A three-dimensional arithmetic model to calculate grain separation and losses for a rotary combine

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Bjork, A. 1991. A three-dimensional arithmetic model to calculate grain separation and losses for a rotary combine. Can. Agric. Eng. 33:245-253. Laboratory studies of grain separation characteristics for a rotary combine were performed. Point grain separation (grain separation through small areas with assigned coordinates), total grain separation (combine capacity), and separation losses were measured for different Mock feed rates and rotor speeds. A three-dimensional arithmetic model to calculate grain separation through the concaves and separating grate of a rotary combine was developed. The model used point grain separation measured at 16 locations in a grid pattern underneath the concaves and separating grate. Curve fitting techniques were used to fit equations to the point separation data. The equations were then appropriately integrated to calculate grain separation and separation losses. The model was run on a personal computer. The computed separation and loss values were compared to the measured values.

INTRODUCTION

A combine operator of today is expected to maximize harvesting capacity without exceeding a certain grain loss level. A too high harvesting capacity will often lead to a rapid increase in grain losses. Operating at a too low loss level will sacrifice harvesting capacity. Both cases will ultimately lead to a higher than necessary harvesting cost.

Unfortunately, a combine operator does not usually have accurate information regarding capacity and losses upon which to base decisions. At best, the operator has a "grain loss monitor" that gives a readout in mass loss per unit time. The operator would, however, be more interested in a device that could continuously indicate harvesting capacity and grain losses as a percentage of harvested amount of grain.

This paper presents a three-dimensional arithmetic model to calculate grain separation and grain separation losses, both in mass per unit time, for a rotary combine. Grain separation is defined as the total mass of grain separated through the threshing concaves and separating grate area per unit time. Grain separation is the equivalent of grain harvesting capacity. The model is based on the measurement of point grain separation (grain separation through small areas with assigned coordinates) at 16 locations underneath the concaves and the separation grate. Point grain separation was here sampled manually, but might in the future be continuously measured by means of "grain loss sensor pads", or other electronic devices.

With information on grain separation and grain separation losses a combine operator can easily find the point of peak performance (i.e. highest possible capacity for a given grain separation loss).

Grain separation through the concaves and grate in a rotary combine

Lo et al. (1978) investigated grain separation through the concave of a stationary rotary corn thresher. The concave area was partitioned perpendicular to the rotor axis in eight equal sections. Corn separation was found to be low underneath the rotor, peak separation to occur halfway underneath the rotor, and separation to decay exponentially underneath the last part of the rotor.

Wang et al. (1984), in field tests, measured point grain separation with piezo-electric grain sensors mounted underneath one rotor on a rotary combine with two parallel rotors. The sensors were mounted on a frame underneath the concaves, without any special provision to catch separated grain from a specific area of the concaves. They reported separation of wheat to decay exponentially with axial distance from the rotor front end, but only if the center region of the concave grate arc was considered. They found more grain to be separated through the center portion of the threshing concave arc than towards either side. The separation distribution along the separating grate arc was reported to be uniform since no distinct peak separation rate existed.

Wacker (1985) used an experimental rotary combine to determine grain separation. He found that prethreshing the crop as a pretreatment only slightly increased the amount of grain separated through the threshing concave. Significant threshing occurs due to the action of the table auger, the intake chain elevator and the rotor vanes. Thus, according to Wacker, a nontreated crop will become prethreshed on the way to the threshing part of the combine rotor.

By assuming the threshing process to have only minor
influence on the separation process, he derived an equation to describe cumulative grain separation. The equation, when converted, is of the same exponential form as the equation used by Reed et al. (1974) and Wang et al. (1984).

Grain separation through the concave in a concave/straw walker combine
Klenin et al. (1970) noted that the greatest quantity of grain is separated through the central part of the concave.

Mahmoud and Buchele (1975) suggested an exponentially decaying equation to best describe the kernel separation through the concave and concave extension of a corn sheller.

