

MODELING OF CORN EARS BY DISCRETE ELEMENT METHOD (DEM)

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KEYWORDS

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ABSTRACT

One of the main aims of today's agriculture is to reduce the losses of different agricultural processes. With more than 1000 billion tons of production annually, corn is one of the most essential agricultural crops in the world so our study focuses on the modeling of corn ears by discrete element method (DEM) from the point of view of losses during corn harvesting. To describe the physical and mechanical properties of corn ears and its connections to the corn stalk, laboratorial and in-situ tests and observations were conducted. During an iteration process the mechanical model of the corn ear and the connection between the corn ear and the corn stalk were validated. There has been a good match between the numerical results and the experimental data. The simulation results clearly demonstrate that the discrete element model of corn ear is capable of modeling losses during corn harvesting in the future.

INTRODUCTION

The increasing demand for more and more and better quality agricultural products presents a big challenge for farmers, breeders and developers of agricultural machineries. Thus, one of the perpetual goals of precision agriculture is to reduce the losses during the agricultural processes. There are several different methods to prevent agricultural losses but in our study the reduction of losses in agricultural machineries is discussed.

Due to the seasonal characteristics of agricultural products in situ tests of constructions are limited in time and often prove to be very expensive. In the field of agricultural machine design numerical methods are not available which could properly replace field tests.

The utilization of corn plants and crops is remarkable worldwide; the corn production in the world is almost 1000 million tons annually. In 2015 almost 7 million tons of corns were harvested by farmers in Hungary (Hungarian Central Statistical Office 2017), which demonstrates the significance of the plant in the agriculture of the country.

During mature corn processing the first step is harvesting, when combines with special corn headers gather the crop. The first time maize gets in contact with

the machine is, when the corn header picks up the corn ears from the stalk. In this process two types of losses can occur: losses of corn kernels and losses of corn ears. Losses of corn kernels are caused by collisions among the ears and different parts of the corn header. Losses of corn ears may be caused by high ear picking forces or collisions in the corn header. Because the average number of corn kernels per ears is 800 pieces, the loss of a corn ear is more significant than the loss of kernels. Therefore, our study focuses on the modeling of corn ears by discrete element method (DEM) from point of view of corn ear loss in corn header during harvesting. DEM is widely used to investigate bulk agricultural materials. The micromechanical parameters of a sunflower DEM model were calibrated based on odometer tests so that the model can sufficiently approach the macro mechanical behavior of the real bulk material (Keppler et al. 2011). In another study the effect of particle shape of corn kernels on flow was investigated by discrete element method simulation of a rotary batch seed coater (Pasha et al. 2016).

In connection with complete plant and corn ear modeling fewer literatures can be found. The iteration among grass stalk and rotation mower was investigated by DEM (Kemper et al. 2014). A special solid geometrical structure of DEM was analysed for corn stalks in quantitative and qualitative ways (Kovács et al. 2015). Several possible DEM geometrical structures for modelling of fibrous agricultural materials were compared (Kovács and Kerényi 2016). The whole corn ear, the corn cob, corn kernels and the connection among the kernels and the cob, were modelled with DEM in order to simulate the corn threshing process (Yu et al. 2015). An interactive digital design system was developed by C++ programming language based on OpenGL graphic library for corn modelling (Xiao et al. 2010).

Consequently, based on the literature review it is clear that there are no DEM model that can model the connection between the corn ear and the corn stalk and the collision among different materials and corn ears. Therefore, experimental apparatus has been developed for measuring the ear picking force and the coefficient of restitution among corn ears and different surfaces in order to develop a DEM model for modeling losses during corn harvesting.

MATERIALS AND METHODS

Discrete element method (DEM) was developed to investigate bulk materials which contain separate parts. The DEM model is defined as follows: it contains separated, discrete particles which have independent degrees of freedom and the model can simulate the finite rotations and translations, connections can break and new connections can come about in the model (Cundall and Hart 1993).

