GRAIN-STRAW SEPARATION IN A CENTRIFUGAL FORCE FIELD

DISSERTATION

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the Degree Doctor of Philosophy in the Graduate
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By

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* * * * *

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INTRODUCTION

The separation of grains from straw is an important process in the over-all harvesting operation. In the combine harvester, separation is performed by means of a straw rack. Most large combines use walker type straw racks. A straw rack has three or more narrow sections placed side by side on a multiple throw crank. After the straw comes out of the threshing unit, it is agitated due to the oscillatory motion of the straw rack. This agitation of the straw causes the grains to separate and move downward due to the force of gravity. The straw, however, is retained on the rack and moves step by step due to oscillatory motion and exits at the rear of the combine. The straw rack makes the combine quite bulky (11)*.

The grain separation efficiency of the straw rack, under typical harvesting conditions, is in the vicinity of 99 percent (23). However, the separation efficiency is very severely affected by many factors like material flow rate, slope of the rack, m.o.g.†/grain ratio, etc. (6, 11, 18, 19, 22, 23). The fact that under certain conditions, rack loss may be as high as 85 percent of the total machine losses, limits the

* Numbers in parentheses refer to appended references.
† Material Other than Grain.
capacity of many combines (18). Expensive, self-leveling hillside combines have been developed to minimize the rack loss due to field slopes (9, 19).

As a matter of fact, a major part of the grains is separated in the threshing unit through the concave. It has been found that 62 to 72 percent separation occurs through the concave (4, 10, 21), whereas, under certain conditions, it could be as high as 92 percent (6).

Several researchers have tried to achieve low-impact threshing by means of centrifugal force (2, 3, 7, 8, 12, 13, 14, 15). The angular speed at which the crop has to be rotated so that it may be subjected to the required level of centrifugal acceleration, posed some problems of mechanical nature and kept the idea of centrifugal threshing from being a reality (7, 8). Forces used in the straw rack are mainly inertia and gravity. Efforts, with limited success, have been made toward utilizing aerodynamic force to separate grain from straw (1, 25).

It has been found that the centrifugal acceleration required to separate grains from straw is not as high as that required for centrifugal threshing (16, 17). Therefore, a centrifugal grain-straw separator would not face the problems of dynamic imbalance, which was the main limiting factor in centrifugal threshing.

The over-all performance of a separation unit depends upon its ability to separate grains from straw, insensitivity to variations in crop conditions and power requirements. It is possible that if centrifugal force is used to separate grains from straw, the resulting separation may have a better over-all efficiency.
OBJECTIVES OF THE RESEARCH

In the introduction, the need for a grain-straw separator which would be independent of gravity and more compact than straw rack, has been argued. The objectives of this research were to investigate a continuous flow centrifugal separator which can be used to replace the straw rack and would be used in conjunction with the conventional drum and concave type thresher. The primary objectives of this research, therefore, were to obtain prediction information about the performance of a centrifugal separator by:

(1) Developing equations of motion of a particle within an assumed shape of rotor.

(2) Experimentally studying the effects of various pertinent parameter on the performance of the centrifugal separator.

(3) Developing equations for predicting the separation efficiency using experimental data.
REVIEW OF THE LITERATURE

Lamp (14, 15), in an attempt to investigate the possibility of achieving low impact threshing by centrifugal force and to combine threshing and separation into one operation, found that a centrifugal force of 0.3 lb. was sufficient to thresh 98 percent or more of the mature wheat independent of the method of holding. A force of 0.20 lb. was sufficient to thresh 98 percent of grains under all typical harvesting conditions. He also found that if a force was applied such that it bent the rachilla, it would result in 50 percent reduction in the threshing force. Lamp recommended a continuous-flow machine in the shape of an inverted frustum of a right cone which was to impart to unthreshed grains a force equal to that determined experimentally.

Buchanan (2, 3) used a continuous flow, conical, centrifugal thresher. The outer cone, which was made out of sheet metal, perforated with \( \frac{1}{2} \)-inch diameter holes, had an entrance diameter of 12 inches, cone angle of 60 degrees and was 21 inches long. The inner cone had three equally spaced rubber paddles and was spaced so that there was a 3-inch clearance between the two cones. Both cones rotated in the same direction with inner cone slower. The unthreshed crop was fed into the apex end of the outer cone. A combination of centrifugal force caused by rotation and a rubbing force caused by a difference in speed resulted in threshing and separation of kernels from straw.
Buchanan (2, 3) studied the cone performance as a separation unit only. He determined that the inner cone speed ratio was the most significant factor contributing to loss. Buchanan speculated that inner cone speed ratios of 90 to 95 percent would result in higher separation efficiency.

Lalor (12, 13) designed and tested a threshing machine which consisted of a truncated stationary outer cone made of perforated sheet metal. A rotor was fitted within the stationary cone and the clearance between the rotor and the stationary cone was approximately ⅛-inch. The rotor consisted of eight rubber covered angle bars. The material to be threshed entered the annular space between the rotor and the outer cone at the apical end of the threshing machine. The component of centrifugal force acting parallel to the cone surface moved the material toward its large end. During this process, threshing and separation occurred. Threshing was mainly caused by rubbing action whereas centrifugal force was a major factor in separation. Lalor determined that the over-all separation efficiency decreased from 77 to 68 percent, as the rotor speed was increased from 300 to 500 r.p.m. He studied the necessary cone length, slot length, and slot orientation.

Hamdy (7, 8) theoretically analyzed a horizontal conical rotor and a vertical generalized rotor by developing equations of motion and forces imparted to a particle within these threshers. The equations were solved on an analog computer to study the threshing performance as a function of system parameters. He determined that some vertical generalized rotors were theoretically capable of subjecting particles sliding inside them to centrifugal accelerations of the same order as that
necessary to thresh wheat under typical harvesting conditions. The results are subject to the limitations of neglecting air drag on the particle, assuming a constant coefficient of friction and surface resistance, and neglecting the interaction between the particles.

Long (16, 17), in an attempt to characterize centrifugal separation, determined that centrifugal accelerations as high as 35 g's may be justified. He developed a model for resistive force experienced by kernel moving through a straw mat. The resistive force was found to be proportional to the centrifugal accelerations and kernel relative velocity to straw. He determined that separation time increased by decreasing the straw length from 7 inches to 4 inches. However, increasing the straw length to 10 inches did not make any significant difference to the separation time.

Turnquist (24) studied the screen effect on the separation of granular particles in a vibratory screening system. He developed a dimensionless homogeneous prediction equation predicting the passage of one size class of undersize particles through a square aperture wire screen. He noted an insignificant change in response due to change in Reynolds number. Froude number had very significant effect on the response. High Froude number, corresponding to high relative motion between the particles and the screen, caused a decline in response.
CHAPTER I
THEORETICAL ANALYSIS

(i) Particle Motion Inside a Horizontal, Conical Screen.

(a) Theory:

In order to achieve separation of grains from straw in a rotor, the crop should be subjected to the correct level of centrifugal acceleration, should have appropriate motion relative to the screen, and should be retained within the rotor for enough time to cause separation. A horizontal frustum of a right cone, made of perforated sheet metal, rotating about its axis was analyzed. The rotor had radial, helical blades mounted on the inside of its wall as shown in Figure 1. These helical blades would impart both tangential and axial acceleration to the particle.

Hamdy (7) did not propose to use any blades because they might impart damaging impact to the kernels at the speeds required to produce enough centrifugal acceleration to cause threshing. Long (16) discovered that for centrifugal separation, lower centrifugal acceleration was required; 35 g's compared to 2400 g's for centrifugal threshing. It was realized that since the angular velocity would be much slower in the case of separation, the impact force of blades on grains would be less damaging.

The following are the assumptions made in developing equations of
Figure 1. A horizontal conical screen.
crop motion within the rotor:

(1) The crop was assumed to be a collection of disconnected particles. After neglecting the interaction between the particles the motion of the crop was represented by the motion of a single particle.

(2) The resistance of screen to the crop motion was assumed to be a combination of friction and mechanical interference. The friction force was taken proportional to the normal reaction. The constant of proportionality being the coefficient of dynamic friction. The total resistance was assumed by taking a constant of proportionality higher than the coefficient of dynamic friction.

(3) The friction force between blade and particle was related to the normal force between them by the coefficient of dynamic friction.

(4) The crop particle was at all times in contact with the rotating screen and slid along the helical blades.

(5) In order to study the performance of the separation as a function of rotor configuration parameters, effects of air movement on the motion of the crop was neglected. It was hypothesized that if the separator did not work when the air movement was neglected, it would not work after including the air movement.

In view of these assumptions, the crop motion was analyzed as if it were a particle sliding inside a smooth rotor (no surface irregularities). The coefficient of surface resistance was taken to be constant and the entire system was assumed in vacuum.

The basic inertial reference frame used in the analysis was the xyz system shown in Figure 2. The more convenient \(\rho \theta y\) cylindrical coordinates were used to describe the particle motion. The cone was located
Figure 2. Coordinate diagram for the horizontal, central rotor.
so that its apex was at the origin and the cone axis coincided with the y-axis of the coordinate system. The symbols used in the analysis are explained in the following list:

- $d$: Cone entrance diameter (ft.)
- $F$: Resistive force on kernel (lb$_f$)
- $g$: Acceleration due to gravity (ft. per sec.$^2$)
- $m$: Mass of kernel (lb$_m$)
- $m_s$: Mass of straw particle (lb$_m$)
- $N$: Normal force exerted by the blade to the particle (lb$_f$)
- $r$: Kernel radius vector (ft.)
- $R$: Normal reaction of cone wall (lb$_f$)

$V_p$/Rotor: Velocity of particle relative to rotor (ft. per sec.)

