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Multi-Body Simulation of a Cutting Process

A demonstration of how a cutting process in harvest technology can be simulated with the SimMechanics multi-body simulation program is presented here. The objective of this research project is to provide a basis for virtually determining the driving power requirements and to optimize a combine harvester straw chopper to achieve a lasting and resource saving increase in performance.

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Expression of thanks

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Keywords

Harvest technology, cutting process, simulation

Environmental regulations becoming more severe require among other things, that straw is disposed after harvest environmentally friendly as possible. A burning down of the straw is not a suitable solution due to the emissions arising in this case and in view of the damages caused to flora and fauna.

Consequently the straw is chopped increasingly. In this connection increasing attention is paid to the design of the devices in an energy-saving way. Simulations can contribute to the efficiency increase of agricultural machiny.

The real cutting process is schematically shown in *Figure 1*.

The grain is stripped from the grain stalk. In the harvester mechanism the ear is threshed and the grain stalk is chopped and spread on the ground.

Firstly, in front of the cutter the stalks are bent. Then they are cut into small pieces and transported through the straw cutter. During the transportation through the straw cutter a comminution occurs, which has a large influence on the stream.

In the following the cutting process is considered as a clearly mechanical process, fluid dynamic influences are disregarded. It is assumed that the stalk is vertically fixed in the soil before the cut.

Precise experimental investigations of the real cutting and transport-process in combine harvester straw choppers can be found in [4]. Here, as opposed to [4], the cutting process is simulated.

Modeling of the Cutter and the Stalk

In order to model a component in SimMechanics[1], its mass, its moment of inertia and the position of its center of gravity have to be known [5, 6].

In reality the stalk is a continuous oscillator and is discretized for the multi body simulation program by several rigid, rod-shaped elements (*Fig. 2*).

The elements are joined with each other by pin joints with an angular spring and an angular damper (not represented in *Figure 2*).

Following average parameters were measured for the model formation [3]:
- Mass/length-relation = 0.014 g/cm,
- Angular spring constant = $1.57 \cdot 10^{-3}$ Nm/° (Coefficient of variation = 41%) and
- Velocity-proportional angular damper constant = $20.96 \cdot 10^{-8}$ Nm/(°/s) (Coefficient of variation = 21%).

Further, the following numerical values were used to simulate the cutting process:
- Material spring constant = 1000 N/m (assumption),
- Material damping constant (velocity-proportional) = 1 N/(m/s) (assumption) und
- Cutting force = 10 N (analogous [2]).

Since the bodies modeled in a multi body simulation program are rigid and indivisible, the cut can only occur through a joint.

[1]) The program SimMechanics is an add-on of the program package Matlab/Simulink, made and marketed by The MathWorks (www.mathworks.com).

