COUPLED DEM-FEM SIMULATION ON MAIZE HARVESTING

Ádám Kovács and Péter Tamás Zwierczyk
Department of Machine and Product Design
Budapest University of Technology and Economics
H-1111, Budapest, Hungary
E-mail: kovacs.adam@gt3.bme.hu

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ABSTRACT

One of the main objectives of today's agriculture is to develop agricultural machineries that guarantee more and better quality agricultural products. However, due to the seasonal characteristics of agricultural products in-situ tests of constructions are limited in time and often prove to be very expensive.
With more than 1000 billion tons of annual production, corn is one of the most essential agricultural crops in the world. Consequently, our study focuses on the modeling of corn harvesting through coupled discrete element and finite element method (DEM-FEM) to provide more input for machine development.
With the use of a complex DEM model of maize and the CAD model of a common corn header unit a large-scale simulation was carried out. The main phenomena were directly analyzed by quantitative and image-based qualitative evaluation methods. For further analysis the stalk rollers of the corn header unit were also investigated by finite element analysis.
The simulation results clearly demonstrate that the discrete element model of maize is capable of modeling the crucial phenomenon during corn harvesting in the future.

INTRODUCTION

The increasing demand for more and better quality agricultural products presents a big challenge for farmers, breeders and developers of agricultural machinery. Most of the agricultural processes are carried out by using different machineries, thus, one of the perpetual goal of precision agriculture is to advance these appliances. There are several different methods to improve agricultural machineries, yet this study discusses how their efficiency and working quality could be increased.
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, which could properly replace field tests, are not available.
The utilization of corn plants and crops is remarkable worldwide; the corn production in the world is almost 1000 million tons annually. In 2016 almost 9 million tons of corn were harvested by farmers in Hungary (Hungarian Central Statistical Office 2018), which demonstrates the significance of the plant in the agriculture of the country.
During mature corn processing the first step is harvesting, during which combine harvesters with special corn headers gather the crop. The first time maize gets in contact with the machine is when the corn header collects the corn ears from the stalk. In this process the maize stalk is pulled down by the stalk rollers while it is chopped by the cutting blade of the chopping unit. The corn ear is separated from the stalk by the deck plates and is conveyed into the machine by the gathering chains. To improve working efficiency and quality of corn headers processing of stalk parts under the corn ear is the most crucial factor because these parts of the plant provide the highest resistance against external loads and their dry matter content is higher than in the upper parts of the plant.
Therefore, our study focuses on the modeling of corn harvesting by coupled discrete element and finite element method (DEM-FEM) to provide input for machine development.
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 the 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 entire plant and corn ear modeling fewer studies can be found. The interaction among grass stalk and rotation mower was investigated by DEM in Kemper et al. (2014). To develop a sensor for monitoring rice grain sieve losses in a combine harvester a special hollow structure was created about rice stems by Liang et al., (2016). A special solid geometrical structure of DEM was analyzed for corn stalks in quantitative and qualitative ways in Kovács et al. (2015). Several possible DEM geometrical structures for modelling of fibrous agricultural materials were compared in Kovács and Kerényi (2016). A DEM model of corn stalks and corn ears was developed for analysis of losses during corn harvesting in Kovács and Kerényi (2017).
Finite element analysis is a more common method to predict the mechanical behavior of machines, thus, several studies can be found in connection to structural analysis of agricultural machinery. Using finite element method (FEM) model analysis on a V-belt pulley of a fodder crushing machine was carried out by Celik et al. (2010). Stresses and displacements of a coffee harvester