Based on the harvest and product processes of harvest-ready maize the main loads of the corn ear were determined. Leaves and husk of the corn ear were neglected in our study. First of all, the physical and physiological properties of the corn ear (mass, length, diameter, shape, position in the stalk, center of mass) were measured and observed. Laboratorial ear picking force and collision tests were conducted to define the main mechanical parameters and the behavior of corn stalks. The quantitative results of the measures weren't directly usable for the modeling method so necessary data and graphs were calculated with mathematical and statistical and image processing methods for the numerical modeling.

The examination of the available contact models was the first step of the modeling. After that the models were compared and the Timoshenko-Beam-Bonded model (Brown et al. 2014), which is based on the Timoshenko-beam theory, was selected for the study.

In the next step, the DEM physical geometry of the corn ear was created to calibrate its mechanical properties based on the experimental results. After that the geometry model of the stalk, the shank were created so as to calibrate the mechanical properties of the stalk-ear connection.

With modifications of the micro-mechanical parameters of the contact models, during an iteration process, the right assembly was found.

MEASUREMENTS AND OBSERVATIONS

Two types of measurements and observations were conducted in connection with the corn ears: in-situ and laboratorial. In both cases the same type of maize from the middle region of Hungary (GPS coordinates: N 47.743692; E 19.613025) were analyzed in October 2016.

In-situ measurements and observations

During the in-situ measurements and observations the position of the ears, the center of the mass of the ears from the stalk and from the ground were analyzed.

There are two types of positions of the corn ear on the corn stalk: hanging and standing, as shown on Figures 1. In the first case the shank of the corn ear is broken while on the other hand it is unbroken. Based on 100 observed plants, 59% of the plants had hanging corn ears.



Figure 1: Positions of corn ears: hanging position on the left side and standing position on the right side

Needless to say, these two different positions mean different parameters for the center of the mass (CM) and from this reason the different positions can cause different dynamic behavior for the corn stalk during harvesting. Based on 20 samples, the distances of CM from the ground and from the stalk of the standing corn ears are higher than the case of hanging corn ears, as shown in Table 1.

Table 1: Center of mass of corn ears

Property	Value (P=0.05) [cm]
CM from ground, hanging	92.9 ± 5.1
CM from stalk, hanging	10.1 ± 1.3
CM from ground, standing	108.2 ± 4.5
CM from stalk, standing	5.6 ± 0.5

Laboratorial measurements and observations

First, the main diameter, the length and the mass of corn ears were measured, as shown in Table 2.

Table 2: Physical properties of corn ears based on 20 samples

Property	Value (P=0.05)
Average main diameter	47.6 ± 0.9 mm
Average length	169.8 ± 8.7 mm
Average mass	211.2 ± 16.0 g

To model the shape of the ears an image based analysis was conducted with 20 corn ears being observed. In this process an axis symmetric property of the corn ears was assumed. First, a picture was taken from each corn ear in front of the same background. After that a background was completely removed by image processing software. In the next step the pictures were transformed to binary images with luminance factor 0.95, so the boundaries of the images were easily found, the process is shown on Figure 2.



Figure 2: Image processing steps of corn ears shape

Based on the boundaries, the centers of mass of the corn ears could be calculated by the equations of first moment of area and an average ear can be formulated, as shown on Figure 3.

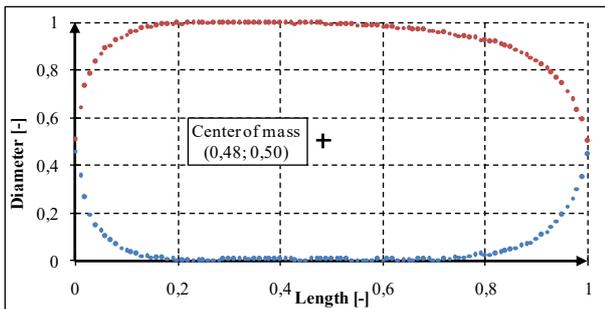


Figure 3: Ideal shape and average center of mass of corn ears

The size of the shank of the corn ear impacts on the ear picking force essentially. The shank has two main dimensions: diameter and length, so these parameters were measured on 20 samples. The results are shown in Table 3.