- $y$: Axial displacement (ft.)
- $\alpha$: Cone half angle (rad.)
- $\beta$: Blade angle (rad.)
- $\omega$: Cone angular speed (rad. per sec.)
- $\mu$: Coefficient of resistive force due to screen
- $\mu_1$: Coefficient of blade friction
- $\rho$: Radial displacement (ft.)
- $\theta$: Angular displacement (rad.)
- $\delta$: Screen-to-kernel distance (ft.)
- $\cdot$: First derivative with respect to time
- $\cdot\cdot$: Second derivative with respect to time

The equations of motion were derived by using Newton's laws of motion. The summation of external forces acting on the particle in $\rho$, $\theta$, and $y$ directions were given by the following expressions:
\( \Sigma F_\rho = \left[ N \sin \beta - (\mu R + \mu_1 N) \cos \beta \right] - R \cos \alpha + m_s \cos \theta \) \hspace{1cm} (1)

\( \Sigma F_\theta = N \cos \beta + (\mu R + \mu_1 N) \sin \beta - m_s \ g \ \sin \theta \) \hspace{1cm} (2)

\( \Sigma F_y = R \sin \alpha + \left[ N \sin \beta - (\mu R + \mu_1 N) \cos \beta \right] \cos \alpha \) \hspace{1cm} (3)

Whereas \( \Sigma F_\rho \), \( \Sigma F_\theta \), and \( \Sigma F_y \) were the summation of forces in \( \rho \), \( \theta \), and \( y \) direction, respectively. Using Newton's second law of motion the following expressions were obtained:

\( m_s \ (\dot{\rho} - \rho \ \ddot{\theta}) = \Sigma F_\rho \) \hspace{1cm} (4)

\( \frac{d}{dt} (m_s \ \rho \ \dot{\theta}) = \rho \ \cdot \ \Sigma F_\theta \) \hspace{1cm} (5)

\( \frac{d^2}{dt^2} (m_s \ y) = \Sigma F_y \) \hspace{1cm} (6)

By substituting (1), (2), and (3) into (4), (5), and (6) the following equations of motion were obtained:

\( m_s \ (\dot{\rho} - \rho \ \ddot{\theta}) = \left[ N \sin \beta - (\mu R + \mu_1 N) \cos \beta \right] - R \cos \alpha + m_s \ g \ \cos \theta \) \hspace{1cm} (7)

\( \frac{d}{dt} (m_s \ \rho \ \dot{\theta}) = \left[ N \cos \beta + (\mu R + \mu_1 N) \sin \beta - m_s \ g \ \sin \theta \right] \ \cdot \ \rho \) \hspace{1cm} (8)

\( \frac{d^2}{dt^2} (m_s \ y) = R \sin \alpha + \left[ N \sin \beta - (\mu R + \mu_1 N) \cos \beta \right] \cos \alpha \) \hspace{1cm} (9)

It was realized that the friction force acting on the particle was opposite to the velocity of the particle relative to the rotor at their point of contact. Figure 2 shows the velocity diagram in the tangential plane to the rotor at the point of contact.

From Figure 2,
\[
\tan \beta = \frac{\rho(\omega - \vec{\theta})}{\rho / \sin \alpha} \quad \cdots \cdots \quad (10)
\]

Based on the assumption that the particle was at all times in contact with the cone surface, the following relations were obtained:

\[
\rho = y \tan \alpha \quad \cdots \cdots \quad (11)
\]

\[
\vec{\rho} = \vec{y} \tan \alpha \quad \cdots \cdots \quad (12)
\]

\[
\vec{\rho} = \vec{\gamma} \tan \alpha \quad \cdots \cdots \quad (13)
\]

Substituting (11), (12), and (13) in (10) resulted in,

\[
\vec{\rho} + \rho \vec{\theta} = \rho(\omega + \vec{\theta}) - \frac{\vec{y} \tan \beta}{\cos \alpha} \quad \cdots \cdots \quad (14)
\]

By rearranging (8) and substituting (14), the following equation was obtained:

\[
m_b \vec{y} = \left[ m_0 \vec{\omega} + \mu N \sin \beta + m_s g \cos \beta \right] \cot \beta \cos \alpha \quad \cdots \cdots \quad (15)
\]

By eliminating \( \vec{y} \) from (9) and (15), \( N \) was explicitly obtained as:

\[
N = m_b (\omega + \vec{\theta}) \cos \beta - R \tan \alpha \sin \beta + m_s g \sin \theta \cos \beta \quad \cdots \cdots \quad (16)
\]

By substituting (11), (12), and (13) in (9), rearranging, and using (7) to eliminate \( \rho \), \( R \) was expressed as follows:

\[
R = m_s (\vec{\rho}^2 + m_s g \cos \theta) \cos \alpha \quad \cdots \cdots \quad (17)
\]

The two simultaneous equations characterizing the motion of the straw particle can be written in the following form:
Figure 3. Velocity diagram in tangent plane.

Figure 4. Coordinate diagram transverse plane.
\[ \ddot{y} = \frac{R}{m_s} (\sin \alpha - \mu \cos \beta \cos \alpha) + \frac{N}{m_s} (\sin \beta - \mu_1 \cos \beta) \cos \alpha \ldots (18) \]

\[ \ddot{\theta} = \omega - \frac{\dot{y}}{y} \tan \beta \div \sin \alpha \ldots \ldots (19) \]

where,

\[ \frac{R}{m_s} = y \dot{\theta}^2 \sin \alpha + g \cos \theta \cos \alpha \ldots \ldots (20) \]

\[ \frac{R}{m_s} = y (\omega + \ddot{\theta}) \cos \beta \tan \alpha - \frac{R}{m_s} \tan \alpha \sin \beta + g \sin \theta \cos \beta \ldots \ldots (21) \]

Equations (18) through (21) characterize the motion of straw particle. To analyze separation of kernels from straw, it was necessary to develop equations which characterized the motion of kernel through straw mat within such a rotor. It was realized that, when a kernel moved, it experienced a resistive force offered by the straw mat. It was assumed that the resistive force model developed by Long (16, 17) approximated the force resisting the kernel motion while it moved through the straw under the influence of the centrifugal force. The resistive force model was given by:

\[ F = m(k_1 \dot{\theta}^2 \sec \psi + k_2 \psi^n) \ldots \ldots (22) \]

Whereas, \( k_1 \) and \( k_2 \) are constants and \( n \) is an integer, \( \psi \) is the angle between radius vector, \( r \) and resistive force, \( F \). Based on observations made by Long of the drop of angular displacement of kernel while moving radially through a medium of straw, \( \psi \) was taken as zero. In absence of any substantial difference of forces acting on kernels from those acting on straw in the axial direction, the motion of kernels and straw was assumed to be identical in this direction. This reduced kernel motion
relative to straw only in the radial direction. Considering the points presented above, (22) was reduced to,

$$\frac{F}{m} = k_1 r \ddot{\delta} + k_2 (\ddot{r} - \ddot{\rho})$$

(23)

Long (16) used the value of n as unity; $k_1$ as 0.9, and $k_2$ as 7. Figure 3 shows the coordinate diagram used to develop equation of kernel motion.

Using Newton's second law of motion the governing equation for kernel motion was obtained as follows:

$$\ddot{\delta} = - (1 - k_1)(\ddot{r} - \ddot{\rho}) \ddot{\delta} - k_2 \ddot{\delta} - g \cos \theta$$

(24)

The three simultaneous equations characterizing the kernel motion can be written in the following form:

$$\ddot{\delta} = - (1 - k_1)(\ddot{r} - \ddot{\rho}) \ddot{\delta} - k_2 \ddot{\delta} - g \cos \theta$$

(25)

$$\ddot{\theta} = \omega - \frac{\dot{y} \tan \rho}{y \sin \alpha}$$

(26)

$$\ddot{y} = \frac{R}{m} (\sin \alpha - \mu \cos \beta \cos \alpha) + \frac{N}{m} (\sin \beta - \mu \cos \beta) \cos \alpha$$

(27)

whereas,

$$\frac{R}{m} = y \ddot{\delta} \sin \alpha + g \cos \theta \cos \alpha$$

(28)

$$\frac{N}{m} = \dot{y} (\omega + \dot{\delta}) \cos \beta \tan \alpha - \frac{R}{m} \tan \alpha \sin \beta + g \sin \theta \cos \beta$$

(29)

Because of the simultaneity and non-linearity of the equations, it was not possible to solve them readily by mathematical means. Approximate methods like numerical analysis and electrical analog were suggested.
The latter method was preferred since the analog computer is suitable for the solution of simultaneous differential equations and is particularly convenient in a study in which several parameters are to be varied.

b. Analog Computer Solutions:

Equations (25), (26), (27), (28), and (29) were written in a non-dimensional form to reduce the maximum amplitude of the system variables.

\[
\left( \frac{\delta}{d\omega^2} \right) = - (1 - k_1) \left[ \tan \left( \frac{\lambda}{d} \right) - \left( \frac{\delta}{\omega} \right) \right] \left( \frac{\delta}{\omega} \right)^2 - \frac{k_2}{\omega} \left( \frac{\delta}{d\omega} \right)
\]

\[
- \left( \frac{g}{d\omega^2} \right) \cos \theta \]

\[
\left( \frac{\varphi}{d\omega^2} \right) = (\sin \alpha - \mu \cos \beta \cos \alpha) \left( \frac{R}{d\omega^m} \right) \]

\[
+ \cos \alpha (\sin \beta - \mu \cos \beta) \left( \frac{N}{d\omega^m} \right) \]

\[
\left( \frac{\delta v}{d\omega} \right) = \left( \frac{v}{d} \right) - \tan \beta \left( \frac{v}{d\omega} \right) \]

\[
\left( \frac{\delta v}{d\omega} \right) = \left( \frac{\delta v}{d\omega^2} \right) \] (30)

whereas,

\[
\left( \frac{R}{d\omega^2} \right) = (\sin \alpha) \left( \frac{\varphi}{d\omega^2} \right) + \left( \frac{g \cos \alpha}{d\omega^2} \right) (\cos \theta) \] (31)

\[
\left( \frac{N}{d\omega^2} \right) = \left( \cos \beta \tan \alpha \right) \left( \frac{(\omega + \delta) \varphi}{d\omega^2} \right) \]

\[
- (\sin \beta \tan \alpha) \left( \frac{R}{d\omega^2} \right) + \left( \frac{g \cos \alpha}{d\omega^2} \right) \] (32)

Equations (30), (31), (32), (33), and (34) were programmed on an EAI PAGE TR-48 Analog Computer. Amplitude scaling was performed to make the voltage levels in the program as high as possible without exceeding the 10-volt range of the computer. The amplitude scaled circuit diagram
Figure 5. Amplitude scaled circuit simulating the particle motion in a horizontal, conical screen.
Figure 6. Amplitude scaled circuit diagram simulating the kernel motion through the straw mat.
is shown in Figures 5 and 6.