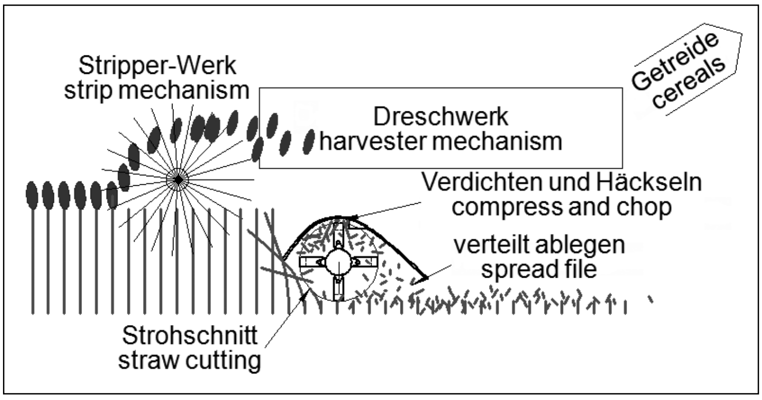


Fig. 1: Schematic presentation of a chopping process

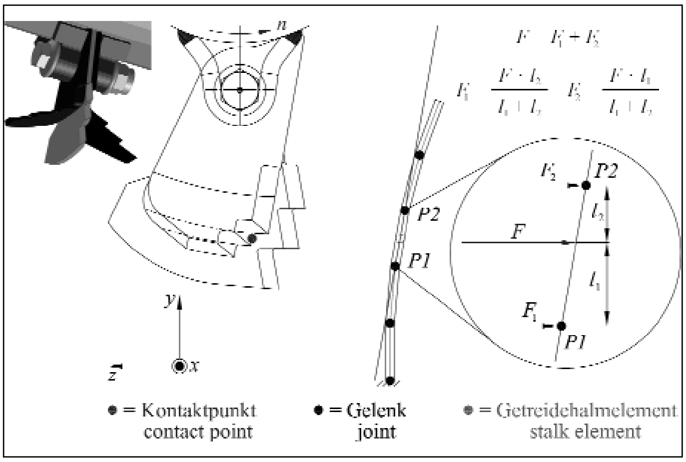


Fig. 2: Determining the contact point, using a chopping knife as an example

The knife construction consists of three blades which are attached to a blade shaft (*Fig. 2*).

Figure 3 shows the SimMechanics-model of a knife segment, consisting of several components, hidden within a subsystem („Black Box“) for the purpose of clarity.

The rotation velocity of the blade shaft is 3800 min^{-1}, the driving speed of the combine harvester straw cutter is 2.7 m/s.

For simplification it is assumed that the cut occurs in a plane perpendicular to the longitudinal axis of the blade shaft. On this plane there is the contact point of the knife as well as all points of the stalk (*Fig. 2*).

Simulation of the Cutting Process

The structure of the SimMechanics-model used to simulate the cutting process is shown in *Figure 4*.

On the knife-edge is a contact point, which causes the cut (*Fig. 2*). Every rod-shaped stalk element has a joint (knot) at each of his two ends. The position and velocity of the knife-sided contact point and the knots are measured continuously and lead to the subsystem force calc. (*Fig. 4*).

By means of the knot positions a straight line equation is formed for every stalk element (*Fig. 5*, equation 1). It describes the position and orientation of every stalk element in the plane and is recalculated continuously.

$$z_S = \left[\frac{z_{P2}-z_{P1}}{y_{P2}-y_{P1}}\cdot(y_M-y_{P1})+z_{P1}\right]\cdot\underbrace{(y_{P2}\ge y_M)}_{1\ (wahr)\ oder\ 0\ (falsch)}\cdot\underbrace{(y_M\ge y_{P1})}_{1\ (wahr)\ oder\ 0\ (falsch)} \qquad \text{Eq. 1}$$

The knife and a stalk element are in contact with each other, if the following conditions are met regarding the space coordinates.

- $|x_{Contact\ Point\_Knife} - x_{Stalk}| \le \varepsilon$, with ε as permissible deviation,
- $y_{lower\_Contact\ Point\_Stalk\ Element} < y_{Contact\ Point\_Knife} < y_{upper\_Contact\ Point\_Stalk\ Element}$ and
- $z_{Contact\ Point\_Knife} \le z_{Stalk\ Element}$.

The z-coordinate z_S of the stalk-sided contact point can be determined by Equation 1.

If a contact is available, the contact force acting in z-direction is calculated as a sum of a spring and damper force (Eq. 2, *Fig. 5*).

$$F_K = \underbrace{c \cdot \Delta z}_{F_F} + \underbrace{k \cdot \Delta v_z}_{F_D} \qquad \text{Eq. 2}$$

For the determining the total spring and total damper constant it is assumed that the knife and the stalk behave like two springs and dampers switched in series. Thus, the constants result from the material stiffness and the material damping of the interacting bodies.

The spring force results from the multiplication of the total spring constant by the amount of the distance of knife penetration into the stalk in z-direction. The damper force is the product from the total damping constant and the relative velocity between the knife and the contact point on the stalk element in z-direction (Eq. 3).

$$v_{Sz} = (v_{P2z} - v_{P1z})\cdot\frac{y_{PValue}}{yl_{Element}} + v_{P1z}, \qquad \text{Eq. 3}$$

with $yl_{Element} = y_{P2} - y_{P1} = l_1 + l_2$, $y_{SValue} = y_M - y_{P1}$

It is accepted that the forces working in x-direction are negligibly small.