Table 3: Physical properties of the shank based on 20 samples

Property	Value (P=0.05) [mm]
Average diameter	10.6 ± 0.4
Average length	115.8 ± 15.7

One of the most significant mechanical parameters of the corn ears is the coefficient of restitution among the corn ears and different surfaces. Thus, the coefficient of restitution among corn ears and steel (S235) and plastic (Polyethylene, PE) sheets were measured in axial and radial directions of the corn ears. The samples were dropped into the sheets (size 50x50 cm, thickness of the

plastic: 5 mm; thickness of the steel: 1 mm) from 1 meter height and the collision was detected with 1000 frames per second by a high-speed camera. The coefficient of restitution (C_R) was calculated from the bounce height (h) and the drop height (H) with Equation (1).

$$C_R = \sqrt{\frac{h}{H}} \quad (1)$$

Based on 10 samples, respectively, significant differences between the axial and radial coefficients of restitution were not found and the coefficient of restitution between the ear and the sheet of plastic was higher, as it was expected (Figure 4).

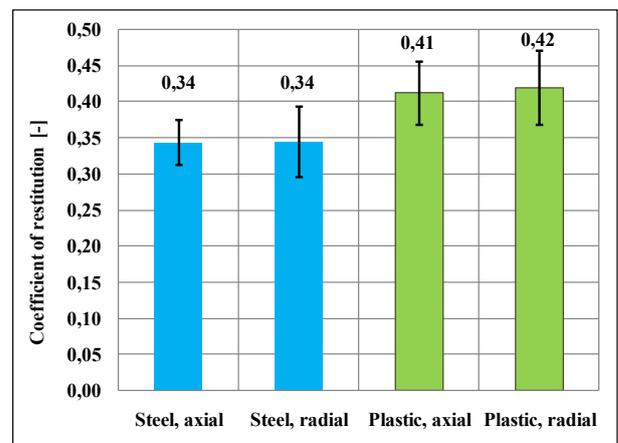


Figure 4: Coefficients of restitution of corn ears

To model the connection between the corn ears and stalks, the ear picking force was measured on a self-developed apparatus that can copy the ear gathering process in the corn header, as shown on Figure 5.



Figure 5: Apparatus for measurement of ear picking force

Based on 20 samples, the average ear picking force was 457.3 ± 58.2 N ($P=0.05$) and the dimensionless characteristics with the confidence interval ($P=0.05$) of the ear picking process is shown on Figure 6.

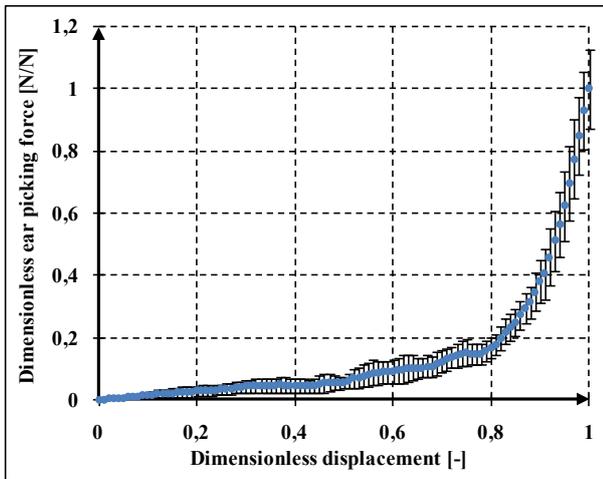


Figure 6: Characteristics of ear picking force

MODEL FORMATION

The discrete element model formation is constituted of four main parts: geometrical and contact structure formation of the stalk, the shank and the ear of the plant and the modeling of the test environment. During the model formation the measured and observed parameters of the plants and EDEM 2.7 Academic (DEM Solution Ltd.) were used.