Mathematical models to predict grain separation through concaves were developed by Huynh et al. (1982) and Trollope (1982). Huynh et al. developed a separation function that peaks near the entrance of the concave and then decays exponentially towards the end of the concave. Trollope developed a model of the same type as the equation used by Wacker (1985) to approximate cumulative grain separation through the concave.

Grain separation through straw walkers
Klenin et al. (1970) and Reed et al. (1974) used an exponentially decaying function, similar to the equation used by Wang (1984), to describe grain separation through straw walkers. Reed et al. noted, however, that separation through the very first part of the walker increases with distance along the walker and then peaks before decaying exponentially. Non-uniform separation across the width of the straw walker was also noted by Reed et al.

Boyce et al. (1974) approximated grain separation through straw walkers with a normal type distribution.

Gregory and Fedler (1986) used Fick's law of diffusion to predict a grain separation that decays exponentially with straw walker length.

MATERIALS AND METHODS
Experimental unit
An experimental unit was fabricated using the rotor complete with housing, concaves, crate, variable speed drive and intake elevator from a 1978 model 1460 International Harvester rotary combine. The rotor and assemblies were mounted into a steel structure totally enclosed in plywood. This enabled collection of the material separated through the concaves and the separating grate. Sixteen sheet metal ducts were welded in a grid pattern onto the concaves and separating grate to enable measurement of point separation of grain (Fig. 1). The material coming through the ducts was collected in removable fabric bags mounted on a slider underneath the rotor housing. With the slider in the front position, pieces of sheet metal prevented material from falling into the bags. As a result, the material separated through the ducts fell freely onto the bottom of the plywood enclosure (Fig. 2a). With the slider in the rear position, the material coming through the ducts was collected in the bags (Fig. 2b). The slider was manually operated by a lever. Two microswitches, one at each end of the slider path, were interfaced with a computer. The location of the slider relative to time, and the duration of the time that grain was collected in the bags could hence be calculated.

Fig. 1. Dimensions of the experimental unit, showing the left-handed cylindrical coordinate system. The origin for the X measurements is at the right hand end of the funnel-shaped vane section. The origin for the θ measurements is at 0° in A-A to C-C, vertically underneath the rotor axis. The rotation of the rotor is clockwise in A-A to C-C.
Fig. 2. Side view of the experimental unit.
(a) Initial part of run while separation is stabilizing, slider in front position, point grain separation is not measured.
(b) Final part of run, slider in rear position, point grain separation and grain separation losses are measured.

A plywood box was attached to the discharge end of the experimental unit to collect the residue. The box had two sections, one to allow for easy removal of the straw, the other one to enable measurements of grain separation losses. The latter section was equipped with a hinged lid that opened when the slider underneath the rotor housing was moved to the rear position (Fig. 2b). The material not separated through the concaves or separating grate and the material separated through the ducts were hence collected simultaneously.

The rotor assembly was driven from the 1000 rpm PTO of a 130 kW diesel tractor. An emergency stop for the rotor was obtained by connecting a solenoid fuel valve on the tractor to emergency stop switches on the experimental unit.

The crop to be threshed was fed, heads first, by a 15 m long conveyor belt assembly straight into the intake elevator of the experimental unit.

Sampling duct locations and cross-sectional areas
The locations of the sampling ducts along the rotor axis were chosen to give an as even spacing as possible, within the limitations of the manufacturer's design of the concaves and the grate. The locations around the concave arcs and grate arc were a compromise between avoiding edge effects from the interface of nonperforated and perforated concave and grate...
area, and the wish to place the ducts as far apart as possible
(Fig. 1).

Due to the design of the concaves and separating grate, equal
cross-sectional sampling areas for all of the ducts could not be
achieved, and the areas ranged from 4836 mm² to 7650 mm².