The stalk has fibers running parallel to his longitudinal axis. Because of this, it is assumed that the amount of the contact force working in y-direction is 10% of the value of the force acting in z-direction.

The contact force is an output of the subsystem force calc. (*Fig. 4*) and acts on the knife-sided contact point and the concerned stalk element. To make sure that the contact force can act on the stalk element, it is distributed onto the two knots positioned at the ends of the relevant element. This is necessary, since in SimMechanics forces can attack only at points on elements exactly defined before the start of the simulation and the elements have a finite number of knots. The contact force is distributed so that the sum of all forces and moments is identical (*Fig. 2*).

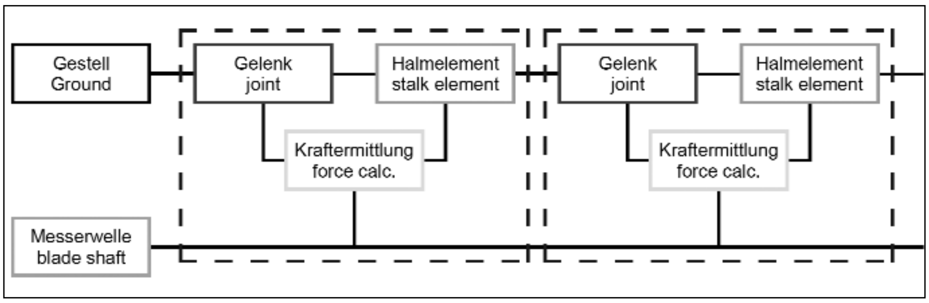


Fig. 4: Structure of a SimMechanics-model for simulating the cutting process

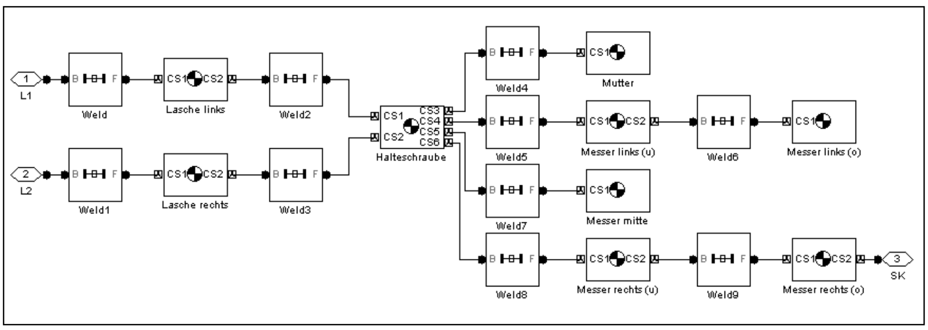


Fig. 3: SimMechanics-model of a knife segment

The stalk elements are connected with each other by joints having two translational and one rotational degree of freedom, to facilitate a separation of two stalk elements for the planar cutting process (*Fig. 4*). If the contact force is smaller than the cutting force, then only a spring with a large spring constant (c = 10^5 N/m) will act onto the joint’s two translational degrees of freedom. Thus the two degrees of freedom are not effective in the initial state, the stalk is only bent and the elements will keep joined with

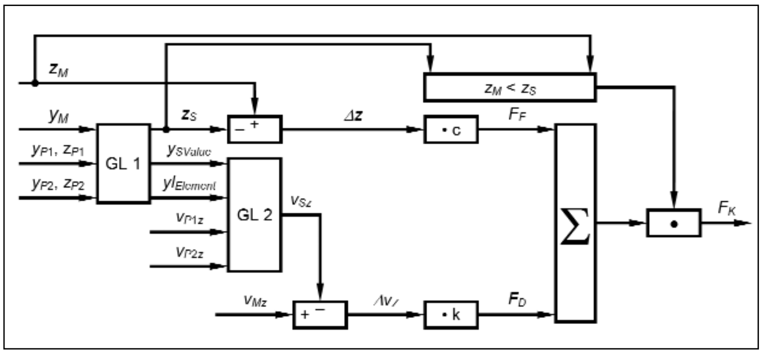


Fig. 5: Structure of a SimMechanics-model for determining the cutting force F_K (Indexes: M = knife; P1 and P2 acc. to Fig. 2; SK = contact point, see Fig. 2; x, y, z = space coordinates)

each other. On the rotational degree of freedom an angle spring and an angle damper act. If the contact force is larger than the cutting force, all spring and damping constants of the joint below the contact point become zero, the stalk element can move freely in the y-z-plane.