In the stalk a hollow geometrical structure with 18 particles in one cross section was used based on our previous studies. In this geometrical structure different bonds among the particles were used in tangential and axial directions to model different mechanical behaviors in these directions of the stalk (Kovács and Kerényi 2016), as seen on Figure 7.

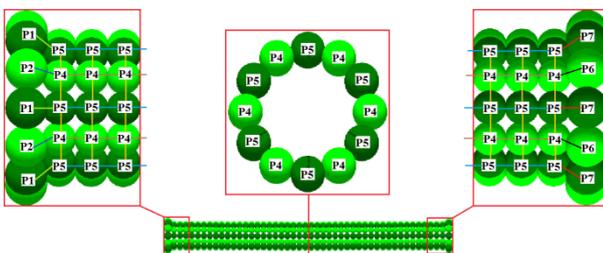


Figure 7: Geometrical and contact structure of the stalk

The shank provides the contact between the stalk and the ear. It was modeled by a simpler geometrical structure of chain of spheres. In this model there is only one type of bonds among the particles in its axial direction but there is another bond among the shank and the stalk. The mechanical properties in tangential properties are provided by the stiffness of the particles. The shape of the shank was formed in such a way that it could carry a hanging ear because this type of ears were

more common during the in-situ observations. It is necessary to note that it is impossible to model this broken condition of the shank so a curved shank with unbroken bonds among the particles was modeled, as shown on Figure 8.

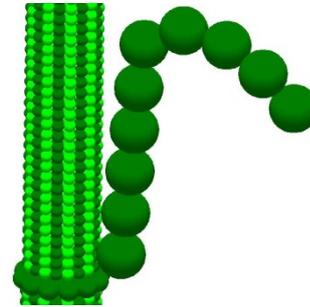


Figure 8: The shank on the stalk

The geometrical model of the corn ear is one particle that is formed by several sphere surfaces and it doesn't contain bonds. The previously described ideal shape of the corn ears (Figure 3) was approached by 25 sphere surfaces, supposing that the corn ears are axis symmetric, as shown on Figure 9.

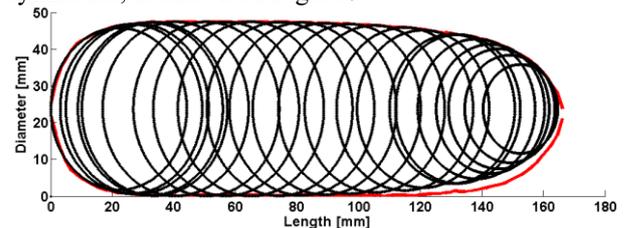


Figure 9: Ideal (red line) and modeled (black spheres) shape of the corn ear

The corn ear was situated in such a way that its center of the mass was near the same as the results from the measures, as shown on Figure 10. Naturally, a bond is needed between the end of the shank and the corn ear.

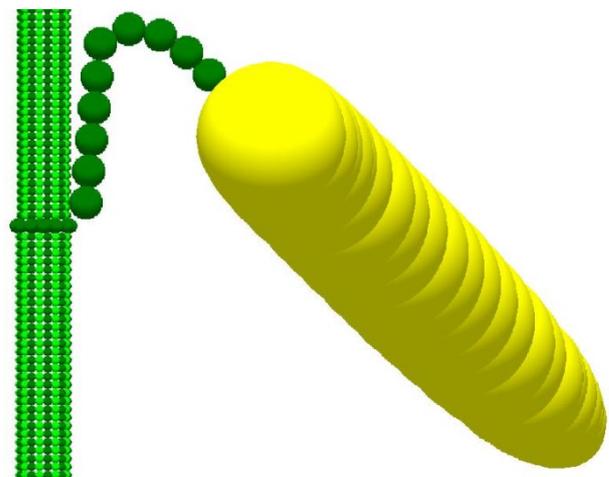


Figure 10: The entire model: stalk, shank and corn ear

Lastly, the testing machines were integrated into the model. In the case of the collision simulation, only a steel and a plastic sheet were modeled, based on the material properties of the real ones. In the other case the clamps that hold the stalk and the half of the ear picking apparatus were modeled, as shown on Figure 11.