The purpose of the simulation was to study the effects of various system parameters on the crop particle motion. The parameters were grouped in two categories; controllable and uncontrollable. Controllable parameters included cone angle, blade angle, angular speed, straw mat thickness, and the particle initial velocity. Uncontrollable parameters were the coefficients of surface resistance and blade friction. The simulation should determine the combinations of the controllable parameters that will subject the particle to sufficient centrifugal acceleration within the rotor, and for a long enough time, to achieve kernel separation from the straw.

Long (16, 17) measured the time a wheat kernel takes to move through a given straw mat thickness under a given centrifugal acceleration. He found that a kernel took 0.25 second to move through a 4-inch thick straw mat under approximately 6 g's and 0.11 second under 35 g's of centrifugal acceleration. Increasing the centrifugal acceleration to 50 g's, however, resulted in a 0.10 second dwell time. He did not recommend centrifugal accelerations higher than 35 g's because of the insignificant drop in the dwell time for higher accelerations.

The particle motion was simulated for several parameter values while changing one parameter at a time. The initial angular displacement was taken as zero which corresponds to placing the crop at the bottom of the cone. The initial position of the kernel was determined by the straw mat thickness.

1. **Effect of Cone Angle**: The kernel-to-screen distance and time were plotted against axial displacement (Figure 7) for a cone angle
Figure 7. Effect of cone angle on the crop motion in the horizontal, conical screen.

- A: $\alpha = 25$ deg.
- B: $\alpha = 30$ deg.
- C: $\alpha = 35$ deg.
of 25, 30, and 35 degrees at 25 radians per second (240 r.p.m.) cone angular speed and 20-degree blade angle. The coefficients of blade friction and surface resistance were assumed to be 0.3 and 0.5, respectively. The kernel-to-screen distance was 0.3 ft. and initial axial velocity was 10 ft. per second. The cone entrance diameter was one foot.

2. **Effect of Blade Angle:** The kernel-to-screen distance and time were plotted against axial displacement (Figure 8) for a blade angle of 10, 20, and 30 degrees at 25 radians per second (240 r.p.m.) cone angular speed and 25-degree cone angle. The coefficients of blade friction and surface resistance were assumed to be 0.3 and 0.5, respectively. The kernel-to-screen distance was 0.3 ft. and the initial axial velocity was 10 ft. per second. The cone entrance diameter was one foot.

3. **Effect of Angular Speed:** The kernel-to-screen distance and time were plotted against axial displacement (Figure 9) for a cone angular speed of 15 (145 r.p.m.), 20 (190 r.p.m.), and 25 (240 r.p.m.) radians per second. The cone angle was 25-degrees; blade angle was 20-degrees; and cone diameter was one foot. The coefficients of friction and surface resistance were assumed to be 0.3 and 0.5, respectively. The initial axial velocity was 10 ft. per second.

4. **Effect of Entrance Diameter:** Figure 10 shows the plots of the kernel-to-screen distance and time against axial displacement for a cone entrance diameter of 0.75, 1.00, and 1.25 ft. The cone angular speed was 25 radians per second (240 r.p.m.); cone angle was 25-degrees; and the blade angle was 20-degrees. The coefficients of friction and surface resistance were assumed to be 0.3 and 0.5, respectively.

5. **Effect of Initial Axial Velocity:** The kernel motion was
Figure 8. Effect of blade angle on the crop motion in the horizontal, conical screen.
Figure 9. Effect of cone angular speed on the crop motion in the horizontal, conical screen.
Figure 10. Effect of conical entrance diameter on the crop motion in the horizontal, conical screen.
Figure 11. Effect of initial axial velocity on the crop motion in the horizontal, conical screen.
computed for an initial axial velocity of 2.5, 5, 7.5, 10, and 12.5 ft. per second. The cone angular speed was 25 radians per second (240 r.p.m.); cone angle was 25-degrees; and the blade angle was 20-degrees. The coefficients of friction and surface resistance were assumed to be 0.3 and 0.5, respectively.

6. **Effect of Surface Resistance**: The kernel-to-screen distance and time were plotted against axial displacement (Figure 12) for a coefficient of surface resistance 0.4, 0.5, and 0.6. The coefficient of friction was assumed to be 0.3. The cone angular speed was 25 radians per second (240 r.p.m.), the cone angle was 25-degrees, and blade angle was 20-degrees. Initial axial velocity was 10.0 ft. per second. The cone entrance diameter was one foot.

7. **Effect of Blade Friction**: Figure 13 shows plots of the kernel-to-screen distance and time against axial displacement for a coefficient of dynamic friction of 0.2, 0.3, and 0.4. Coefficient of surface resistance was 0.5. The cone angular speed was 25 radians per second; the cone angle was 25-degrees; and the blade angle was 20-degrees. The initial axial velocity was 0.4. The cone entrance diameter was one foot.

c. **Discussion**:

The theoretical analysis of the conical rotor has shown that it is possible to retain the crop in the rotor for enough time at the level of centrifugal acceleration required for separation. This was, however, possible under a very limited range of parameter values. Surface resistance and blade friction have a highly significant effect on the particle motion inside the conical rotor. Figure 12 shows that changing the
Figure 12. Effect of surface resistance on the crop motion in the horizontal, conical screen.
Figure 13. Effect of blade friction on the crop motion in the horizontal, conical screen.
surface resistance from 0.4 to 0.6, caused the particle to lodge in the rotor. Unfortunately, these two parameters are quite uncontrollable. Among the many factors that affect surface resistance and blade friction, moisture content is, perhaps, the most important one. It is expected that during a harvesting period, after a slight rain, the surface moisture content of the crop would change. This change in surface moisture content would be accompanied by a change in the frictional properties of the crop which would drastically change the performance of such a centrifugal separator.
(11) PARTICLE MOTION INSIDE A HORIZONTAL CYLINDRICAL SCREEN:

(a) Theory:

Theoretical analysis of particle motion inside a horizontal, conical rotor indicated that the cone was capable of subjecting the crop to the required level of centrifugal acceleration for a sufficient time to achieve separation of grains (in a limited range of crop frictional parameter values). However, experimentation indicated that airflow through the perforated cone disrupted the theoretical flow of grain and straw so greatly that, coupled with the problem of wide variation in probable surface resistance with moisture contents, this approach of separation in a perforated cone was abandoned. It was suggested that a mechanism which would allow better control on particle motion be analyzed. The axial motion in the cone was mainly due to the component of centrifugal force parallel to the cone wall and was opposed by frictional and surface resistive forces. These forces were dependent upon crop frictional characteristics. Frictional characteristics of a crop vary quite significantly during a harvesting period.

A horizontal, rotating, cylindrical screen would impart tangential acceleration to the particle by virtue of friction between the particle and the cylindrical surface. Helical, radial blades, mounted on a smaller diameter cylinder rotating at a faster rate inside the screen, could impart axial and also tangential acceleration to the particle. The cylindrical shape of screen would make the axial motion of the particle independent of the centrifugal force acting on it, thereby, allowing a
better control on the crop motion by other means (Figure 14).

Equations of particle motion inside a horizontal, rotating screen with inner configuration as described above were developed. Crop was treated as an aggregate of disconnected particles and the interaction between particles was neglected. A constant coefficient of screen surface resistance was assumed. To determine whether this configuration was potentially capable of subjecting the crop to desired centrifugal and axial acceleration, the effect of air drag was omitted from the analysis.

The basic inertial reference frame was xyz system as shown in Figure 15. The rθy cylindrical coordinates were used to describe the motion. The following is the list of symbols used in the analysis.

\[\begin{align*}
\beta &: \text{Angle between blade and the axis of rotation} \\
\phi &: \text{Angle between frictional force and axis of rotation in tangent plane} \\
\omega &: \text{Angular speed of the blades} \\
\omega_l &: \text{Angular speed of the screen} \\
\mu &: \text{Coefficient of surface resistance} \\
\mu_l &: \text{Coefficient of friction between the particle and the blade} \\
\theta &: \text{Angular displacement} \\
a &: \text{Screen radius} \\
d &: \text{Screen diameter} \\
g &: \text{Acceleration due to gravity} \\
m &: \text{Mass of the kernel} \\
m_s &: \text{Mass of the straw particle} \\
N &: \text{Force applied by the blade} \\
R &: \text{Normal reaction of cylinder wall}
\end{align*}\]
Figure 14. A horizontal cylindrical screen.
Figure 15. Coordinate diagram for the horizontal cylindrical screen.

