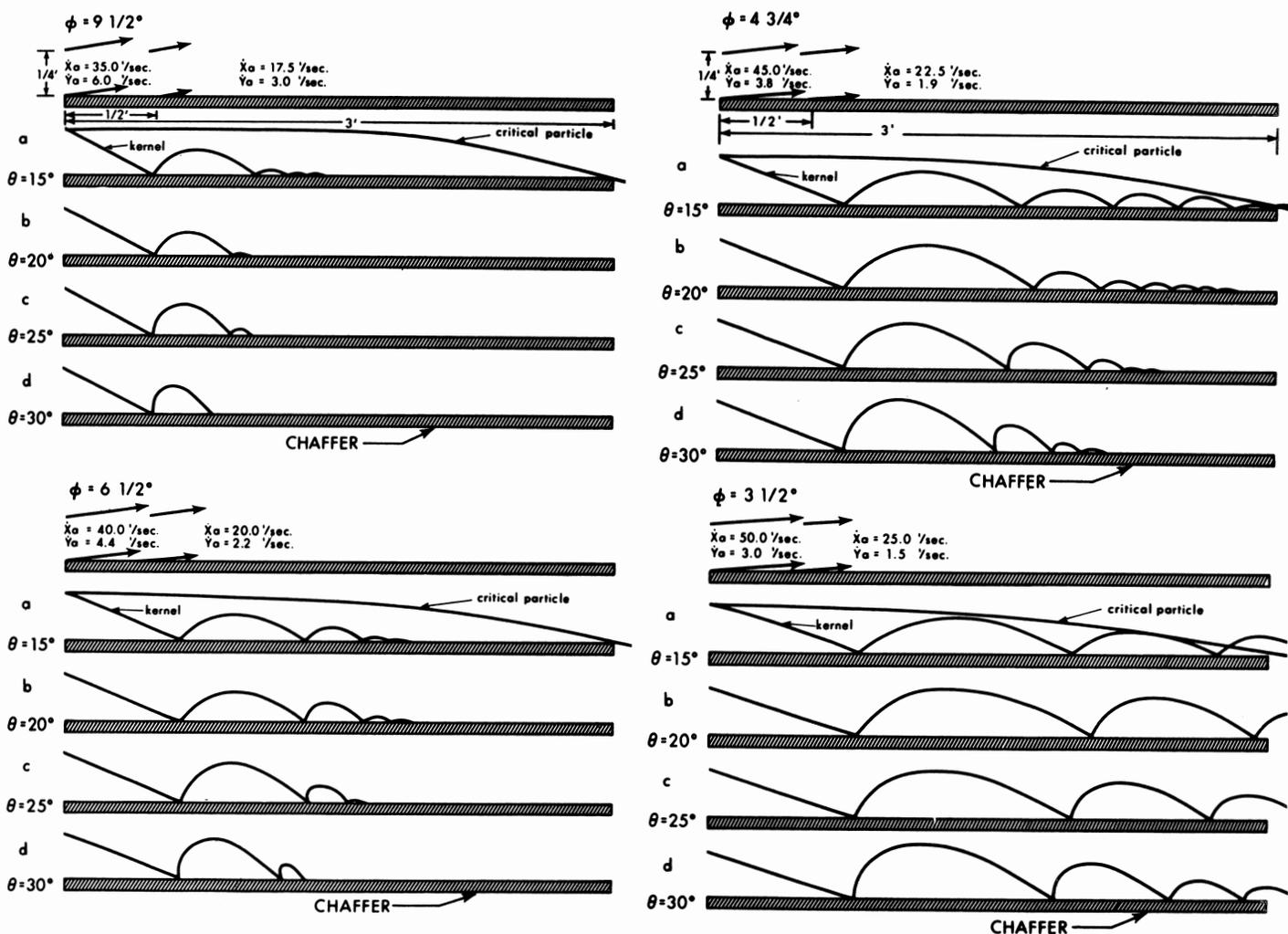
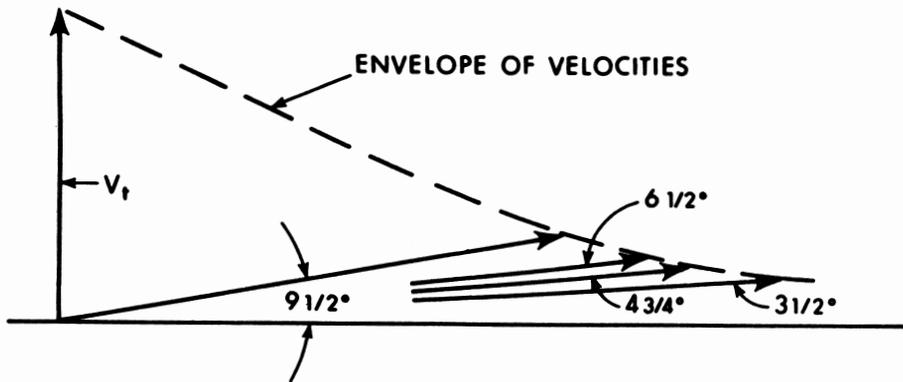


Figure 8. Critical particle and kernel rebound trajectories.



$\phi$ (degs)	V (ft/sec)	
	FRONT OF PLENUM	REAR OF PLENUM
3 1/2	50.1	25.0
4 3/4	45.2	22.6
6 1/2	40.4	20.2
9 1/2	35.5	17.8

Figure 9. Air velocities for pneumatic separation of critical particle.

plenum (space above the chaffer) and in turn by the slope of the trough of the walkers or the return pan under the walkers. Some control may be effected on those combines which provide for different chaffer locations. If the value of  $\phi$  is less than  $5^\circ$  (Figure 8) the operator may reduce loss by reducing the magnitude of the air velocity and use a wide-open chaffer. The compromise may not be ideal in terms of clean sample, but it may keep grain loss from being excessive.

### CONCLUSIONS

The kernel rebound trajectories are very sensitive to the direction of the air flow. Increasing the vertical component of the velocity (or  $\phi$ ) would allow a reduction in the horizontal component and still satisfy separation requirements of the critical particle. This would reduce the magnitude and number of kernel rebound trajectories which in turn would decrease the grain loss.

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