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structure (engine frame, body right and left sides, front and rear end, main beam, coffee reservoir, wheels and fuel tank) were analyzed by using FEM static simulation in da Silva et al. (2014).
Consequently, based on the literature review there is no numerical method that can provide useful input for machine development. Therefore, this paper analyzes interactions among parts of the machine and maize, external loads on the parts of the machine and working quality by a coupled DEM-FEM simulation method 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). Thus, this method enables the investigation of the mechanical beahviour and breaking phenomenon of solid materials under different loading cases.
Based on the harvesting processes of harvest-ready maize the main loads of the stalk and maize ear were determined. Tassel, leaves and husk of the plant were neglected in our study. First, the physical and physiological properties of the plant parts (mass, length, diameter, shape, position, center of mass) were measured and observed. Laboratorial tests (compression, bending, cutting test on the stalk and ear detachment) were conducted to define the main mechanical parameters and the behavior of maize. The 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.
In the next step, the DEM physical geometry of maize was created to calibrate its mechanical properties based on the experimental results. With modifications of the micro-mechanical parameters of the contact models, during an iteration process, the right assembly was found. Based on observations of 13 commercial maize heads the CAD geometry of a common maize header unit was designed and imported into the discrete element software (EDEM®, DEM Solutions Ltd., Edinburgh, UK), where its kinematics was also defined.
By using the whole plant DEM model and the model of the maize header unit a large-scale simulation was carried out in EDEM® software. The main phenomena were directly analyzed by quantitative and image-based qualitative evaluation methods. For further analysis the stalk rollers of the maize header unit were also investigated by finite element software (Ansys®, Ansys Inc., Canonsburg, Pennsylvania, US) based on the DEM predicted external loads.

MODEL FORMATION

During the model formation hollow, solid and chain of spheres geometrical structures were used to create each part of the model. Based on the importance and role of maize parts during harvesting, their geometrical structure is more or less detailed in our model, as shown on Figure 1. Section “A” contains the most important parts of the stalk and the maize ear with the shank. Here, the internodes and nodes provide the highest resistance against external loads, their bending behavior plays an important role in losses. Another important part of the stalk is the shank that holds the maize ear thus it has a significant effect on gathering. In section “B”, parts don’t play an important role in losses but they provide significant resistance during processing. In section “C”, stalk parts provide very low resistance against external loads. In the stalk model, all cross sections of nodes and internodes are circular while special traits (groove, wrinkle) and core of internodes were neglected.

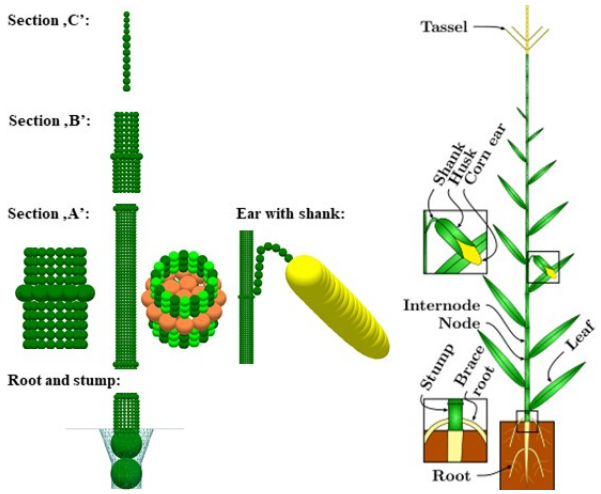

Figure 1: DEM geometrical model for maize

The root and soil-root connection was approached with chain of spheres geometrical model that is situated in a conical geometry to provide relaxation against external bending loads. The stump is modelled with a hollow structure with 18 particles in one cross section.
From the 1st to the 10th, nodes were modelled by a solid geometrical structure in which particles were composed in one circular layer of particles that is made up of 19 particles: 12 in the outer circle, 6 in the middle circle and 1 in the center. This model provides higher resistance against external loading near the nodes. Above the 10th node, nodes were modelled by larger spherical particles.
From the 1st to the 6th, internodes were modelled with hollow geometrical structure. In a cross section of internode, particles were composed in one circular layer that is made up of 18 particles. This model provides a good opportunity to model the typical failure modes (buckling and ovalisation) of internodes. Between the 7th and 10th, internodes were modelled with hollow geometrical structure but there are 12 particles in each

circular layer. Above 10th, internodes were created with chain of spheres geometrical model.

The shape of the shank was formed in such a way that it can carry a hanging ear by using the chain of spheres model. It is impossible to model this broken condition of the shank so a curved shape with unbroken bonds was created.

The geometrical model of the maize ear is one particle that is formed by several sphere surfaces. The previously described ideal shape of the maize ears was approached with 25 sphere surfaces, supposing that the maize ears are axis symmetric. This detailed maize ear model provides a good opportunity to analyze the interaction between the maize ear and parts of the machine. The maize ear was situated in such a way that its center of the mass was near the same as the results from the measurements.

