Simulation of grain-straw separation by a Discrete element Approach with bendable straw particles

Bart Lenaerts¹*, Engelbert Tijskens¹, Josse De Baerdemaeker¹, Wouter Saeys¹

¹KU Leuven, Division of Mechatronics, Biostatistics and Sensors (MeBioS). Kasteelpark Arenberg 30, B-3001 Heverlee, Belgium

*Corresponding author. E-mail: bart.lenaerts@biw.kuleuven.be

Abstract

Grain losses are the principal quality indicator of the threshing and separation process in combine harvesters. The acceptable grain loss over all sub-processes is typically not higher than 1% and the losses due to an incomplete separation of the threshed grain kernels from the straw layer (separation losses) usually have the biggest share. The efficiency in separating the grain kernels from the straw in a combine harvester depends on the crop properties and the settings and configuration of the separation system. Traditionally, the configuration and settings of a separation system are optimized through trial and error. A separation model allowing to simulate the impact of the crop properties, the system configuration and the settings would allow to optimize these system parameters in silico prior to building a prototype system.

Discrete element modeling (DEM) is a natural choice to model the behavior of granular materials, like grain kernels, as it allows to model the behavior of each kernel through its interactions with the other kernels and the system elements. However, simulating the straw particles with discrete elements is more challenging as straw has a large aspect ratio resulting in a clear orientation. Moreover, straw is bendable, a property which is known to have an important impact on the separation process. To our knowledge this property of straw has always been neglected in DEM simulations of the separation process. To overcome this limitation, a discrete element approach including bendable straw has been implemented in the DEMeter++ software. In this study, a separation experiment described in literature involving a shaking box filled with straw and kernels has been repeated in silico to validate the DEM simulations by comparing the simulated separation profiles to the measured ones.

Keywords: DEM, bendable cylindrical particles, separation, straw, grain, combine harvester

1.Introduction

In the separation section of a combine harvester, the grain kernels which have been released from the ears through the threshing actions are expelled from the straw layer, while the plant material is conveyed to the straw discharge. All free grain that is still present in the straw layer at the end of the separation section is lost. This separation loss depends on both the grain penetration through the straw layer and the conveying velocity of the straw layer as the residence time of the plant layer in the separation section limits the time available for a grain kernel to migrate to the bottom of the layer where it falls through the openings in the concaves. The thicker and more dense the plant layer is, the more this penetration is restrained as the kernels have to follow a longer and more tortuous path.

Quantitative insight in the effects of crop properties, design –and adjustments of the combine harvester on both processes is required for an optimal operation of the separation system. As optimization of the design and settings of the separation section is very challenging and labor intensive, an accurate model describing the separation process in a grain harvester would allow to (Kutzbach, 2003):

- Reduce the test expenditure
- Improve the understanding of the fundamental relationships
• Hint for possible improvements
• Simulate the influences of different parameters
• Estimate possible performance increases.

The models which have been reported in literature (e.g. Kutzbach, 2003) fit well to the experimental data, but their empirical nature typically limits their practical relevance to specific crop- and machine conditions. A more generic approach would be to divide the model into a kernel penetration and a bulk transport model.

An idealized setup to study the first aspect has been used by Baader (1969) and Beck (1992). The setup consists of a straw layer contained in a vertically, sinusoidally oscillating box. After the crop has been agitated for a certain time, a layer of grain kernels is released at once on top of the oscillating straw layer. Grain passage through the grating at the bottom of the box is recorded in function of time. The grain penetration shows a vertical sinking, combined with a lateral dispersion of the particles. This results in a sigmoidal curve of the separated fraction in function of time. The lower the area density of the straw layer, the steeper the kernel penetration function will be. Furthermore, the penetration function is influenced by a combination of crop properties. Beck attributed a technical crop property to the penetration time of 80% of the kernel mass and showed a linear relationship of the capacity of the walker section of a combine with this penetration time.

As the crop properties influence the unit process to the same amount as the process on the walkers, this technical crop property bundles the influence of individual crop properties. Still, little fundamental knowledge is gained on the influence of crop particle properties like the Young’s modulus in bending, friction coefficients and dimensions of straw and grain particles. The influence of these factors has been underlined in the work of Hall and Husman (1981) Shandilya (1987) and Srivastava (1990). As many of these properties are interdependent (Hall and Husman, 1981), it is not feasible to make an experimental design including different levels of each of these crop properties in a real-life experiment.