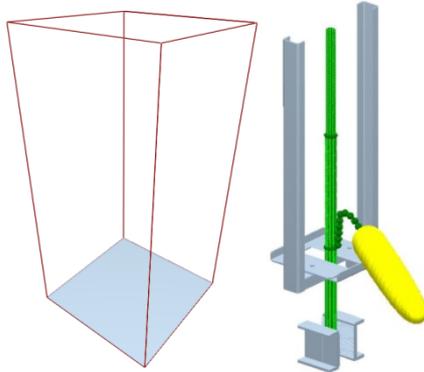


Figure 11: Model of the collision (left) and the ear picking (right) simulation

RESULTS

After the model formation the mechanical parameters of the models were modified during an iteration process in order to find the right set of parameters that can accurately mimic the real behavior of the different plant parts.

First, the coefficients of restitution between the corn ears and the different surfaces were analyzed. In the simulations the collision between the ear and the sheet was taken place in radial direction. Based on the collision test the coefficients of restitution among the corn ear and sheets of steel and plastic were chosen at 0.34 and 0.41, respectively. From these values the bounce heights could be calculated with Equation (1): 115.6 mm; 176.4 mm on steel and plastic respectively.

The collisions are calculated in the software from the following numerical material properties: coefficient of restitution between the materials and shear moduli of the materials. The shear moduli of the steel and plastic are well known: $8e10$ Pa and $1.17e8$ Pa, respectively. These values were set to the material parameters of the model.

After that the coefficients of restitution were set to the measured values and the shear modulus of the corn ear was modified in the range of $1e8 - 1e14$ Pa until it reached the maximum value ($1e14$ Pa) that the software allowed. Unfortunately, the expected bounce height was not reached with these parameters so another calibration method was chosen.

In the next step the shear modulus of the corn ear was chosen for a fixed value $1e10$ Pa, based on our experiences and the literature (Yu et al. 2015). With the fixed shear moduli the numerical coefficient of restitution was modified from 0.5 to 1.0.

In both cases the relationship between the bounce height and the coefficient of restitution shows a second order polynomial characteristics with $R^2=0.99$. The exact

numerical coefficient of restitution values for the observed bounce heights are 0.77 and 0.88 for steel and plastic, respectively, as shown on Figure 12. The difference among the measured and the numerical coefficient of restitution values comes from the calculation method of the bounce in the discrete element software where it uses an algorithmic damping.

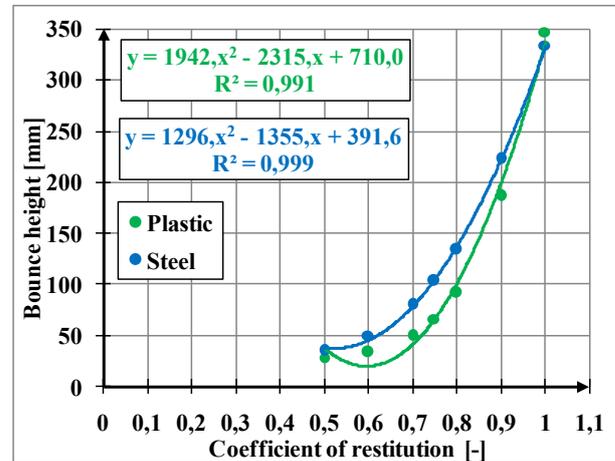


Figure 12: Characteristics of bounce height as a function of coefficient of restitution among corn ear and steel and plastic

After the right set of parameters for the collision of the ear had been selected, the ear picking force of the plant was calibrated. In this step the main objective was the calibration of the mechanical parameters of the bonds among the stalk, the shank and the corn ear in order to simulate the ear gathering process.