The examination of the available contact models was the first step during the calibration of mechanical behavior of different parts of the model. 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 chain of spheres geometrical structure three different contacts could be defined among the particles (Figure 2, a). The red line marks the connection between particle type one, which formed the node of the stalk, and particle type three, which is the first particle of the internode. Among the particles of the internode (particle type three) the same connections can be observed, on the figure these are marked by pink lines. The blue line marks the connection between the last particle of the internode and the particle of the next node. These types of connections have different mechanical parameters that can model the mechanical characteristic of the stalk in axial direction. In the model of the chain of spheres the mechanical properties of the stalk in tangential direction can be described by the stiffness of the different particle types.

In the hollow geometrical structure, the mechanical properties of the internode were modeled with the connections among the same type of particles (P4:P4; P5:P5) in axial direction and were modeled with the connections among the even-numbered and the odd-numbered type of particles (P4:P5) in tangential direction. The mechanical properties among the particles of the node and the internode were defined through P1:P5; P2:P4; P7:P5; P6:P4 in axial direction and the mechanical properties of the node were defined through the P1:P2; P6:P7 connections in tangential direction (Figure 2, b).

The imported CAD geometry of a maize header unit is shown on Figure 3. Each part was designed based on the parts of a real machine, however, the entire design is not identical with any of them. The kinematics of the parts was also determined based on real operation parameters of a maize header; thus, the pace of the unit is 2 m s^{-1}; the speed of the gathering chains is 4 m s^{-1}; the rotational speed of the stalk rollers and chopping unit are 400 rpm and 3500 rpm, respectively.

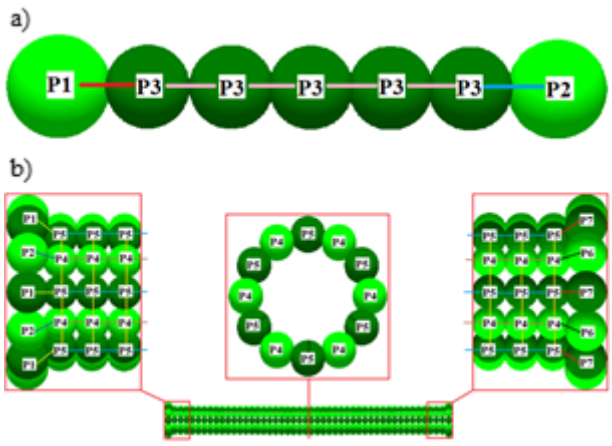

Figure 2: Geometrical and contact structure of the stalk: a) chain of spheres in Section C; b) hollow geometrical structure in Section A and B

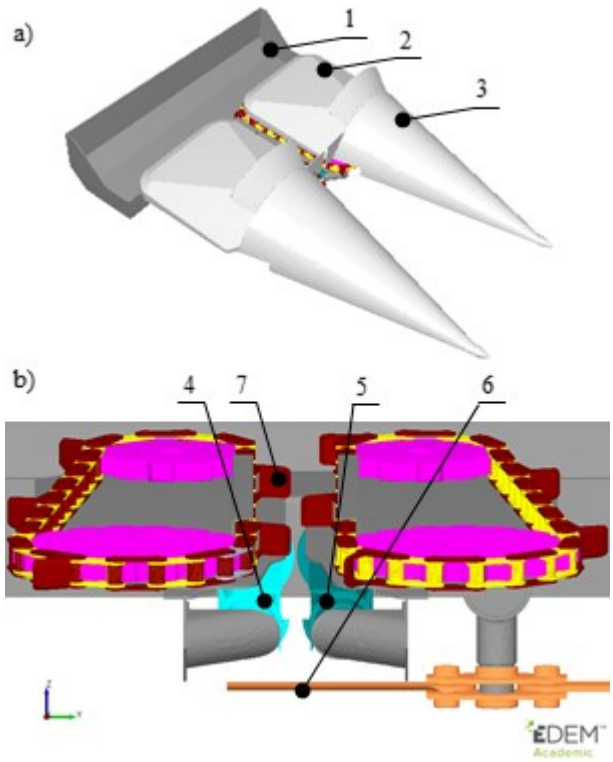

Figure 3: Imported CAD model of a common maize head: 1. gathering box; 2. hood; 3. row divider; 4. right stalk roller; 5. left stalk roller; 6. chopping blade; 7. gathering chains

RESULTS

In this study DEM predicted external loads and working quality of stalk rollers and chopping unit were analyzed in the time interval of the first contact between the header and the stalk and the ear-detachment. For this analysis quantitative and image-based qualitative methods were used.