When modeling the behavior of a collection of particles, like grain kernels, Discrete Element Modeling (DEM) is a straightforward choice as it allows to model the behavior of each kernel through its interactions with the other kernels and the system elements. Also in agricultural processes it is more and more used for process simulation of e.g. grain flow in silos (González-Montellano et al., 2011), fertilizer spreading (Tijskens et al, 2003; Van Liedekerk et al, 2009) or manure handling and land application equipment (Landry et al. 2003). In this way, the influence of particle properties and boundary conditions can be assessed with a set of in silico experiments that can be run in parallel. However, simulating the straw particles with discrete elements is more challenging as straw has a large aspect ratio resulting in a clear orientation. To study the alignment of straw particles and cutting blades in the chopper section of a combine Kattenstroth et al. (2011) employed a Discrete Element Model with straw particles built up of connected spheres. Additionally, straw is bendable, a property which is known to have an important impact on the separation process. To the authors’ knowledge this has not been reported in scientific literature to date. To overcome this limitation, in this study a discrete element approach including bendable straw has been implemented in the DEMeter++ software. Once the straw particles have been constructed in the DEM software, the crop properties can be easily defined and changed independently. This makes it relatively easy to study the effect of these individual crop properties and their interaction on the separation profile in simulation. The Discrete Element Model with bendable straw particles is then used to simulate a separation experiment described by Baader (1969) and Beck (1992). The accuracy of the DEM simulations is evaluated by comparing the simulated separation profiles to the reported experimental profiles.

2. Discrete Element Modeling of grain separation

In the simulated experiment, the segregation of the binary mixture is studied. Therefore, the first step consists of defining both particle classes such that these behave similarly to the true particles. Once both classes have been defined, the simulation structure is set up.
1.1. Grain particles and bendable straw particles

Grain kernels are ellipsoid in shape. Even though this shape can be approximated in DEMeter++ by composite particles built up of several overlapping spheres, it was chosen to represent them as simple spheres. Composite particles would result in higher computation times while the effect of this approximation is expected to be negligible.

Subsequently, bendable straw particles have been constructed. To allow the particles to flex, the stalks were segmented. Each segment consists of a rigid hollow cylinder. The cylinders are connected by a spherical joint. An additional sphere is placed at both ends of the simulated straw particle.

To give the joints bending stiffness a virtual disk was positioned at the intersection of each cylinder with the spherical joint. This means there are two disks per segment joint. Six springs on an axisymmetric pattern connect both disks of a joint. The springs' stiffness determines the bending resistance of the joint. A seventh spring was placed at the center of the pattern for tensile stiffness. The bending stiffness of these joints can be calibrated by performing a simulated three-point bending test on the simulated straw stalk as a whole. The springs' elasticity is then adjusted so that the simulated bending stiffness of the stalk confirms the real one.

The number of segments is arbitrary, but similar to the number of grain particles considered in the simulation this has an important impact on the simulation time. In this study, 5 segments have been used to balance accuracy and simulation time. The particles obtained in this way behaved realistically in a simulated three-point bending test.

1.2. Particle interaction

Contact detection was done grid-based for the contacts between the particles while for the walls the contacts were detected with a brute-force approach.

When in contact with each other or with the walls, the particles experience normal and tangential forces. The normal contact is modeled by a nonlinear spring-damper model, while the tangential contact is modeled as Coulomb-friction.

1.3. Simulated experiment

The experiment performed by Beck (1992) consists of a cubic box of 0.707 m which oscillates sinusoidally in the vertical direction with an amplitude of 0.03 m and a frequency of 4 Hz. At the bottom of the box, a grating holds back the straw, but allows the grain to pass.

Initially, the box is filled with straw up to a certain area density. In a next step, the straw is shaken for 20 s to randomize it. After the randomization a homogenous layer of grain is released on top of the shaking straw.

A weighing scale underneath the box records the separated fraction in function of time. The experiment has been repeated for several grain and straw area densities in order to assess their effect on the penetration time.

1.4. DEM-simulation of the separation experiment

Although the real-life separation experiment takes a short time to execute, the corresponding simulation is computationally expensive due to the high number of particles. Therefore, the DEM-experiment has been changed compared to the true experiment in some aspects to shorten the simulation time.

The simulation consists of 4 phases:

a. Initialization of the straw layer.

The straw is aligned at the bottom of the box in horizontal layers of 70 particles. The centerlines of the straw particles in a layer are 0.01 m apart, horizontal layers are also at 0.01 m apart. Subsequently, the joints of each straw particle are given a
random initial deviation with a maximum of 2.5 mm. This is a property of true straw particles and besides it reduces the number of contacts at the first moment that the straw particles touch.

b. Randomization of the straw layer.

After the initialization of the straw layers the oscillatory movement as mentioned in the real-life experiment is started. In this way, the straw is allowed to randomize in the box for 2 s. As in a real experiment, the particles experience aerodynamic drag, this effect has also been implemented in the simulation. The straw randomization was shortened in comparison to the real experiment to reduce the simulation time. The timestep of discretization was set to 6 µs. Afterwards, the state of all particles is saved. This allows for a rerun of the experiment with different area densities of grain. Simulations have been performed with two straw area densities: 0.4 kg/m² and 1 kg/m².

c. Grain initialization

5213 grains (0.5 kg/m²) are randomly spread over the area of the box in one layer at the top of the box. Beck observed that the area density of grain at initialization did not influence the separation rate when he tested densities between 1 - 4 kg/m². This means that at these densities grain kernels don’t impede each other's penetration through the straw. Therefore, the number of kernels below 4kg/m² does not influence the cumulative separation curve and it was opted to perform the simulations with 0.5 kg/m² to speed up the simulations.