Figure 16. Forces in the transverse plane.
\( V_p/\text{Blade} \): Velocity of particle relative to blade

\( y \): Axial displacement

\( r \): Kernel radius vector

\( \delta \): Screen-to-kernel distance

\( F \): Resistive force on kernel

\( ^\circ \): First derivative with respect to time

\( ^{\circ\circ} \): Second derivative with respect to time

Equations of motion were derived using Newton's Laws of Motion. Writing momentum and force balance in \( \theta \) and \( y \) directions, respectively, the following equations were written:

\[
a^2 m_s \dot{\theta} = \Sigma M_\theta \\

m_s \ddot{y} = \Sigma F_y
\]  \hspace{1cm} (35) \hspace{1cm} (36)

whereas,

\[
\Sigma M_\theta = a(NCos\beta - \mu_RSin\phi + \mu_1NSin\beta - m_s g \ Sin\theta) \\

\Sigma F_y = NSin\beta - \mu_RCos\phi - \mu_1NCos\beta
\]  \hspace{1cm} (37) \hspace{1cm} (38)

Substitution of (37) and (38) in (35) and (36) resulted in the following equations:

\[
a^\theta = - \mu \frac{R \ Sin\phi}{m_s} + \frac{N}{m_s} (Cos\beta + \mu_1Cos\beta) - gSin\theta \\

\ddot{y} = - \mu \frac{R}{m_s} Cos\phi + \frac{N}{m_s} (Sin\beta - \mu_1Cos\beta)
\]  \hspace{1cm} (39) \hspace{1cm} (40)

According to Figure 16,

\[
\frac{R}{m_s} = a^\theta + gCos\theta
\]  \hspace{1cm} (41)
According to Figure 17,

$$(\tan \beta) \ddot{y} = a(\omega - \dot{\beta}) \quad \ldots \quad (42)$$

Differentiation of (42) resulted;

$$(\tan \beta) \dddot{y} = -a \ddot{\beta} \quad \ldots \quad (43)$$

By substitution of (43) in (40), the following equation was obtained:

$$-a \ddot{\beta} = (\tan \beta) \left[ -\mu \frac{R}{m_s} \cos \phi + \frac{N}{m_s} (\sin \beta - \mu \cos \beta) \right] \quad \ldots \quad (44)$$

Equation (44) was added to (39). After rearranging the resulting equation, the following expression was obtained:

$$\frac{N}{m_s} = \mu \frac{R}{m_s} (\cos \beta \sin \phi + \sin \beta \cos \phi) \quad \ldots \quad (45)$$

Figure 18 shows the velocities and forces in tangent plane, from which the following expressions were obtained:

$$\sin \phi = \frac{(\theta - \omega_1) \tan \beta}{\sqrt{a^2 - 2\dot{\theta}(\omega - \omega_1 \tan \beta) + \omega_1^2 \tan^2 \beta + \dot{\beta}^2 \sec^2 \beta}} \quad \ldots \quad (46)$$

$$\cos \phi = \frac{\dot{y}}{\sqrt{a^2 - 2\dot{\theta}(\omega - \omega_1 \tan \beta) + \omega_1^2 \tan^2 \beta + \dot{\beta}^2 \sec^2 \beta}} \quad \ldots \quad (47)$$

Substituting equations (46) and (47) in (39) and (45) and rearranging, the following set of governing equations can be obtained:

$$a \ddot{\beta} = (\cos \beta + \mu_1 \sin \beta) \frac{N}{m_s} - \frac{(\mu \tan \beta) \left( R/m_s \right)(\dot{\beta} - \omega_1)}{\sqrt{a^2 - 2\dot{\theta}(\omega - \omega_1 \tan \beta) + \omega_1^2 \tan^2 \beta + \dot{\beta}^2 \sec^2 \beta}} \quad (48)$$
Figure 17. Relative velocity diagram.

\[ a(\omega - \theta) \]

\[ \sqrt{v^2 + a^2 (\theta - \omega_1)^2} \]

Figure 18. Velocity and forces in the tangent plane.

\[ \mu R \cos \phi \]

\[ \mu R \sin \phi \]

Figure 19. Coordinate diagram for the kernel motion.
\[
\frac{R}{m_s} = a \delta^2 + g \cos \theta \quad \cdots \cdots \quad (49)
\]

\[
\frac{N}{m_s} = \frac{\mu \sin \beta (\omega - \omega_1) (R/m_s)}{\sqrt{\omega^2 - 2 \dot{\omega} (\omega - \omega_1 \tan \beta) + \omega_1^2 \tan^2 \beta} + \theta^2 \sec^2 \beta} + (g \cos \beta) \sin \theta \quad \cdots \cdots \quad (50)
\]

and,

\[
\dot{\gamma} = (a \cot \beta) (\omega - \dot{\omega}) \quad \cdots \cdots \quad (51)
\]

To characterize the motion of kernel through a mat of straw, equation of kernel motion was developed. The assumptions made during the analysis have been discussed while developing the similar equation in the case of horizontal, conical rotor. The equation of kernel motion through the mat of straw is the following (Figure 19).

\[
\dot{\delta} = -(l-k_1) (a-\delta) \dot{\delta}^2 - k_2 \delta - g \cos \theta \quad \cdots \cdots \quad (52)
\]

Equations (48) through (52) characterize the motion of straw particle and kernel inside a horizontal, cylindrical, rotation screen.

(b) **Analog Computer Solution:**

The governing equations of motion were rearranged in non-dimensional form for the purpose of reducing the amplitude of the system variables. The following set of equations represent the governing equations in non-dimensional form.

\[
\begin{pmatrix}
\dot{\delta} \\
\frac{\delta}{a \omega^2}
\end{pmatrix} = -(l-k_1) \begin{pmatrix}
1-a \\
a
\end{pmatrix} \left(\frac{\delta}{a \omega}\right)^2 - k_\delta \frac{\delta}{a \omega} - \frac{g}{a \omega^2} (\cos \theta) \quad \cdots \cdots \quad (53)
\]
\[
\left( \frac{\delta}{2\omega^2} \right) = (\cos \beta + \mu_1 \sin \beta) \left( \frac{N}{a\omega^2m} \right)
\]

\[
- \frac{\mu \tan \beta}{\omega} \left( \frac{\delta}{\omega} - \frac{\delta_1}{\omega} \right) \left( \frac{R}{a\omega^2m} \right)
\]

\[
\sqrt{1 + \left( \frac{\omega_1}{\omega} \right)^2 \tan^2 \beta - 2 \left( \frac{\delta}{\omega} \right) \left( 1 + \frac{\omega_1}{\omega} \tan \beta \right) + \sec^2 \beta \left( \frac{\delta}{\omega} \right)^2}
\]

\[
\left( \frac{\delta}{2\omega^2} \right) = (\sin \theta)
\]

\[
\left( \frac{V}{\omega} \right) = \cot \beta \left( 1 - \frac{\delta}{\omega} \right)
\]

\[
\left( \frac{R}{a\omega^2m} \right) = \left( \frac{\delta}{\omega} \right)^2 + \left( \frac{\delta}{\omega} \right) \left( \cos \theta \right)
\]

\[
\left( \frac{N}{a\omega^2m} \right) = \mu \sin \beta \left( 1 - \frac{\omega_1}{\omega} \right) \left( \frac{R}{a\omega^2m} \right)
\]

\[
\sqrt{1 + \left( \frac{\omega_1}{\omega} \right)^2 \tan^2 \beta - 2 \left( \frac{\delta}{\omega} \right) \left( 1 + \frac{\omega_1}{\omega} \tan \beta \right) + \sec^2 \beta \left( \frac{\delta}{\omega} \right)^2}
\]

\[
+ \left( \frac{\delta}{2\omega^2} \right) \left( \sin \theta \right)
\]

Equations (53) through (57) were programmed on an EAI PACE TR-48 Analog Computer. Amplitude scaling was required and the amplitude scaled circuit diagram is shown in Figure 20. Figure 21 shows the amplitude scaled circuit diagram for kernel motion through the mat of straw. The motion of particle was computed for several values of one parameter while the other parameters were held constant. The following are the effects of various parameters:

1. **Effect of Blade Angle**: Kernel-to-screen distance and time were plotted against axial displacement for a blade angle of 55, 65, and
\[
1 + \left( \frac{\omega}{\omega} \right)^2 \tan^2 \beta = 1 + \left( \frac{\omega}{\omega} \right)^2 \tan^2 \beta - 2 \left( \frac{\omega}{\omega} \right) \left( 1 + \frac{\omega}{\omega} \right) \tan \beta + \sec \beta \left( \frac{\omega}{\omega} \right)^2
\]

Figure 20. Amplitude scaled circuit diagram simulating the particle motion in the horizontal, cylindrical screen.
Figure 21. Amplitude scaled circuit diagram simulating the kernel motion through the straw mat.
75-degrees at the blade angular speed of 25 radians per second (240 r.p.m.). The screen-to-blade speed ratio was 0.6. The coefficients of surface resistance and blade friction were assumed to be 0.5 and 0.3, respectively. Initial angular velocity was 7.5 radians per second. The cylinder diameter was 1.5 ft. The results are shown in Figure 22.

2. Effect of Screen-to-Blade Speed Ratio: Kernel-to-screen distance and time were plotted against non-dimensional axial displacement for a screen-to-blade speed ratio of 0.4, 0.6, and 0.8 at a speed of 25 radians per second (240 r.p.m.). The coefficients of surface resistance and blade friction were 0.5 and 0.3, respectively. Initial angular velocity was 7.5 radians per second. The cylinder diameter was 1.5 ft. Blade angle was 75-degrees. The results are plotted in Figure 23.

3. Effect of Blade Angular Speed: Figure 24 presents the plots of kernel-to-screen distance and time against axial displacement for a blade angular speed of 15 (145 r.p.m.), 20 (195 r.p.m.), and 25 (240 r.p.m.) radians per second. The screen-to-blade speed ratio was 0.6. Initial angular velocity was 7.5 radians per second. Coefficients of the surface resistance and the blade friction were 0.5 and 0.3, respectively. The blade angle was 75-degrees. The screen diameter was 1.5 ft.

4. Effect of Screen Diameter: Kernel-to-screen distance and time were plotted against axial displacement for a screen diameter of 1.5, 2.0, and 2.5 ft. at a blade angular speed of 25 radians per second (240 r.p.m.) The screen-to-blade speed ratio was 0.6 and the initial angular velocity was 7.5 radians per second. The coefficients of the surface resistance and the blade friction were assumed to be 0.5 and 0.3,
Figure 22. Effect of blade angle on the crop motion in the horizontal, cylindrical screen.
Figure 23. Effect of screen-to-blade angular speed ratio on the crop motion in the horizontal, cylindrical screen.
Figure 24. Effect of beak angular speed on the crop motion in the horizontal, cylindrical screen.
respectively. The blade angle was 75-degrees. The results are plotted in Figure 25.