With the right set of parameters the maximum ear picking force from the simulation was 439 N that is in accordance with the measured value. The simulated characteristics coincide very well with the measured characteristics of the real process, as shown on Figure 13.

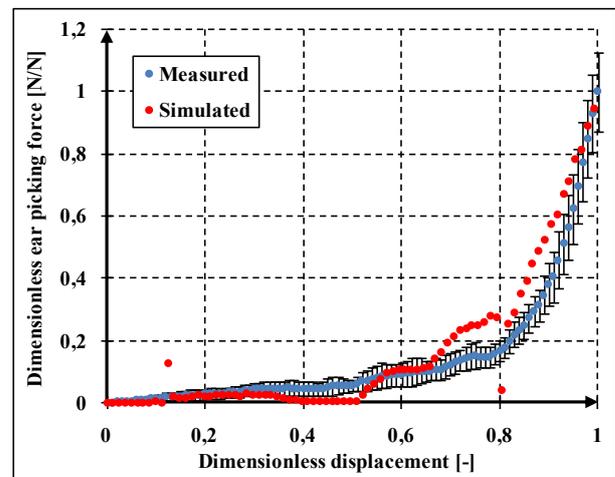


Figure 13: Measured and simulated characteristics of ear picking process

Based on our practical experiences the bonds were calibrated in such a way that the shank is torn from the stalk but it is in contact with the ear after the gathering, as shown on Figure 14.

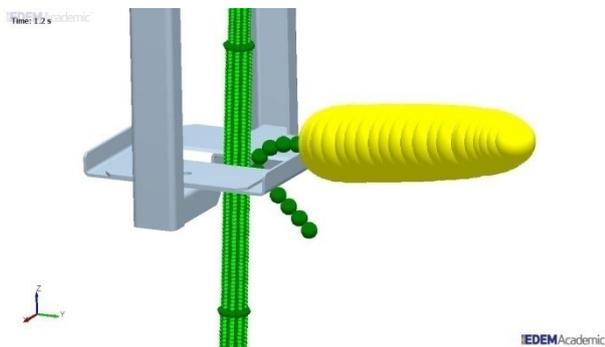


Figure 14: The final state of the ear gathering process in the simulation

The obtained simulation results are referred to a quasi-static measurement method but they are adaptable to analyze the basic phenomena during ear gathering process.

CONCLUSIONS

A numerical and experimental study of the corn ear collision and picking force was undertaken using discrete element method in order to simulate corn ear losses during the harvesting process of harvest-ready maize. The effect of numerical shear moduli, coefficient of restitution on collision among corn ear and steel and plastic sheets was analyzed and a right set of bond parameters among the stalk, the shank and the corn ear was calibrated for the simulations in the future. The following conclusions could be drawn:

- (1) The applied measurement method is usable to provide experimental results for discrete element models of shank and ear of maize and for the contacts among these parts.
- (2) The applied geometrical structures of the stalk, shank and corn ear are suitable for further analysis.
- (3) The bounce height as a function of coefficient of restitution shows a second order polynomial characteristics for the collisions between the corn ear and sheets of plastic and steel.
- (4) The calibrated physical and mechanical properties of the interactions and bonds among the stalk, shank, ear of corn and geometrical elements are suitable for further analysis.
- (5) The characteristics of simulation and the measurement are coincided very well; thus, the discrete element model of ear picking is capable to simulate the harvesting process.
- (6) The discrete element numerical models are capable of simulating the interactions among the testing apparatus and different parts of maize and compare the simulation and experimental results.

As to the measurement, the applied method should be extended for more samples, more maize species and different fertilizing conditions.

In the future, the current results and models can be adapted to more detailed and realistic simulations on losses of corn ears in a corn header of a combine harvester during harvesting process.

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AUTHOR BIOGRAPHIES



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