Quantitative results from DEM analysis

To improve the energy efficiency of a maize header one of the most important aspects is the power requirement of each unit. In case of a maize header the stalk rollers and the chopping unit provide the highest power consumption, thus, results on these parts will be explained here.

While the stalk rollers are spinning in opposite directions their knifes compress the maize stalk locally and pull it down. During the compression the stalk provides high resistance that appears as a torques on the stalk rollers, it is shown on Figure 4. At the beginning of the process, when the stalk is virgin, an extremely high torque-peak (~180 Nm) is observable because of the supporting effect of the roots. In this case the stalk is compressed locally in its radial direction and in its longitudinal direction as well, that causes that special, initial loading case of the stalk rollers. After the first cut the stalk lost its connection to the ground and the peaks are more similar. In the steady state the peaks are between 40 and 70 Nm, while the mean torque on each stalk roller is 23.3 Nm. Except one peak torque on the left stalk roller around its third rotation the characteristics are nearly the same on both stalk rollers.

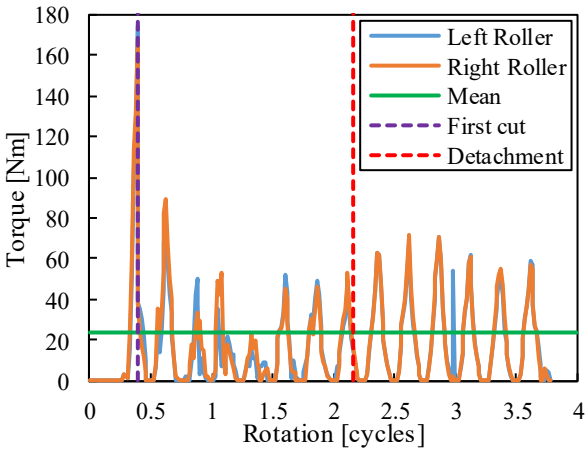

Figure 4: Plot of the external torque on the axes of each stalk roller vs its rotation in cycles with highlights of the first cut and ear detachment during simulation of maize harvesting

Based on the external torque and the rotational speed of the stalk rollers the total power requirement was calculated as shown on Figure 5. In the steady state the peaks are in the range of 2.5-5.5 kW, while the mean required power was 1.9 kW that corresponds to the power requirement of a real maize header unit.

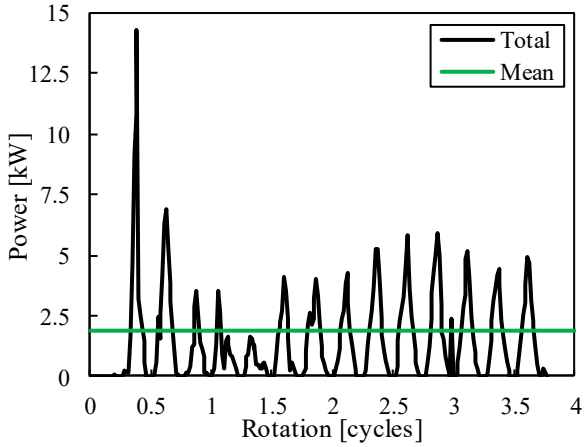

Figure 5: Plot of the total power requirement of stalk rollers vs rotation in cycles during simulation of maize harvesting

While the stalk rollers are pulling down the stalk the chopping unit cuts it into small pieces. During this process the stalk provides resistance against the chopping blade and a resistance torque can be calculated on the axis of the chopping unit, as shown on Figure 6. The range of the appeared peaks is between 8 and 230 Nm. The high peaks can be caused by a numerical error. By decreasing the time-step of the DEM simulation these extremely high peaks will disappear. The calculated mean torque on the chopping unit was 11.8 Nm during the analyzed period.