Experimental crop

Spring wheat (CV Katepwa) was harvested with a binder,
stacked and protected from the environment by tarpaulins. The
average MOG/grain ratio was 1.2 with a standard deviation of
0.063. The moisture contents (wet basis), as used, of the straw
and grain were in the range 7 to 13 % and 11 to 14 %
respectively with average moisture contents of 10.6 % and
12.7 % respectively.

Experimental design

A randomized complete block design was used, with four
replicates, three feed rates (6, 8 and 10 kg of crop per second)
and five rotor speeds (700, 800, 900, 1000 and 1100 rpm). A
major driveline failure forced termination of the experiment at
run number 34, giving a total of two completely replicated
blocks plus four odd runs. Each run lasted ten seconds, out of
which two-thirds were used to initially stabilize the threshing
and separating process.

Experimental procedure

The threshing concave clearance was initially set at 56 mm in
and 8 mm out and held constant throughout the experiments.

The necessary number of bundles for the respective feed
rate was taken from the stack, weighed on a platform balance
and evenly distributed onto the conveyor belt. The rotor speed
was adjusted according to a tachometer, and when correct the
conveyor belt was started. When two-thirds of the material on
the conveyor belt had been fed into the experimental unit, the
slider underneath the rotor housing was instantly moved to the
rear position. Slightly before the last material disappeared into
the experimental unit, the slider was instantly moved to the
front position.

The content of the bags and the material collected on the
bottom of the rotor housing enclosure was cleaned and the
grain masses were measured. The loose grain kernels expelled
with the straw into the lid covered section behind the experi-
mental unit were recovered by passing the material over the
straw walkers and the cleaning shoe of a stationary plot
thresher. The mass of the grain kernels was then determined.
A random sample was taken during each run from the straw
and separated grain. The moisture contents of the grain and
straw samples were determined according to ASAE S352.2
standard (ASAE 1986).

All data were entered manually and stored on computer
diskettes for later analysis.

A THREE-DIMENSIONAL ARITHMETIC MODEL TO
CALCULATE GRAIN SEPARATION AND
SEPARATION LOSSES

Grain separation through the concaves and the separating grate
was assumed to be uniform in time. Point grain separation
rates were calculated as the collected mass of grain divided by
the collection time and the cross-sectional area of the respec-
tive sampling duct.

The center-point of each sampling duct was assigned coor-
dinates in a left-handed cylindrical coordinate system (Fig. 1).

The x-axis was coincident with the rotor axis, and the origin
for the coordinate system was immediately after the intake
vane section, at the very beginning of the threshing concave.
The angle θ was zero at the mid-portion of the concave and
grate arcs, vertically underneath the rotor axis.

Three main criteria were used in the search for mathemati-
cal functions representing grain separation: (1) the function
representing grain separation along the rotor axis should have
an exponentially decaying tail, (2) the functions should each
have as few coefficients as possible, and (3) the functions
should be versatile enough to represent previously presented
separation data from straw walkers and rotary separators.

Mathematical procedure

Curve-fitting to the point separation data from each run was
done in three steps;

(i) fitting quadratic equations around the concave and grate
arcs,
(ii) calculating averages around each arc, and
(iii) fitting a non-linear equation to the averages, along the
concaves and the grate, parallel to the rotor axis.

Total grain separation and separation losses were then based
on integrations of the non-linear equation.

The function chosen to represent point separation around
the concave arcs and grate arc was

\[ \begin{align*}
S_p &= A + B \theta + C \theta^2 \\
\end{align*} \]

where:

- \( S_p \) = point grain separation (kg·m⁻²·s⁻¹),
- \( A, B \) and \( C \) = coefficients determining shape of curvature of
  separation function, and
- \( \theta \) = cylindrical coordinate around concave arcs or
  grate arc.

Average point separation of grain around a concave arc
respective a separating grate arc was found by integrating Eq.
1 between the two extremities of each arc, and dividing by the
arc. Thus, average point separation of grain was estimated for
each of the five rearmost arcs representing three ducts each.

