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Simulation of grain–straw separation by Discrete Element Modeling with bendable straw particles

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ABSTRACT

The combine harvester owes its name to the integration of the whole chain of grain harvesting steps in one machine. Running these interdependent processes simultaneously requires insight in the influence of crop factors and adjustments on the individual processes and the consequences for downstream processes. This paper introduces changes to the Discrete Element Method (DEM) in order to be suitable for the simulation of grain–straw separation, which is one of the most critical processes in the combine harvester. Segmented bendable straw particles have been constructed in the DEMeter++ simulation environment and their physical properties have been calibrated with realistic straw properties. The use of these particles for modeling separation has been validated by reconstructing an existing separation experiment by Beck (1992) in DEMeter++ and comparing the simulation result with the experiment. Once validated, the practical use of the simulation framework to assess the sensitivity of separation to crop properties is illustrated.

1. Introduction

Grain and straw have a different shape and density. Grain can therefore be separated from straw by accelerating the mixture. In the separation section of a combine harvester, the grain kernels which have been released from the ears through threshing have to be expelled from the straw layer. The necessary acceleration is induced by the action of oscillating walkers or centrifugation. Obviously, as the combine harvester is a continuous-flow machine, the residence time of the grain–straw mixture in the threshing and separation unit limits the time available for the grain to migrate through the straw layer to the walker's surface. Grain kernels that are threshed but are still lodged in the straw layer when it leaves the machine are called separation losses. Modern combine harvesters separate more than 100 tons of this grain and straw mixture per hour, meanwhile, the acceptable grain loss over all subprocesses is typically not higher than 1%. The separation and cleaning losses usually have the biggest share. Designing a new separation section and optimizing its settings is not straightforward due to the complex interaction between the machine and the crop. In addition, for an optimal operation of existing separation sections, quantitative insight in the interference of crop, design and settings is required. 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.
- Make a targeted choice on future improvements.
- Simulate the influences of different parameters.
- Estimate possible performance increases.

A modeling framework for separation should be able to describe the particle interactions adequately and to include particle properties involved. The models which have been reported in literature (summarized, e.g. in Kutzbach (2003)) fit well to the experimental data, but their empirical nature typically limits their practical relevance to specific crop and machine characteristics. Furthermore, the effect of crop properties on separation is mostly unclear as different crop property combinations can give the same end result in separation. However, the importance of their influence on the separation process has been underlined by Hall and Husman (1981); Shandilya (1987) and Srivastava et al. (1990). As many of these properties are interdependent (Hall and Husman, 1981; Huisman, 1978) it is impossible to correlate individual crop properties to separation performance statistically. Moreover, the biological variability of the crop in the field is high and the strong effect of feedrate on separation will shade the effect of other factors. In order to have better control over the variables involved and to be able

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Nomenclature

a	model parameter	GR	grain radius (m)
a_i	acceleration (m/s^2)	GW	grain weight (kg)
A	particle area (m^2)	I	inertia tensor (kg m^2)
$AICc$	Akaike's information criterion	I_b	second moment of area (m^4)
b	model parameter	k	spring constant (N/m)
BIC	Bayesian Information Criterion	L	straw length (m)
C_p	Mallow's criterion	m	mass (kg)
dl	bending deformation (m)	ML	straw unit mass (g/m)
e	straw wall thickness (m)	R	straw radius (m)
E_b	Young's modulus in bending (GPa)	r_c	position of contact w.r.t. center of mass of particle (m)
E_e	Young's modulus in tension (N/m^2)	S	cumulative separated fraction
F_b	straw bending force (N)	t	time (s)
F_c	contact force (N)	α_i	rotational acceleration (rad/s^2)
F_e	extension force (N)	Δt	time step (s)
G, H	body forces (N)	$t_{0.8}$	time to separate 80% of the grain mass (s)

to monitor the process more accurately, laboratory experiments on separation have been carried out under known conditions of crop weight and properties. In this context an idealized experiment representative of separation on straw walkers, employed by Baader et al. (1969) has been repeated in several research works in the last decades, for instance by Huisman (1978) and Beck (1992). The set-up consists of a straw layer contained in a vertically, sinusoidally oscillating box. After the straw 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 sinks through the straw layer, while it disperses laterally. This results in a sigmoidal curve of the separated fraction in function of time. The lower the area density of the straw layer, the faster the kernels can sink and the steeper the separation curve will be. Shandilya (1987) used a similar setup but with horizontal instead of vertical shaking.

Although empirical models can describe the macroscopic separation behavior well if they are calibrated with experiments, physical relations are scarcely evident (Kutzbach, 2003). Knowledge on the mechanical interactions between grain and straw particles would yield fundamental insight into the influence of the boundary conditions and the properties of these particles on the separation performance. As this interaction takes place at the particle level, a modeling framework on this level should be set up.

When modeling the behavior of a collection of particles, like grain kernels, Discrete Element Modeling (DEM) is a logical 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, DEM is more and more used for simulating particulate processes as, e.g. grain flow in silos (González-Montellano et al., 2011), fertilizer spreading (Tijskens et al., 2003; Van Liedekerke et al., 2009) or manure handling and land application equipment (Landry et al., 2006). 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 constructed with connected spheres. However, straw is bendable, a property which is expected to have an important impact on the separation process. To the authors' knowledge, DEM simulation with bendable straw particles has not been reported in scientific literature to date.

Therefore, in this study a discrete element approach including bendable straw has been implemented in the DEMeter++ (Tijskens et al., 2003) software. Once the straw particles have been constructed, the crop properties can be easily defined and changed independently. This makes it relatively easy to study the sensitivity of the separation profile with reference to the individual crop properties. The Discrete Element Model with bendable straw particles is then used to simulate the stationary separation experiment described by Beck (1992). As the properties of the straw and grain kernels employed in the real-life experiment are not known, an experimental design of crop properties is set up and a simulation is run with each set of crop properties. The validation then consists of a statistical comparison of simulated separation profiles to the reported experimental profiles. Once validated, the different separation profiles can be used to perform a sensitivity analysis of the crop properties on the separation rate.

2. Discrete Element Modeling framework

The Discrete Element Method (DEM), also called Discrete Element Modeling, is a numerical technique to model the motion of an assembly of particles which interact with each other through collisions. It was originally developed by Cundall and Strack (1979) for predicting the behavior of soil grains and belongs to the group of "Particle Based Simulations". By applying DEM, the trajectory of each particle in a system can be obtained using a numerical time integration scheme. At each time step, all forces acting on the particles like contact forces and body forces are summed. Newton's equations of motion are then integrated to obtain the velocity and position of each particle at the next time step (Tijskens et al., 2003). A DEM problem can be described mathematically as a system of non-linear differential ODE's formed by Newton's equations of translation (Eq. (1)) and rotation (Eq. (2)) for each individual particle i:

$$m_i a_i = G_i + \sum_c F_{ci} \quad (1)$$

$$I_i \alpha_i = H_i + \sum_c r_{ci} \times F_{ci}, \quad i = 1, \ldots, N \quad (2)$$

a_i and α_i are the translational and rotational acceleration of the ith particle and m_i and I_i are the mass and inertia tensor. G_i and H_i are the body force and moment that act on the ith particle. Additionally F_{ci} is the contact force acting on the particle caused by the cth contact with a neighboring particle. Finally, r_{ci} represents the position