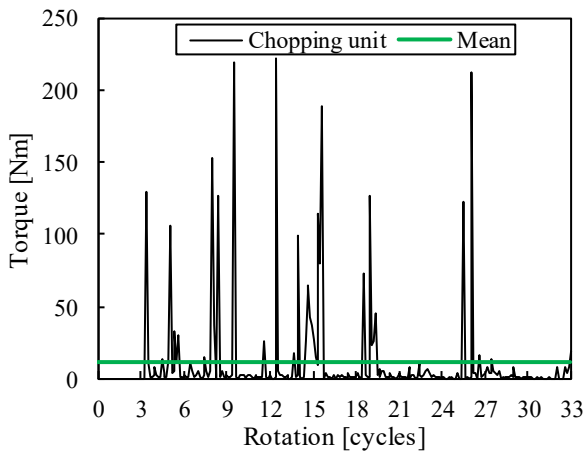

Figure 6: Plot of the external torque on the axis of the chopping blade vs its rotation in cycles during maize harvesting

Similarly to the stalk rollers, the power requirement of the chopping unite was calculated, see on Figure 7. The extremely high peaks caused extremely high power requirement for a short time interval but the calculated mean power requirement was 4.3 kW that corresponds to the power requirement of a real maize header unit.

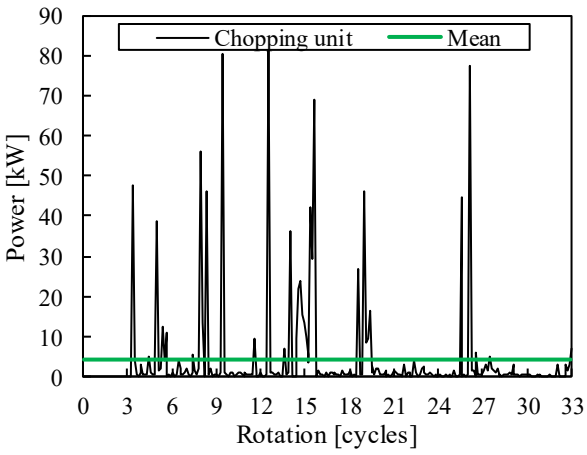

Figure 7: Plot of the power requirement of the chopping unit vs its rotation in cycles during maize harvesting

Image-based qualitative results from DEM analysis

To improve the working quality of a maize header it is important to analyze every phenomenon during maize harvesting. Here, an image-based analysis on the working process of stalk rollers and the chopping unit is shortly explained.

The most important function of the stalk rollers is to fix the position of the stalk during the chopping and ear-detachment. On Figure 8, the main stages of the interaction among the stalk and stalk rollers can be observed: approaching, maximal compression and distancing. There is a short time interval between the distancing and approaching when there is no interaction among the stalk rollers and the stalk. To know what happens in this time interval can be significant for development of the number and shape of the knives.

The phenomenon of the first cut provides very important information about the speed of the maize header unit; the speed ratios and positions of stalk rollers and chopping unit, see on Figure 9. This is an optimal case because the stalk rollers fix the stalk before the first cut, thus, the chance of losing the maize ear is less.

To analyze the working quality of the chopping unit the size distribution and shape of the chopped material are usable. On Figure 10, two types of chopped material are observable: fibrous and cylindrical. In both cases the DEM predicted shape and the real one is very similar. For the fibrous chopped material the stalk was torn up during cutting or the chopping blade hit it several times, while the cylindrical chopped material is the result of two perfect cut on the stalk.