Average point separation of grain around the concave arc
where the first (single) duct was located had to be estimated
differently. A trial-and-error approach was used to find what
fraction of the measured separation should be used in the
model to give the highest number of computed values within
the least error range. Best results were obtained when taking
80 % of the measured point separation as average point sepa-
ration.

Non-linear regression techniques were used to fit the fol-
lowing equation, in direction parallel to the rotor axis, to the
average point separation data:

\[ S_{axx} = D(x-E)^2 e^{-Fx} \]

where:

- \( S_{axx} \) = average point separation of grain along the
  rotor axis (kg·m⁻²·s⁻¹),

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$D, E & F =$ coefficients determining shape of curvature of
separation function, and

$x =$ axial distance from beginning of first
concave (m).

This function peaks sharply near the entrance of the rotor,
and then decays exponentially with the distance along the rotor
axis.

To obtain cumulative grain separation per unit width of the
concaves and separating grate for an axial interval, Eq. 2 was
integrated with respect to axial distance along the concaves
and separating grate:

$$S_{cw} = \left[ -\frac{x^2}{2} - \frac{2E}{F}x - \frac{2Ex^2}{F^2} + \frac{2E}{F} - \frac{E^2}{F} \right] e^{-Fx}d_2$$

where:

- $S_{cw} =$ cumulative grain separation per unit width for
  interval $d_1$ to $d_2$ (kg-m⁻¹-s⁻¹), and
- $d_1, d_2 =$ lower and upper end respectively of interval to be
  integrated (m).

By multiplying Eq.3 by the width of the separating area,
total grain separated through the area was calculated as:

$$S_c = S_{cw} W_a$$

where:

- $S_c =$ total mass of grain separated through area of
  interval (kg-s⁻¹), and
- $W_a =$ width of separating area (m).

Hence, the mass of grain separated per unit time through the
concave area of the experimental unit was given by multiply-

By a personal computer running software written in APL.

RESULTS

Errors and omissions
Due to a computer disc error, the results from run no. 4 (1000
rpm, 10 kg/s) were not available for analysis. A manual error
made the measured separation losses for run no. 23 too large.
The measured grain separation and measured grain separa-
tion losses were based on the assumption that grain separation
was uniform relative to time. The effect of non-uniform sepa-
ration rate is unknown.

Curve fitting of the average point separation data along the
rotor axis
Based on the standard deviation, $s$, of the fit of the non-linear
equation, the selected Eq.2 gave a reasonable representation of
the mass flow of grain separated through the concaves and the
separation grate. The standard deviation, $s$, of the fit is given
in Table I for the individual runs.

Computed grain separations
The relative deviations of computed grain separation from
measured grain separation are plotted versus measured grain
separation in Fig. 5. The linear correlation coefficient, $r$, for
computed and measured grain separation was $r = 0.83$. The
coefficient of variation, CV, of the ratio computed/measured
grain separation was 13 %. Grain separation was computed
within ±15 % of the measured separation for 26 runs out of a
total of 33 valid runs.
Table I. Measured and computed data for the individual experiments

<table>
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<th>Run #</th>
<th>Rotor speed (rpm)</th>
<th>Feed rate, s of crop (kg s⁻¹)</th>
<th>Grain separation ** computed (kg·m⁻²·s⁻¹)</th>
<th>Grain separation loss computed (kg·s⁻¹)</th>
<th>Measured adjusted (kg·s⁻¹)</th>
<th>Measured (kg·s⁻¹)</th>
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* Standard deviation for the non-linear regression of the average point grain separation of each segment, in direction parallel to the rotor axis.

