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A discrete element approach for modelling the compression of crop stems

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ABSTRACT

The discrete element method (DEM) offers a powerful tool for simulating the interactions of large numbers of particles. Recently, DEM was used to simulate the interactions of tubular particles. While the existing linear elastic and Hertzian contact models can approximate the reversible compression for small deformations, they are inadequate for larger deformations. Here, the force–deformation behaviour is highly non-linear and plastic. In this study, data based contact models were developed for crop stems. These models combine realistic deformation behaviour with a minimal number of model parameters. Furthermore, the effect of plastic deformation and damage was incorporated in the model. The contact models were successfully used to validate, through comparison of simulations and measurements, individual stem and bulk compression. A good agreement was found between both. These validated DEM contact models for compression of crop stems allow to simulate the processing of large numbers of crop stems.

1. Introduction

The importance of simulations for the optimisation of various processes is increasing because simulations can provide a huge potential in terms of process understanding and development of machines. Development costs can be reduced by evaluating machine adjustments in early stages via computer simulations before building costly and complex prototypes. This simulation approach also enables the investigation of new and unconventional ideas with acceptable effort (Jünemann et al., 2013). To obtain realistic simulations, both the machine and the material to be processed should be simulated with sufficient accuracy. In the case of biomaterial processing, the biological variation adds an extra challenge.

In this study, we focus on the processing of crop stems by harvesting machines such as combines and balers. When the interactions between individual stems or between stems and machine components are important, traditional bulk approaches (e.g. finite element modelling) are often inadequate. As these interactions take place at the particle level, a modelling framework on this level is required.

1.1. Discrete element modelling of crop stems

When modelling the behaviour of a collection of particles, Discrete Element Modeling (DEM) is a logical choice as it allows to describe the behaviour of each particle through its interactions with the other particles and the system elements (Tijskens et al., 2003). In this way, the influence of particle properties (both geometrical and mechanical properties) and boundary conditions (shape and motion of machine parts) can be assessed with a set of in silico experiments that can be run in parallel (Lenaerts et al., 2014). To obtain reliable simulation results, the virtual stems must have realistic geometries and deform realistically during contact. The stems should, therefore be compressible in both longitudinal and radial direction and also bendable in every direction. However, few reports have been published on particles with large aspect-ratio, as simulating the movement and collisions of these particles is considerably more complex than for rigid spherical particles.

In the last years, tubular particles were created by a number of researchers (Ross and Klingenberg, 1997; Favier et al., 1999; Grof et al., 2007; Kattenstroth et al., 2011; Geng et al., 2011; Guo et al., 2012b, 2013a,b; Nguyen et al., 2013; Grof and Štěpánek, 2013; Jünemann et al., 2013; Kajtar and Loebe, 2014; Nan et al., 2014; Lenaerts et al., 2014; Leblicq et al., 2014, 2015a). The accuracy of the simulations with these particles varies greatly. Ross and Klingenberg (1997) studied the dynamics of flowing

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suspensions of rigid and flexible fibres composed of linked rigid bodies. They demonstrated that the method can reproduce known dynamical behaviour of both types of fibres in a flow field. Favier et al. (1999) developed a method for representing smooth-surfaced, axi-symmetrical particles using overlapping spheres of arbitrary size. Virtual straw stems were developed by Kattenstroth et al. (2011) by connecting spheres. The stems in this research were, however, rigid and unbendable. The same method was used to create rigid fibres and rodlike particles (Grof et al., 2007; Grof and Štěpánek, 2013; Nan et al., 2014). Flexible filamentous particles composed of chains of rigid bodies connected through ball and socket joints were developed by Geng et al. (2011, 2013a,b,). Jünemann et al. (2013) and Kajtar and Loebe (2014) created bendable crop stems by connecting spheres with cylindrical bonds. Guo et al. (2012b) compared glued-spheres particles and true cylindrical particles and concluded that for smooth particles the most realistic results are obtained with cylindrical particles. Guo et al. (2012a) also described methods for more optimal contact detection and dense packing of cylindrical particles. Lenaerts et al. (2014) created segmented bendable straw stems by connecting rigid cylinders with flexible configurable bonds. They used the DEMeter++ software (Tijskens et al., 2003) to simulate grain-straw separation and validated the results with measurements. Leblicq et al. (2014, 2015a) improved the bending model of Lenaerts et al. (2014) and obtained tubular particles (crop stems as well as metal and plastic tubes) with realistic bending and buckling behaviour.