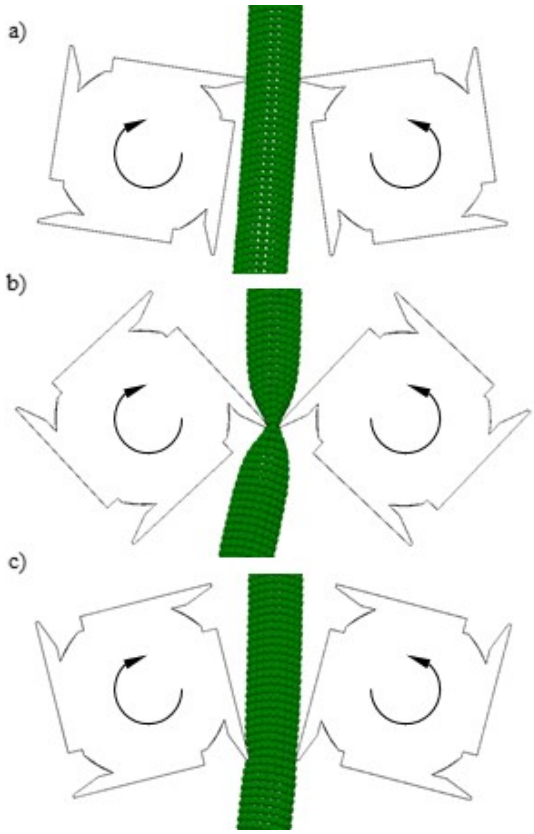

Figure 8: Image-based qualitative analysis on the working efficiency of the stalk rollers during simulation of maize harvesting: a) approaching; b) maximal compression; c) distancing

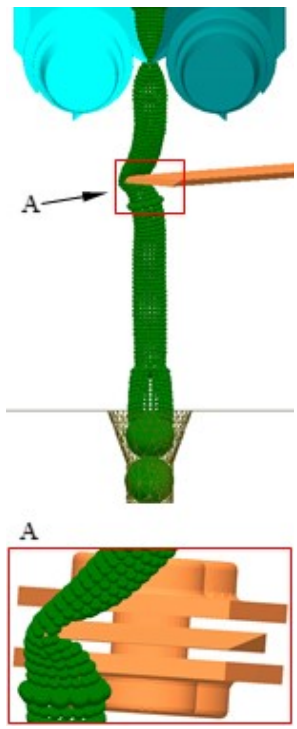

Figure 9: Image-based qualitative analysis on the phenomena of the first cut during simulation of maize harvesting

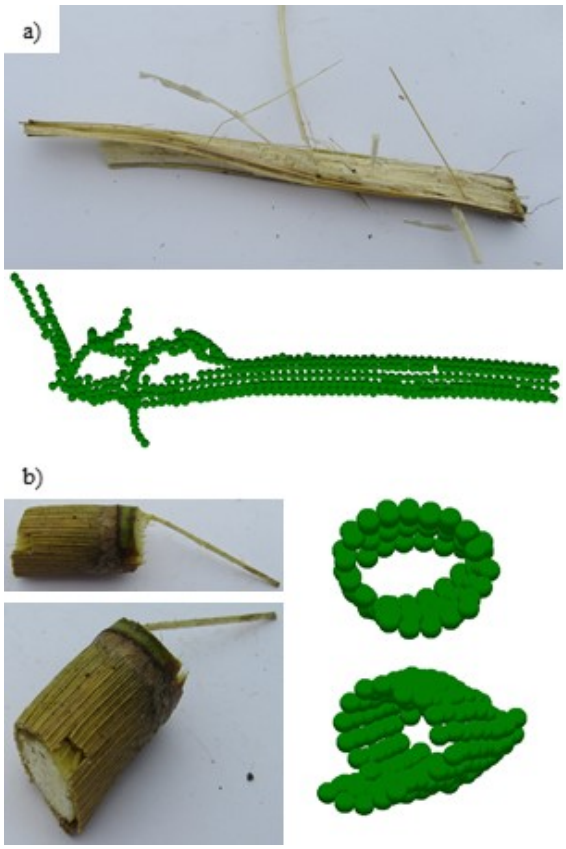

Figure 10: Image-based qualitative analysis on the chopping material during simulation of maize harvesting: a) fibrous chopped material; b) cylindrical chopped material

Quantitative results from FEM analysis

Through the FE analysis the left stalk roller was examined in case of the first cut when the external torque on the rollers reaches its maximum (see Figure 4).
During the simulation the same mesh configuration was used as in the DEM analysis. The FE mesh consisted of 10-nodes tetrahedron elements with 2 mm size. The material of the stalk roller and its blades was considered to be structural steel. The modulus of elasticity was 200 GPa, the Poisson's ratio was 0.3. Because the analysis only focused on one time moment, when the external torque is at its maximum, two fixed constrains were applied both sides of the roller where the hydro drives connecting to. The load imported from the DEM solution as nodal forces using the EDEM® – Ansys® Add-In.
The resulted von Mises equivalent stress can be seen in Figure 11. Comparing the FEM results with the DEM results (e.g. Figure 8 and 9) it can be concluded that the maize branch when it is contacting with the stalk roller causes stresses on the roller's blade. Furthermore, it is also visible in Figure 11 that the branch is pressing not only the edge of the blade but also the top surface of it while the roller's blade is cutting.