d. Grain and straw simulation

The grain layer is released at once above the straw mass. The kernels' fall is counteracted by aerodynamic drag. After about 0.5 s, the kernels reach the straw mass. The straw restrains the kernels' movement. As the straw is randomized, the particles' trajectory length as well as their velocity on the trajectories differ. As the kernels approach the floor they pass through freely as there is no contact detection between the kernels and the floor of the box. This is different from physical experiments where a grid floor slightly slows down the grain kernels. This influence is, however, very limited as stated by Beck (1992) because a grid of 1x1 cm was employed. Due to the large number of contacts between the particles, it was necessary to reduce the time discretization in comparison to the randomization phase from 6 µs to 2 µs.

e. Post-processing

In step d the number of grain kernels passing through an imaginary plane at 5 cm below the floor of the box is detected. This is different from the experiment described by Beck (1992) in that this would imply that the weighing scale would have to move with the box' oscillating movement. This was not the case in the experiment described by Beck (1992) as it would introduce more measurement noise and the need for dynamic weighing. This could introduce some small variance compared to the experiment of Beck, but is more useful from a modeling point of view as there is a fixed distance between the point where the kernels are separated and the point of detection, keeping the distance that the kernel is subjected to aerodynamic drag constant. Only the plane of detection is moving, for which can be corrected easily.

In post-processing, the cumulative separated fraction is plotted in function of time.

3. Results

Stable simulations were obtained with the use of the above-mentioned particle parameters and time discretization step. The combination of sinking and lateral dispersion of the kernels shows itself in sigmoidal curves for the cumulative separated fraction. These are plotted for straw area densities of 0.4 kg/m² and 1 kg/m² in Fig. 2. When the straw area density is higher, the straw layer is thicker and less porous as it is compacted under its own weight. This results in a lower sinking velocity of the kernels together with more lateral dispersion.
Therefore, the separation rate will be lower and the cumulative separation function will be less steep, as can be seen in Fig. 2.

The observed trends agree with the ones reported by Beck (1992). However, for a full one-to-one comparison, higher straw area densities would have to be simulated and the crop properties should be fully calibrated to the ones employed in the real experiment. From these curves the time to separate 80% of the kernel mass can be easily read. This was previously employed by Beck to predict the capacity of the walkers.

A slight boundary effect appears in the data. As the void space is higher near the walls perpendicular to the stalks, and the kernels can only be scattered in one direction, the sinking velocity of the grains is higher in this part of the box than in the straw bulk. Additionally, the sinusoidal movement of the box translates into a sinusoidal course of the forces on the particles. This results in more separation when the box rises and can be seen in a slight superposition of a sinus on the cumulative separated fraction.

![Figure 2: Cumulative separated fraction with 0.5 kg/m² of grain kernels and resp. 0.4 kg/m² and 1 kg/m² of straw.](image)

4. Conclusion

A grain-straw separation simulation with bendable straw particles has been performed successfully. The grain particles have been kept spherical even though the realistic shape is elliptical. The innovative aspect in this paper lies in the approximation of bendable straw particles by segmented cylindrical particles.

The particles can be given realistic properties. In the experiments for this paper, the bending resistance was only roughly approximated as the main goal was to test the feasibility of bendable straw particles in separation simulation.

The experiment as performed by Beck has been simulated as closely as possible so as to be able to compare the results with the ones by Beck. However a trade-off had to be made with simulation time and only qualitative agreement was intended as the particles still have to be calibrated.

The curves of cumulative separated fraction in function of time show good qualitative agreement with the ones of Beck. Beck concluded that the area density of grain at initialization did not influence the separation rate when he tested densities between 1 and 4 kg/m². This means that at these densities grain kernels don't impede each other's penetration through the straw. Therefore the number of kernels below 4 kg/m² does not influence the cumulative separation curve and it was opted to perform the simulations with 0.5 kg/m² to speed up the simulations.

Beck concluded a lower separation rate at a higher area density of straw. This can be intuitively understood as the straw layer is thicker and less porous as it is compacted under its own weight. This can also be seen in the DEM experiments. Additionally, the sinusoidal movement of the box translates into a sinusoidal course of the forces on the particles. This results in more separation when the box rises and can be seen in a slight superposition of a sinus on the cumulative separated fraction.
For a simplified grain-straw separation experiment, qualitative agreement was observed between the trends in the simulated profiles and the experimental ones reported in literature. To be able to also quantitatively validate this DEM approach, a larger number of simulations involving larger simulation times and the correct particle properties is needed. As the relevant physical properties of the particles were not reported in literature, the crop particles will have to be calibrated with the properties found in literature. There is, however, a large variation in these properties such that a full quantitative agreement of the separation results will never be attained unless all the properties of the particles used in the separation experiment are known.

### Reference list