1.2. Contact models for tubular particles in DEM

The discrete element method uses the Newton–Euler equations of motion to compute the translatory and rotational movements of every particle in the simulation. Due to these movements, particles make contact and interact. Interacting particles are allowed to virtually overlap. The normal forces which particles exert on each other are determined by a contact model (based on this virtual overlap and potentially on the contact history). Contact models for calculating normal and tangential forces are usually analogues models based on spring, damper and friction elements (Jünemann et al., 2013).

Contact forces are typically decomposed into a normal and tangential component, with respect to the contact surface. The normal component of the contact force acting on a particle is generally described as a function of the virtual overlap (δ) and its time derivative ($\dot{\delta}$) (Tijskens et al., 2003). The simplest model assumes a linear elastic component and a linear viscous damping.

$$F_n(\delta, \dot{\delta}) = k_1\delta + \gamma_1\dot{\delta} \quad (1)$$

For viscoelastic materials, a non-linear model, based on Hertz contact law can be derived (Tijskens et al., 2003):

$$F_n(\delta, \dot{\delta}) = k_2\delta^{3/2} + \gamma_2\delta^{1/2}\dot{\delta} \quad (2)$$

Tangential contact forces arise when two particles take part in an oblique collision or when contacting particles are rotating relative to each other. The simplest contact model in the tangential direction describes Coulomb friction with a viscous damper enforcing the no-slip regime. As for impact in the normal direction, realistically behaving contact models in the tangential direction also require elastic and viscous terms (Tijskens et al., 2003).

These basic contact models were also used to model the interactions between tubular particles. Grof et al. (2007), Nguyen et al. (2013), Jünemann et al. (2013), Kajtar and Loebe (2014) and Leblicq et al. (2015a) used linear spring-damper systems. Guo et al. (2012b), Nan et al. (2014) and Lenaerts et al. (2014) used Hertz contact models. All studies used Coulomb friction.

1.3. Limitations of the existing contact models

Although it has been shown that stem deformation processes are definitely non-linear (Leblicq et al., 2015b), in DEM the processes have typically been assumed to be linear. Only for the first, linear elastic part of the force–deformation curve this assumption is acceptable. At larger deformations, ovalisation, buckling and cracking of the particles takes place. This results in a highly non-linear and plastic deformation behaviour. Plastic deformation implies that stems will respond differently to re-compression or further deformation, which is ignored by the DEM contact models. The bulk behaviour of a collection of stems is the sum of the behaviours of the individual stems. Incorrect stem behaviour could thus result in incorrect simulation results and incorrect decisions for machine optimisation. Therefore there is a need for DEM contact models that can realistically describe the deformation behaviour of crop stems and that takes plastic deformation into account.

1.4. Objectives of this study

To the knowledge of the authors, no studies have been conducted to define DEM contact models for tubular particles describing the contact behaviour realistically both for undeformed and damaged stems. Therefore, the general objective of this study was to create and validate these contact models. In order to achieve this goal, there are some specific objectives. First, the forces required to deform crop stems need to be measured. Then, the deformation of individual stems has to be modelled using data based models. Afterwards, the interactions between individual stems and between stems and plates (representing a machine part) need to be modelled. Finally, the contact models need to be validated both on stem and bulk level.

2. Material and methods

In this study, we started from the segmented crop stems developed by Lenaerts et al. (2014) in DEMeter++ (Fig. 1). Each segment consists of a capsule connected to its adjacent capsules by joints. The joints are responsible for the flexibility of the particle. In each joint, a number of spring-dampers (k_b, c_b) is placed which creates a moment that counteracts bending forces. The tensile stiffness of each segment of the straw particle is provided by one spring and damper (k_t, c_t) per segment. The Werner and Haff model is used to model the tangential contact forces (friction) (Haff and Werner, 1986). When stems interact, they virtually overlap and exert normal forces on each other. An extra spring-damper system (k_c, c_c) is responsible for these forces. However, in this study the value of the contact spring is not a constant (as is the case in the linear elastic and in the Hertz model), but depends on the overlap

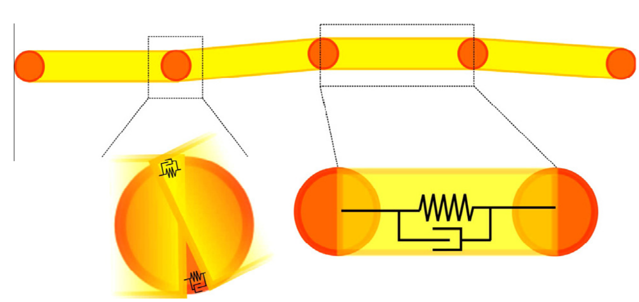

Fig. 1. Bendable straw in DEMeter++ (Lenaerts et al., 2014).