Figure 6 shows the contact force working during a simulated cut as a function of time, which can be divided into two cases according to *Figure 7*.

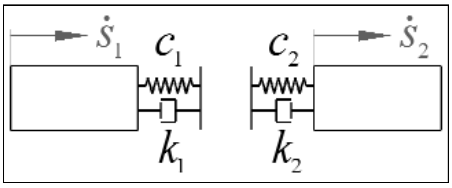
The largest velocity difference between the knife and the resting stalk appears at the beginning of the cutting process. At this time, the spring force has hardly any influence on the time function of the contact force, since their value is approximately zero due to the small deformations. According to Equation 2 this explains the curve displayed in *Figure 6*.

In the further curve of the movement the spring force increases while the damper force is decreasing.

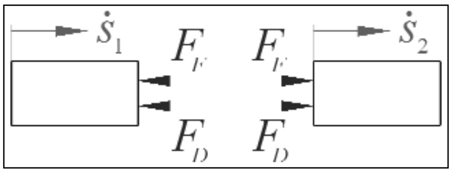
Towards the end of the simulated cutting process the two impact partners separate from each other and the spring force decreases due to the relaxation of the spring.

The increasing velocity difference of the two bodies results in an increase of the damper force which shows another direction in this second case than in the first (*Fig. 7*). Because of this, the direction changes in which the contact force works (enlargement in *Figure 6*). If the components do not stand in contact with each other anymore, the contact force falls rapidly.

Fig. 7: For explanation of the contact force curve in Fig. 6

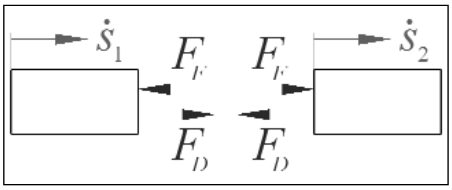


Contact case1: $\dot{s}_1 > \dot{s}_2$



Spring forceF_F : ↑; damper force F_D : ↓

Contact case 2: $\dot{s}_1 < \dot{s}_2$



Spring force F_F : ↓; damper force F_D : ↑

Summary and Outlook

Cutting processes in harvesting processes can be modeled virtually by means of multi body simulation programs. The output data of the determined motion of the chopped stalk can serve as input for a following particle flow simulation.

In the next step a measuring technique validation of the simulation model is intended for selected cases. The target is to bring the calculated and the real contact force curves to congruence. Also a reduction of CPU times for the simulations has to be addressed:

- distributed computing using computer clusters,
- use of physic engines and
- use of a software based on the theory of the discrete element method (DEM).

These simulations should contribute to determine as well as to optimize the power requirement of agricultural machinery and the particle stream in future. Thus simulations will replace field tests in the area of the agricultural technique increasingly due to the costs and time savings.

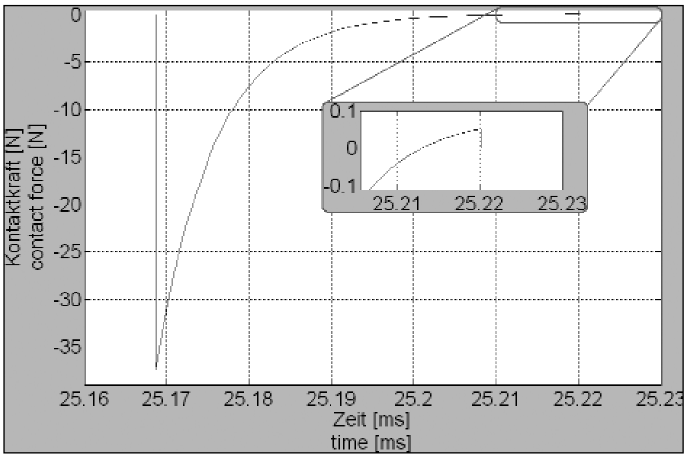


Fig. 6: Contact force curve over time

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