5. **Effect of Initial Angular Velocity:** Kernel-to-screen distance and time were computed for initial angular velocities of 0.2, 0.3, and 0.4. The blade angular speed was 25 radians per second (240 r.p.m.) and the screen-to-blade speed ratio was 0.6. The coefficients of the surface resistance and the blade friction were 0.5 and 0.3, respectively. The screen diameter was 1.5 ft. The blade angle was 75-degrees. Results are presented in Figure 26.

6. **Effect of Surface Resistance:** The values of coefficient of surface resistance used to simulate particle motion were 0.4, 0.5, and 0.6 at a blade angular speed of 25 radians per second (240 r.p.m.). The value of coefficient of blade friction was 0.3. Screen-to-blade angular speed ratio was 0.6. The screen diameter was 1.5 ft. and the blade angle was 75-degrees. During simulation the initial angular velocity was taken as 7.5 radians per second. The results are included in Figure 27.

7. **Effect of Blade Friction:** The motion of crop was simulated for a coefficient of dynamic friction of 0.2, 0.3, and 0.4. The coefficient of surface resistance was assumed to be 0.5. The blade angular speed was 25 radians per second (240 r.p.m.) and the screen-to-blade speed ratio was 0.6. The screen diameter was 1.5 ft. The blade angle was taken as 75-degrees. The initial angular velocity was 7.5 radians per second. Results are shown in Figure 28.

(c) **Discussion:**

Simulation results have shown that it is possible to subject the crop to a required level of centrifugal acceleration for enough time to
Figure 25. Effect of screen diameter on the crop motion in the horizontal, cylindrical screen.
Figure 26. Effect of initial angular velocity on the crop motion in the horizontal, cylindrical screen.
\( \beta = 75 \text{ deg.} \)
\( \omega_1 = 0.6 \)
\( \omega = 25 \text{ rad. per sec.} \)
\( d = 1.5 \text{ ft.} \)
\( \dot{\theta}(t) = 7.5 \text{ rad. per sec.} \)
\( \mu_1 = 0.3 \)

A : \( \mu = 0.4 \)
B : \( \mu = 0.5 \)
C : \( \mu = 0.6 \)

Figure 27. Effect of surface resistance on the crop motion in the horizontal, cylindrical screen.
Figure 28. Effect of blade friction on the crop motion in the horizontal, cylindrical screen.
separate grains from straw. It has also been shown that the uncontrol-
lable parameters like surface resistance and blade friction do not have
any significant effect on the crop motion. This kind of a configuration
provided for a better control on the crop motion inside the rotor. The
axial and tangential motion of the crop were controlled by changing the
blade angular speed and screen-to-blade speed ratio. Blade angle had a
significant effect and provided another parameter to control the crop
motion.

A cylindrical rotating screen has shown definite advantages over
conical rotor in that it is not so dependent on the frictional character-
istic of the crop. This feature of the cylindrical screen allows a proper
control of the crop over a wide range of crop characteristics. The re-
sults of this analysis are, however, subject to the limitation of neglect-
ing the aerodynamic effect on the motion of the particle.
CHAPTER II

EXPERIMENTAL ANALYSIS

(i) Horizontal, Conical Screen

A horizontal, conical rotor with radial, helical blades affixed on the inside wall was built. Use of the theoretical analysis was made to obtain the specifications of the conical screen. The half-cone angle was 25-degrees, the entrance diameter was 1 ft., and the axial length of the cone was 1.75 ft. (Figure 29). The cone was made of sheet metal perforated with $\frac{1}{2}$ in. diameter holes. The larger end of the cone was connected to a hub by means of four spokes made out of angle iron. A 6-in. long and 12-in. inside diameter pipe was welded to the small end on the periphery. The small end was supported by three rubber wheels on the outside of the pipe. The rubber wheels were mounted on a rigid frame. The big end of the cone was supported by means of a 1-in. diameter steel rod running through the hub and supported by two self aligning bearings mounted on a rigid frame. The cone had two radial, helical blades mounted inside on the cone perforated wall. The angle between the blade and an axial line drawn on the inner surface, was 20 degrees. The blades were made of 16-gage G.I. sheet metal. The height of the blades was 2-in. at the small end and gradually increased to 9-in. at the large end. The two blades were mounted opposite to each other. The cone was rotated by a variable speed hydraulic motor. The motor transmitted the power to a
Figure 29. Side view of the experimental, conical screen.
V-pulley mounted on the 1-in. shaft. The shaft, in turn, rotated the screen by means of a cotter-key connecting the shaft and the hub. The big end of the cone was enclosed in a tangential exit for the straw to leave the rotor (Figure 30).

The grain-straw mixture was fed to the rotor at the small end by means of an auger extending into the rotor. A flat endless belt driven by a variable-speed electric motor was used to deliver the grain-straw mixture onto the auger. The auger was also driven by means of a variable-speed electric motor. To collect the separated grains, the rotor was covered by plywood boards on the three sides. The space between the boards and the screen surface was a minimum of ¾-in. The entire length of the conical screen was divided in four equal segments on the outside for the purpose of studying the effect of cone length on the grain separation. A removable tray with four compartments was fitted under the screen to collect the grains.

Preliminary test runs showed that the crop failed to move axially and lodged within the rotor. The grain, however, was separated mostly in the first compartment. A careful observation revealed that the air movement was an important factor controlling the motion of the straw. To study the effect of airflow through the rotor, the exit of the cone was connected to a powerful suction fan through a settling chamber. The suction of the fan was controlled by a gate. Test runs were made at various levels of airflow and cone angular speed. It was noted that at the airflow that resulted in axial motion of crop in the rotor, a major portion of the crop was caught in the main stream of air and was moved axially without rotating in the cone. To prevent this from happening
Figure 30. Experimental, conical rotor, small end support, tangential chute, and the drive mechanism.

Figure 31. Modified conical rotor with inner cone and helical, radial blade.
another solid cone was fitted inside the perforated cone (Figure 31). To distribute the crop more uniformly, four instead of two blades were fitted inside the cone as shown in Figures 31 and 32. In order to enhance axial motion of the straw, perforation up to 15-in. from the entrance was blocked by means of sheet metal filled on the inside of the cone wall. These modifications created a serious problem of feeding (Figure 33). This and the other problems in controlling the crop motion within the cone led to the decision of abandoning this approach.
Figure 32. Crop entrance to the modified conical rotor.

Figure 33. Problem in crop feeding to the modified conical rotor.
(ii) Horizontal, Cylindrical Screen

(a) **Dimensional Analysis:** The analytical model to predict the performance of the horizontal, cylindrical screen has been discussed in the previous chapter. The separator performance, as affected by different variables, was analyzed. Many variables like crop flow rate, grain-to-straw weight ratio in the crop, screen perforations, and the air flow through the rotor were, however, not included in the analytical model. It was suggested to study the effects of these variables on the performance of the separator by experimental means. Use of dimensional analysis was made to design the experiments. It was proposed to develop a generalized prediction equation for separation efficiency as a function of system variables. Table 1 presents the list of pertinent system variables, their units and dimensions. The total number of variables were 30. The basic dimensions used were M: Mass; L: Length; and T: Time. According to Buckingham \( \pi \)-Theorem, the total number of independent \( \pi \)-terms were \( 30 - 3 = 27 \).

One possible set of \( \pi \)-terms is:

\[
\begin{align*}
\pi_1 &= \frac{Q_m}{\rho g} \\
\pi_2 &= \frac{\rho g}{\alpha_B} \\
\pi_3 &= \frac{d a_8^2}{g} \\
\pi_4 &= \frac{Q_m}{\rho g \alpha_B d_3^3} \\
\pi_5 &= \frac{s}{L_r} \\
\pi_6 &= \gamma_m \\
\pi_7 &= \frac{d}{L_r} \\
\pi_8 &= \frac{d_1}{d_2}
\end{align*}
\]
\[
\pi_9 = \frac{l_1 g}{d_1}, \quad \pi_{10} = \frac{l_2 g}{L_2 g}
\]

\[
\pi_{11} = \frac{d_s}{L_s}, \quad \pi_{12} = \frac{d_s}{d_1}
\]

\[
\pi_{13} = \frac{\rho_s d_s g}{E I}, \quad \pi_{14} = \frac{\rho_s g}{r}
\]

\[
\pi_{15} = \frac{\rho_s g}{c_r d_s}, \quad \pi_{16} = \frac{g}{\rho_s}
\]

\[
\pi_{17} = r_s, \quad \pi_{18} = \frac{L_r}{d_1}
\]

\[
\pi_{19} = \frac{\rho_a}{\rho_s}, \quad \pi_{20} = \beta
\]

\[
\pi_{21} = \lambda, \quad \pi_{22} = s
\]

\[
\pi_{23} = \frac{\rho_a d^2 \omega_s}{\mu}, \quad \pi_{24} = \frac{Q_s}{Q_m}
\]

\[
\pi_{25} = \frac{h}{L_r}, \quad \pi_{26} = \frac{c}{L_r}
\]

and \[
\pi_{27} = \frac{t}{L_r}.
\]
<table>
<thead>
<tr>
<th>No.</th>
<th>Symbol</th>
<th>Definitions</th>
<th>Units</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>d</td>
<td>Screen diameter</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>2</td>
<td>β</td>
<td>Blade angle</td>
<td>deg.</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>λ</td>
<td>Orientation of holes</td>
<td>deg.</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>s</td>
<td>Shape of holes</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>d₁</td>
<td>Hole dimension along the row</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>6</td>
<td>d₂</td>
<td>Hole dimension across the row</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>7</td>
<td>Lₚ</td>
<td>Length of screen</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>8</td>
<td>rₛ</td>
<td>Percent area under perforations</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>L₁ₖ</td>
<td>Average maximum dimension of wheat kernel</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>10</td>
<td>L₂ₖ</td>
<td>Average minimum dimension of wheat kernel</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>11</td>
<td>Lₛ</td>
<td>Length of straw</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>12</td>
<td>dₛ</td>
<td>Average diameter of straw</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>13</td>
<td>Eₛ</td>
<td>Average straw stiffness</td>
<td>lbmft.³/sec²</td>
<td>ML⁻¹T²</td>
</tr>
<tr>
<td>14</td>
<td>τ</td>
<td>Average straw shear strength (Transverse)</td>
<td>lbm/ft.sec²</td>
<td>ML⁻¹T⁻²</td>
</tr>
<tr>
<td>15</td>
<td>Cₛ</td>
<td>Average straw crushing strength</td>
<td>lbm/sec²</td>
<td>MT⁻²</td>
</tr>
<tr>
<td>16</td>
<td>rₘ</td>
<td>Grain to straw ratio</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>ρₛ</td>
<td>Density of grains</td>
<td>lbm/ft.³</td>
<td>ML⁻³</td>
</tr>
<tr>
<td>18</td>
<td>ρₛ</td>
<td>Density of straw</td>
<td>lbm/ft.³</td>
<td>ML⁻³</td>
</tr>
</tbody>
</table>
TABLE 1. (continued)