** Grain separated through the concaves and separating grate.

Computed grain separation loss

Grain separation losses calculated by the computer model were consistently too low (Fig. 6). By using linear regression techniques, the computer modeled losses were adjusted as:

\[ S_{ca} = 0.02 + 1.33 S_c \]  \hspace{1cm} (6)

where:

\[ S_{ca} = \text{adjusted computed grain separation loss (kg·s}^{-1}) \text{, and} \]
\[ S_c = \text{total mass of grain separated in interval from end of separating grate to infinity (kg·s}^{-1}). \]

The outlier run no. 5 was not used in the regression. The square of the linear correlation coefficient achieved by the least square fit was \( r^2 = 0.93 \), standard deviation for the fit, \( s = 0.024 \text{ kg·s}^{-1} \).

The relative deviations of adjusted computed grain separation losses from measured grain separation losses are plotted versus measured separation losses in Fig. 7. Adjusted computed grain separation losses and measured grain separation losses had a \( r = 0.88 \) and their ratio a \( CV = 36 \% \). Adjusted computed grain separation losses were within ±15 \% of measured grain separation losses for 10 runs out of a total of 32 valid runs.
Computed relative grain separation loss

Relative grain separation loss is obtained when grain separation loss is divided by grain separation. This loss on a percentage basis is the loss a farmer would be most interested in. The relative deviations of computed relative grain separation losses from measured relative grain separation losses are plotted in Fig. 8. The adjusted computed grain separation losses were used in the calculations. Computed relative grain separation losses and measured relative grain separation losses had \( r = 0.83 \) and their ratio a CV = 36%. Relative computed grain separation losses were within \( \pm 15 \% \) of relative measured grain separation losses for 12 runs out of a total of 32 valid runs.

DISCUSSION

Mathematical representation of the average point separation of grain along the rotor axis

The equation chosen to represent average point separation along the rotor axis (Eq. 2) has not previously been cited in literature seen by the author. However, the exponentially decaying tail produced by the equation agrees with previously presented grain separation characteristics of rotary combines, threshing cylinders and straw walkers. Furthermore, the initially increasing grain separation suggested by the equation is similar to data presented by Wacker (1985), Lo et al. (1978), Boyce et al. (1974) and Reed et al. (1974).

In some cases (Fig. 9a) the computed grain separation is initially high and rapidly decreasing to nil, then increasing and finally exponentially decaying. Such initial grain separation will not be achieved by any grain separating mechanism, but is merely a product of the nature of Eq. 2. The discrepancy does not significantly influence the computed grain separation, and could if desired easily be eliminated by computer software.

Since grain separation depends on preceding threshing, it follows that when threshing is insufficient or inefficient in the first part of a rotary threshing mechanism, initial grain separation has to be low or delayed. This can clearly be seen in the initial part of the grain separation computed at low feed rates.
and high rotor speeds (Fig. 9a). The density of the straw mat between the rotor and the rotor cage might here be too low to allow early threshing by efficient rubbing of the grain heads. However, prethreshing by the table auger and intake elevator might offset poor initial threshing, as noted by Wacker (1985). This might explain the initially high or initial peak grain separation found for a rotary combine by Wang et al. (1984). Also, for grain sensors to be given accurate location coordinates, they need probably to be located in an enclosure mounted on the concave or separating grate.

Monitoring grain loss

A number of grain loss monitoring systems have been developed throughout recent years. The models, of which the author is aware, treat separation across the width of the concave, straw walker, sieves, concave arc, and separating grate arc as being uniform. This is not a valid assumption, however. The non-uniform separation along the concave arc and separating grate arc presented here agrees with data on separation through straw walkers presented by Reed et al. (1974), and separation through the concave arc on a rotary combine presented by Wang et al. (1984).

CONCLUSIONS

Two mathematical functions with three coefficients each can be used to describe point grain separation around and along the concaves and separating grate of a rotary combine. A three-dimensional arithmetic model, based on integration of the two mathematical separation functions, can be used to calculate grain separation and grain separation losses for a rotary combine. The arithmetic model was tested with experimental data. The model placed most computed grain separation values within a range of measured grain separation values that would be acceptable for practical purposes. The model was less successful in computing the grain separation losses close to the measured values, particularly at low loss levels.

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