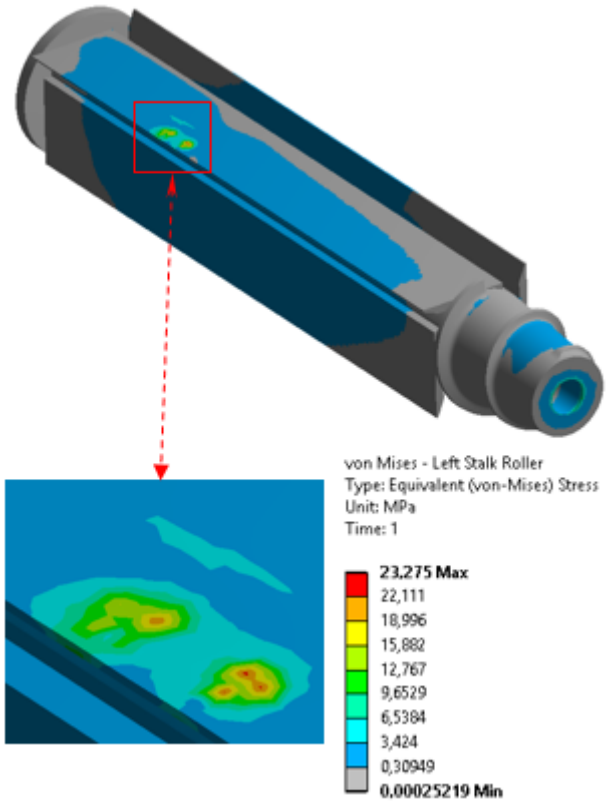

Figure 11: Image-based qualitative analysis of the stresses on the left stalk roller of the first cut during simulation of maize harvesting

CONCLUSIONS

A numerical and experimental study of maize harvesting was undertaken using coupled discrete and finite element method in order to simulate the interactions among the parts of a common maize header unit and a maize stalk.
The course of harvesting was analyzed through quantitative and image-based qualitative evaluation methods: the external torque; the power requirement and the working quality of stalk rollers and chopping blade were analyzed in detail. To provide data for structural design of stalk rollers they were also analyzed by finite element method.
Based on our results the following conclusions could be drawn:

(1) The applied coupled DEM-FEM simulation method is suitable to provide input for development of maize headers.
(2) The geometrical model for maize is usable to analyze the interactions among the maize header unit and the maize stalk during maize harvesting.
(3) The CAD model about a common maize header unit is usable for further simulations on maize harvesting.
(4) The quantitative evaluation method is directly usable to analyze the external loads on different parts of the maize header, thus, to provide input data for design.

(5) The qualitative evaluation method is usable to analyze the working quality of different parts of a maize header, thus, to provide input data for design.
(6) By using coupled DEM-FEM simulations it is possible to examine the stress distribution during the maize harvesting not just on the stalk rollers but in the future also on the cutting blades.

In the future, current results and models can be adapted to more detailed and realistic simulations on maize harvesting process. These techniques can be extended with wear simulations. Together with these simulations the whole harvesting process can be examined not just on the agricultural side but also on the full mechanical engineering side.

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AUTHOR BIOGRAPHIES

ÁDÁM KOVÁCS was born in Debrecen, Hungary and went to Budapest University of Technology and Economics, where he studied agricultural machine design and obtained his MSc. degree in 2016. Currently he is a PhD student in the same institution and his topic is discrete element modeling of maize. He worked for the WIGNER Research Center for Physics at the Department of Plasma Physics for two years, where he designed diagnostic devices for fusion reactors. His e-mail address is: kovacs.adam@gt3.bme.hu and his Web-page can be found at http://gt3.bme.hu/en.

PÉTER T. ZWIERCZYK is an assistant professor at Budapest University of Technology and Economics Department of Machine and Product Design where he received his M.Sc. degree and then completed his Ph.D. in mechanical engineering. His main research field is the railway wheel-rail connection. He is member of the finite element modelling (FEM) research group. His e-mail address is: z.peter@gt3.bme.hu and his web-page can be found at http://gt3.bme.hu/zwierczykpetertamas.