<table>
<thead>
<tr>
<th>No.</th>
<th>Symbol</th>
<th>Definitions</th>
<th>Units</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>$\mu$</td>
<td>Absolute viscosity of air</td>
<td>lbm/ft.sec</td>
<td>ML$^{-1}$ T$^{-1}$</td>
</tr>
<tr>
<td>20</td>
<td>$\rho_a$</td>
<td>Density of air</td>
<td>lbm/ft.$^3$</td>
<td>ML$^{-3}$</td>
</tr>
<tr>
<td>21</td>
<td>$g$</td>
<td>Acceleration due to gravity</td>
<td>ft/sec$^2$</td>
<td>LT$^{-2}$</td>
</tr>
<tr>
<td>22</td>
<td>$\omega_s$</td>
<td>Screen angular velocity</td>
<td>rad/sec</td>
<td>T$^{-1}$</td>
</tr>
<tr>
<td>23</td>
<td>$\omega_a$</td>
<td>Angular velocity of blades</td>
<td>rad/sec</td>
<td>T$^{-1}$</td>
</tr>
<tr>
<td>24</td>
<td>$S$</td>
<td>Distance along the axis of the screen measured from the entrance</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>25</td>
<td>$Q_m$</td>
<td>Straw flow rate</td>
<td>lbm/sec</td>
<td>MT$^{-1}$</td>
</tr>
<tr>
<td>26</td>
<td>$Q_a$</td>
<td>Air flow rate through the rotor</td>
<td>lbm/sec</td>
<td>MT$^{-1}$</td>
</tr>
<tr>
<td>27</td>
<td>$h$</td>
<td>Blade height</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>28</td>
<td>$c$</td>
<td>Clearance between the blade and the screen</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>29</td>
<td>$t$</td>
<td>Thickness of screen material</td>
<td>ft.</td>
<td>L</td>
</tr>
<tr>
<td>30</td>
<td>$P$</td>
<td>Dependent variable: Ratio of grains passed through the screen to the total amount of grains measured at $S$</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>
The samples of wheat grain and straw used in this study were collected from the same field, same combine and the same day. The straw was collected by holding canvas under the rear end of the combine while it was in operation. In this way everything coming out at the rear end of the combine was collected. Grain used was also collected from the same combine in the same field on the same day. The straw and grain were stored under partially controlled environment. Straw was not cut into different lengths. The average straw length, straw diameter, bending strength, shear strength, and crushing strength were, therefore, assumed to be constant for the entire sample. Since, the study was limited to only wheat crop, $\pi_{10}$, $\pi_{11}$, $\pi_{13}$, $\pi_{14}$, $\pi_{15}$, $\pi_{16}$, and $\pi_{19}$ were held constant through the entire investigation. The study was limited to only one cylindrical separator and, therefore, $\pi_{7}$, $\pi_{8}$, $\pi_{9}$, $\pi_{12}$, $\pi_{17}$, $\pi_{18}$, $\pi_{20}$, $\pi_{21}$, $\pi_{22}$, $\pi_{25}$, $\pi_{26}$, and $\pi_{27}$ were also held constant.

$\pi_{23}$ is a form of Reynolds number.

$$\pi_{23} = \frac{\rho_a d^2 \omega_b}{\mu}$$

If, $\rho_a = 0.075$ lb. per cu. ft.$^1$

$d = 1.5$ ft.

$\omega_b = 25$ rad. per sec.

$\mu = 0.018$ centipoise

$$\pi_{23} = 32.88 \times 10^4$$

$^1$ Density of air at NTP and 70 percent relative humidity.
The drag coefficient in this range of Reynolds number is constant. The drag force, however, depends on the free stream velocity which, in our case, depends upon the air flow rate \( Q_a \). Since, during the investigations no provision was made to vary the air flow rate independently, it was completely determined by the operating variables. \( \pi_{23} \) and \( \pi_{24} \), therefore, were dropped from the analysis.

The prediction equation can be written in the following form.

\[
\pi_1 = \phi \left( \kappa_2, \pi_3, \pi_4, \pi_5, \pi_6 \right) \tag{58}
\]

or,

\[
P = \phi \left[ \frac{w}{x}, \frac{w}{g}, \frac{Qm}{\rho g w_{1/2} d^3}, \frac{S}{L}, \eta_m \right] \tag{59}
\]

(b) **Experimental Design**: Due to the large number of independent variables under investigation, the experimental schedule suggested by Murphy (20) was used. One pi-term was varied while the others remained constant. Availability of the material and the analytical work were the decisive factors in determining the design specifications of the test apparatus. It will be discussed in detail in the next section. To determine the operating range of material flow rate, several preliminary runs were made at different material flow rates. A random sample of 10 grains was taken from the wheat grain that was to be used for the investigations. The average \( L_{1g} \) and \( L_{2g} \) were measured to be 0.244 and 0.118 in., respectively. The solid density of wheat kernel was taken to be 50 lb. per cu. ft. (2). Screen-to-blade angular speed ratios used in the experimental investigations were in the same range of values as that in analytical work. The experimental schedule is given in Table 2.
TABLE 2. The experimental schedule.

<table>
<thead>
<tr>
<th>x_1</th>
<th>x_2</th>
<th>x_3</th>
<th>x_4</th>
<th>x_5</th>
<th>x_6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.726</td>
<td>16.5</td>
<td>1.69</td>
<td>0.78</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>0.685</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.500</td>
<td>5.4</td>
<td>1.69</td>
<td>0.78</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>0.460</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.500</td>
<td>12.1</td>
<td>16.5</td>
<td>21.6</td>
<td>33.8</td>
<td></td>
</tr>
<tr>
<td>0.500</td>
<td>16.5</td>
<td>1.13</td>
<td>1.69</td>
<td>2.25</td>
<td>2.82</td>
</tr>
<tr>
<td>0.500</td>
<td>16.5</td>
<td>1.69</td>
<td>0.195</td>
<td>0.390</td>
<td>0.584</td>
</tr>
<tr>
<td>0.500</td>
<td>16.5</td>
<td>1.69</td>
<td>0.78</td>
<td>1.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>
(c) **Experimental Equipment and Method:** A horizontal, cylindrical centrifugal separator as shown in Figure 14 was built (Figure 34). The separator was made out of a cylindrical screen, 19.5 in. in diameter and 36-in. long. The screen was made out of a sheet metal with circular perforation size of 3/8 in. The perforated sheet metal had 47 percent of the area in perforations. The screen was fitted to two steel hoops one on each end. The hoops were connected to each other by means of four angle irons on the outside of the screen. The screen was supported on three rubber rollers at each end on the outside. An auger with 10-in. pipe diameter, 19.25 in. total diameter, and with the flights making 75-degree angle with pipe axis, was fitted inside the screen. The auger was supported on two self-aligning bearings such that the auger flights covered the entire length of the screen with 15-in. of the flights extending out of the screen on one side. The 15-in. of the auger blades extending out of the screen were housed in a U-shaped feeding trough supported on a rigid frame (Figure 37). Another U-shaped trough with downward opening was placed on the other side of the screen and served to exit the straw (Figure 38).

The entire screen length was divided into four 7-in. effective screen sections on the outside by fitting 5 plywood boards with holes big enough to allow the screen to rotate in it. The three sides of the screen were covered to contain the separating kernels. A bottom tray with four matching sections was placed at the bottom of the screen to collect the wheat kernels (Figure 35).

The auger was connected to the P.T.O. shaft of a tractor (Figure 34). A V-belt pulley mounted on the auger center shaft drove a jackshaft
Figure 34. Experimental horizontal, cylindrical rotor with feeding belt, feeding hopper, exit hopper, and the drive from a P.T.O. shaft.
Figure 35. Cylindrical rotor showing the screen and its drive and collection tray.

Figure 36. Top view of the cylindrical screen.
Figure 37. Entrance to the screen.

Figure 38. Exit from the screen.
which in turn rotated the screen by means of three V-belts on the outside of the exit-end hoop of the screen. The auger speed was controlled by the throttle of the tractor. Screen-to-auger speed ratio was changed by different size pulleys on the jackshaft.

The straw weight was constant for each sample at 8.34 lb. The weight of grain in the straw was determined by the grain-to-straw weight ratio. The correct amount of grain was weighed and was mixed with the straw. The chaff present in the feeding mixture was not weighed. The straw and chaff were treated as a homogeneous mixture while weighing straw sample of 8.34 lb.

A horizontal endless flat belt with variable speed drive was used to feed the grain and straw mixture into the feeding auger (Figure 34). The sample of grain and straw was placed on the belt after properly setting its linear speed to control the feed rate. Samples of the output were collected and weighed separately for each section of the bottom tray. Material other than grain was cleaned out by placing the samples in a tray with perforated bottom. Air flowing upward through the bottom of the tray separated the material other than grain, from the grain. The sample in the perforated bottom had to be agitated by hand to clean the grain. The clean grain was weighed separately. By subtracting the weight of the clean grain from the total weight of the sample, weight of the material other than grain was obtained. Grain in the straw discharge was separated from long straw by hand. Chaff was separated by the same procedure as described before. The data for each set of runs were recorded on a separate data sheet (Appendix). The separation efficiency, P, was calculated by dividing the amount of grain recovered by the total
amount of grain in the sample.

(d) Results and Discussion:

1. Effect of $\pi_2$: The percent grain and m.o.g. were plotted against various values of $\pi_2$ (Figure 39). A component equation was developed using linear regression. The regression line is also shown in Figure 39. The model evaluated was: $F = b_0 + b_1 \pi_2$. Table 3 presents the analysis of variance.

**TABLE 3. Analysis of variance for $\pi_2$**

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>D.F.</th>
<th>Mean Square</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>30773.24</td>
<td>4</td>
<td>7693.30</td>
<td></td>
</tr>
<tr>
<td>Term of deg. 0</td>
<td>30733.59</td>
<td>1</td>
<td>30733.59</td>
<td>2325.37</td>
</tr>
<tr>
<td>Residual</td>
<td>39.65</td>
<td>3</td>
<td>13.21</td>
<td></td>
</tr>
<tr>
<td>Term of deg. 1</td>
<td>3.51</td>
<td>1</td>
<td>3.51</td>
<td>0.19*</td>
</tr>
<tr>
<td>Residual</td>
<td>36.13</td>
<td>2</td>
<td>18.06</td>
<td></td>
</tr>
<tr>
<td>Total Reduction</td>
<td>30737.1</td>
<td>2</td>
<td>15368.55</td>
<td>8505.15</td>
</tr>
</tbody>
</table>

* Insufficient at 50 percent confidence interval.

The regression analysis showed that changing $\pi_2$ did not affect the separator performance. The reason for this may be that at lower values of $\pi_2$, due to small relative velocity between crop and the screen, lack of enough agitation was the major factor affecting the performance. On the other hand, at higher values of $\pi_2$, despite the higher agitation, high velocity of crop relative to screen made screen effect to dominate.

2. Effect of $\pi_3$: The percent grain and m.o.g. separated were
Figure 39. Effect of $\pi_2$ on Separator Performance.
plotted for various values of \( \pi_3 \) in Figure 40. A component equation was developed using linear regression. The regression line is shown in Figure 40. The model evaluated was \( F = b_0 + b_1 \pi_3 \). Table 4 presents the analysis of variance. The regression analysis showed that increasing the value of \( \pi_3 \) resulted in a decrease in percent of grain separated. It was hypothesized that at high values of \( \pi_3 \), compaction of straw impeded the separation even though the centrifugal force acting on the kernel was higher.

**TABLE 4. Analysis of variance for \( \pi_3 \)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>D.F.</th>
<th>Mean Square</th>
<th>( F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>40836.27</td>
<td>5</td>
<td>8167.25</td>
<td></td>
</tr>
<tr>
<td>Term of order 0</td>
<td>40811.97</td>
<td>1</td>
<td>40811.97</td>
<td>6723.55</td>
</tr>
<tr>
<td>Residual</td>
<td>24.30</td>
<td>4</td>
<td>6.07</td>
<td></td>
</tr>
<tr>
<td>Term of order 1</td>
<td>7.58</td>
<td>1</td>
<td>7.58</td>
<td>1.36*</td>
</tr>
<tr>
<td>Residual</td>
<td>16.71</td>
<td>3</td>
<td>5.57</td>
<td></td>
</tr>
<tr>
<td>Total Reduction</td>
<td>40819.56</td>
<td>2</td>
<td>20409.78</td>
<td>3664.23</td>
</tr>
</tbody>
</table>

* Significant at 50 percent confidence interval.

3. Effect of \( \pi_4 \): The percent grain and m.o.g. separated were plotted against various values of \( \pi_4 \) in Figure 41. A component equation using linear regression was developed and is also shown in Figure 41. The model evaluated was \( F = b_0 + b_1 \pi_4 \). Table 5 shows the analysis of variance.
Figure 40. Effect of $\pi_3$ on Separator Performance.

Regression line:
$P = 92.6 - 0.128 \pi_3$

$\pi_2 = 0.5$
$\pi_4 = 1.69$
$\pi_5 = 0.78$
$\pi_6 = 0.80$
Figure 41. Effect of $\pi_4$ on Separator Performance.
TABLE 5. Analysis of variance for \( \pi_4 \)

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Square</th>
<th>D.F.</th>
<th>Mean Square</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>29862.44</td>
<td>4</td>
<td>74656.09</td>
<td></td>
</tr>
<tr>
<td>Term of order 0</td>
<td>29790.75</td>
<td>1</td>
<td>29790.75</td>
<td>1246.99</td>
</tr>
<tr>
<td>Residual</td>
<td>71.69</td>
<td>3</td>
<td>23.89</td>
<td></td>
</tr>
<tr>
<td>Term of order 1</td>
<td>21.12</td>
<td>1</td>
<td>21.12</td>
<td>0.84*</td>
</tr>
<tr>
<td>Residual</td>
<td>50.56</td>
<td>2</td>
<td>25.28</td>
<td></td>
</tr>
<tr>
<td>Total Reduction</td>
<td>29811.87</td>
<td>2</td>
<td>14905.93</td>
<td>589.63</td>
</tr>
</tbody>
</table>

* Significant at 50 percent confidence interval.

Increasing the numerical value of \( \pi_4 \) caused a decrease in the response because there was more straw per perforation per unit time. There was more grain per perforation which decreased the probability of grain separation through a perforation and, therefore, decreased the response.

4. **Effect of \( \pi_5 \):** The percent grain and m.o.g. separated were plotted against various values of \( \pi_5 \) (Figure 42). A component equation was developed using polynomial regression and was plotted in Figure 42. The model evaluated was: \( P = b_0 + b_1 \pi_5 + b_2 \pi_5^2 \). Table 6 presents the analysis of variance. Increasing the separator length increased the response by providing longer time for grain to separate.
Figure 42. Effect of π₅ on Separator Performance.
TABLE 6. Analysis of variance for $\pi_5$

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>D.F.</th>
<th>Mean Square</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>26914.49</td>
<td>4</td>
<td>6728.62</td>
<td></td>
</tr>
<tr>
<td>Term of order 0</td>
<td>26502.19</td>
<td>1</td>
<td>26502.19</td>
<td>192.84</td>
</tr>
<tr>
<td>Residual</td>
<td>412.29</td>
<td>3</td>
<td>137.43</td>
<td></td>
</tr>
<tr>
<td>Term of order 1</td>
<td>371.57</td>
<td>1</td>
<td>371.57</td>
<td>18.25*</td>
</tr>
<tr>
<td>Residual</td>
<td>40.72</td>
<td>2</td>
<td>20.36</td>
<td></td>
</tr>
<tr>
<td>Term of order 2</td>
<td>37.63</td>
<td>1</td>
<td>37.63</td>
<td>12.21**</td>
</tr>
<tr>
<td>Residual</td>
<td>3.08</td>
<td>1</td>
<td>3.08</td>
<td></td>
</tr>
<tr>
<td>Total Reduction</td>
<td>26911.41</td>
<td>3</td>
<td>8970.46</td>
<td>2909.85</td>
</tr>
</tbody>
</table>

* Significant at 90 percent confidence interval.

** Significant at 75 percent confidence interval.

5. Effect of $\pi_6$: The percent grain and m.o.g. separated were plotted against various values of $\pi_6$ (Figure 43). A component equation was developed and is plotted in Figure 43. The model evaluated for the component equation was: $P = b_0 + b_1 \pi_6$. Table 7 presents the analysis of variance.
Figure 43. Effect of $\pi_6$ on Separator Performance.
TABLE 7. Analysis of variance for \( \pi 6 \)

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>D.F.</th>
<th>Mean Square</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>39098.19</td>
<td>5</td>
<td>7819.63</td>
<td></td>
</tr>
<tr>
<td>Term of deg. 0</td>
<td>39078.08</td>
<td>1</td>
<td>39078.08</td>
<td>7771.59</td>
</tr>
<tr>
<td>Residual</td>
<td>20.11</td>
<td>4</td>
<td>5.02</td>
<td></td>
</tr>
<tr>
<td>Term of deg. 1</td>
<td>1.13</td>
<td>1</td>
<td>1.13</td>
<td>0.18*</td>
</tr>
<tr>
<td>Residual</td>
<td>18.97</td>
<td>3</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>Total Reduction</td>
<td>39079.21</td>
<td>2</td>
<td>19539.60</td>
<td>30887.04</td>
</tr>
</tbody>
</table>

* Insignificant at 50 percent confidence interval.

The regression analysis shows that changing the grain/m.o.g. ratio did not affect the separation performance. At lower values of \( \pi 6 \), there was more straw in the mixture which reduced the number of perforations available for grain. For higher values of \( \pi 6 \), more grain competed for the same aperture and this reduced the probability of grain separation per perforation.

The following model for the prediction equation was developed on IBM 3/360 Digital Computer, employing Multiple Linear regression via BMD-03R.

\[
P = C_0 + C_1 \pi_2 + C_2 \pi_3 + C_3 \pi_4 + C_4 \pi_5 + C_5 \pi_6
\]

\[
+ C_6 \pi_2^2 + C_7 \pi_3^2 + C_8 \pi_4^2 + C_9 \pi_5^2 + C_{10} \pi_6^2
\]

Table 8 shows the values of the constants evaluated through the regression analysis. The multiple correlation coefficient was 0.9636. The analysis of variance is given in Table 9.
TABLE 8. Regression coefficients

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_0$</td>
<td>-175.018</td>
</tr>
<tr>
<td>$c_1$</td>
<td>631.390</td>
</tr>
<tr>
<td>$c_2$</td>
<td>-0.539</td>
</tr>
<tr>
<td>$c_3$</td>
<td>35.918</td>
</tr>
<tr>
<td>$c_4$</td>
<td>119.795</td>
</tr>
<tr>
<td>$c_5$</td>
<td>42.596</td>
</tr>
<tr>
<td>$c_6$</td>
<td>-536.515</td>
</tr>
<tr>
<td>$c_7$</td>
<td>0.010</td>
</tr>
<tr>
<td>$c_8$</td>
<td>-9.947</td>
</tr>
<tr>
<td>$c_9$</td>
<td>-82.792</td>
</tr>
<tr>
<td>$c_{10}$</td>
<td>-30.961</td>
</tr>
</tbody>
</table>

TABLE 9. Analysis of variance for the generalized prediction equation

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>D.F.</th>
<th>Mean Square</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Due to Regr.</td>
<td>6360532</td>
<td>10</td>
<td>6360532</td>
<td>167046*</td>
</tr>
<tr>
<td>Deviation about Regr.</td>
<td>4186428</td>
<td>11</td>
<td>380766</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>67793750</td>
<td>21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant at 99 percent confidence interval.
Experimental analysis showed that separation efficiency can be expressed as a function of $\pi_2$, $\pi_3$, $\pi_4$, $\pi_5$, and $\pi_6$. Data on percent m.o.g. separated from the total m.o.g. fed into the separator is comparable to the m.o.g. separated through straw rack (23).

Analytical investigation indicated that for a blade angle of 75-degrees, screen-to-blade speed ratio of 0.6 and 1.5 ft. screen diameter, the kernel separated at an axial displacement approximately equal to 5 in. Experimental data showed that 65 percent of the grain was separated at $\pi_5 = 0.196$. The rotor under investigation was 36 in. long which corresponds to an axial displacement (for $\pi = 0.196$) equal to approximately 7 in. This, to a certain extent, verifies the theoretical predictions and gives a measure of combined screen, aerodynamic and particle interaction effects. Theoretical predictions about the effects of changing screen-to-blade speed ratio and blade angular speed, as shown in Figures 23 and 24, respectively, compare with similar experimental data. Figure 23 shows that changing screen-to-blade speed ratio did not affect the separator performance which agrees with the experimental data plotted in Figure 39. Figure 24 indicates that increasing the blade angular speed (which corresponds to increasing Frude number) caused an increase in separator length required to separate the kernel. This is verified by a decline in response for higher Frude number, as shown in Figure 40. In short, it can be stated that the experimental data were in good agreement with the theoretical predictions.
CHAPTER III
CONCLUSIONS

(1) Theoretical analysis of particle motion inside a horizontal, conical rotating screen, with radial, helical blades affixed on the inside of the screen, indicated that in this type of centrifugal separator, the crop motion would be very sensitive to the crop frictional characteristics. This separator would not exert any positive control over the crop motion.

(2) Theoretical analysis of particle motion under the influence of rotating blades in a horizontal, cylindrical screen indicated that the performance of this type of centrifugal separator would not be sensitive to the frictional properties of the crop. This separator would allow a better control on the crop motion.

(3) Experimental work on horizontal, conical, rotating screen pointed out that air movement was a very important factor affecting the performance of such a separator. The movement of air through the screen of the rotor was responsible, to a considerable extent, for the failure of the conical, experimental rotor, as constructed and modified, to separate grains from straw.

(4) Experimental work on the horizontal, cylindrical rotating screen with helical blades rotating inside, revealed that this type of separator was, in principle, capable of separating the grains from straw.
CHAPTER IV

SUMMARY

In an attempt to replace the straw racks of the combine by a compact separator, the use of centrifugal force instead of gravity as the primary separating force was investigated. The performance of two different centrifugal separators was analyzed by solving the equations of crop motion inside them. To derive these equations, the crop was treated as a collection of disconnected particles and the aero-dynamic effects were neglected. The equations of motion were solved on an analog computer.

Analog computer simulation results indicated that the first rotor, which was a horizontal, conical rotating screen with radial, helical blades affixed on the wall inside the screen, was capable of subjecting the crop to the centrifugal acceleration for enough time to separate grain from straw. The performance of the conical rotor was very sensitive to the crop physical characteristics that may and do change during a harvesting period. The theoretical analysis of a horizontal, rotating screen with radial, helical blades rotating inside the screen at a faster rate, showed that the separator was not so sensitive to the crop physical characteristics. The cylindrical rotor was capable of separating the grains from straw.

A conical separator was built to study the performance as affected by the system parameters. The horizontal, conical, rotating screen was made of sheet metal perforated with \( \frac{1}{4} \)-in. diameter holes. The entrance
diameter was one foot, the cone half-angle was 25-degrees and it was 21-in. long, axially. Two radial blades making an angle of 20-degrees with an axial line drawn on the inner surface of cone, were fitted 180-degrees apart. During the preliminary test runs it was found that the crop did not move axially mainly due to an air movement through the rotor wall. The conical rotor was not successful.

A horizontal, cylindrical, perforated rotor with faster-rotating radial, helical blades inside the rotor, was built to study its performance as affected by the system parameters. The rotor was made of sheet metal perforated with 3/8-in. holes. The diameter of the screen was 19.5 in. The screen was fitted inside with an auger of 19.25 in. outside diameter, 10-in. pipe diameter, which rotated faster than the screen. The screen was 28-in. long. A prediction equation, for the separation efficiency was developed by using dimensional analysis. The variables included in the equations were blade angular speed, screen-to-blade speed ratio, grain-to-straw mixing ratio, material flow rate, and the screen length used for separation. Separation efficiency in excess to 90 percent was achieved.
CHAPTER V
SUGGESTIONS FOR FURTHER WORK

(1) Effect of air movement on crop motion should be analyzed theoretically for the horizontal, cylindrical screen.

(2) Experiments should be designed to verify the effect of air on the crop movement and separation efficiency.

(3) Since this study was limited to only wheat crop, experiments should be designed to develop a generalized prediction equation for other common crops.

85.
APPENDIX
APPENDIX

EXPERIMENTAL DATA

(i) Effect of $\pi_2$:

Sample size = 8.34 lb. of straw

Values of constant dimensionless groups:

<table>
<thead>
<tr>
<th></th>
<th>$\pi_3$</th>
<th>$\pi_4$</th>
<th>$\pi_5$</th>
<th>$\pi_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16.5</td>
<td>1.69</td>
<td>0.78</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zone</th>
<th>Values of $\pi_2$</th>
<th>Grain separated (lb.)</th>
<th>Material other than grain separated (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.726 0.685 0.500 0.460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.37 4.51 4.49 4.35</td>
<td>1.09 0.71 0.56 0.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.85 0.99 1.03 0.90</td>
<td>0.25 0.38 0.37 0.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.15 0.27 0.27 0.21</td>
<td>1.18 0.25 0.14 0.15</td>
</tr>
<tr>
<td>Loss</td>
<td></td>
<td></td>
<td>0.98 0.20 0.14 0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.31 0.15 0.08 0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(ii) Effect of $\pi_3$:

Sample size = 8.34 lb. of straw

Values of constant dimensionless groups:

<table>
<thead>
<tr>
<th>$\pi_2$</th>
<th>$\pi_4$</th>
<th>$\pi_5$</th>
<th>$\pi_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.69</td>
<td>0.78</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>Values of $\pi_3$</th>
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</thead>
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<tr>
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<tr>
<td></td>
<td>Grain separated (lb.)</td>
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<tr>
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<td>4.55</td>
</tr>
<tr>
<td>2</td>
<td>1.03</td>
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<tr>
<td>3</td>
<td>0.29</td>
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<tr>
<td>4</td>
<td>0.21</td>
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<tr>
<td>Loss</td>
<td>0.43</td>
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<table>
<thead>
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<th>Material other than grain separated (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.39</td>
</tr>
<tr>
<td>2</td>
<td>0.41</td>
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<tr>
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<td>0.20</td>
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<tr>
<td>4</td>
<td>0.11</td>
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</table>
(iii) **Effect of $\pi_4$:**

Sample size = 8.34 lb. of straw

Values of constant dimensionless groups:

<table>
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<th>$\pi_2$</th>
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<th>$\pi_5$</th>
<th>$\pi_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>16.5</td>
<td>0.78</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<table>
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<tr>
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<th>Values of $\pi_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>Grain separated (lb.)</td>
</tr>
<tr>
<td></td>
<td>3.98</td>
</tr>
<tr>
<td>1</td>
<td>1.05</td>
</tr>
<tr>
<td>2</td>
<td>0.39</td>
</tr>
<tr>
<td>3</td>
<td>0.22</td>
</tr>
<tr>
<td>Loss</td>
<td>0.95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material other than grain (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>
(iv) Effect of $\pi_6$:

Sample size = 8.34 lb. of straw

Values of constant dimensionless groups:

<table>
<thead>
<tr>
<th>$\pi_2$</th>
<th>$\pi_3$</th>
<th>$\pi_4$</th>
<th>$\pi_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>16.5</td>
<td>1.69</td>
<td>0.78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zone</th>
<th>Values of $\pi_6$</th>
<th>Grain separated (lb.)</th>
<th>Material other than grain (lb.)</th>
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</thead>
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<tr>
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<td>5.07</td>
<td>4.29</td>
<td>3.65</td>
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<tr>
<td>2</td>
<td>1.23</td>
<td>1.08</td>
<td>0.85</td>
</tr>
<tr>
<td>3</td>
<td>0.47</td>
<td>0.41</td>
<td>0.39</td>
</tr>
<tr>
<td>4</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
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BIBLIOGRAPHY


90.


