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Influence of elliptical sieve movements on the functioning of the combine cleaning unit

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To increase the throughput of the cleaning unit in a combine harvester, an improvement of the separation process and thus an optimization of the mechanic and aerodynamic excitations is necessary. One opportunity to improve the functioning of the cleaning unit is to optimize the sieve movement. For this purpose, the cleaning unit test rig of the Institute of Agricultural Engineering was extended with a drive system that enables the investigation of linear, circular and elliptical sieve movements. The evaluation of the conducted investigations allows an assessment of the functioning of the cleaning unit. Parallel conducted Discrete-Element-simulations in combination with Computational-Fluid-Dynamics-simulations (DEM-CFD-simulations) allow the investigation of the particle movement of grain and material other than grain (MOG) and therefore a more detailed analysis of the processes.

Keywords
Cleaning unit, Combine harvester, Sieve movement, Segregation, Separation, DEM, CFD, simulation

The demand for increasing the performance increase of modern combine harvesters causes the further development of the process components threshing unit, residual grain separation and cleaning unit. Due to the high throughputs and the intensive straw handling of the threshing unit and the separation rotors, the amount of MOG in the cleaning unit increases (Rothaug and Kutzbach 2005). Various different investigations have been carried out to enhance the separation of grain and MOG (Böttinger 1993, Freye 1980, Dahany 1994, Zhao 2002, Zehme 1972). One opportunity is to optimize the movement pattern of the sieve. In combine harvesters, the sieves executes linear movements. The direction of this movement is upwards in conveying direction. Compared to a linear movement pattern, circular movements cause a lower throughput sensitivity. However, the grain loss level is slightly higher (Rothaug et al. 2006, Yin et al. 2001). One option for combining the advantages of the linear and the circular sieve movement pattern is to use an elliptical movement pattern, because an elliptical movement pattern is a combination of a linear and circular movement. Compared to the circular movement, an elliptical movement allows different values of acceleration for the x- and y-direction accordingly in sieve direction and vertical to the sieve. This additional degree of freedom enables a higher flexibility, which is expected to have a positive effect on the segregation and separation process. Indeed, previous work demonstrates a throughput increase of 10–15 % at a grain loss of 1 % on a straw walker with an elliptical movement pattern under laboratory conditions. A higher power requirement was also determined, but referred to the entire engine power of the combine harvester the increase is negligibly small (Bernhardt 2015).

Investigations with elliptical movements of the sieve in the combine cleaning unit are presented in the following. The sieve movement is analyzed and evaluated by comparing the results with investigations of linear and circular sieve movements. Furthermore, results of simulations are explained and

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the accuracy of the simulations are evaluated. Based on these results the actual capability of elliptic sieve movements can be determined. If the functioning of the cleaning unit is significantly higher, more experiments can be carried out with the test rig. Field-tests with a combine harvester with sieves that are modified to carry out elliptical movements are conceivable next steps.

Theoretical pre-examinations

A linear sieve movement causes a throw-like motion of the grain-MOG-mixture and a segregation and separation of the grain through the MOG layer and the sieve. The flight number *Fr* is defined as the maximal acceleration of the mixture vertical to the sieve related to the appropriate component of the gravitational acceleration g and characterizes the mechanical excitation. It consists of the amplitude a and the frequency *f* of the sieve movement as well as the inclination of the sieve α and the angle of sieve oscillation β. (Freye 1980)

$$Fr = \frac{a \cdot (2 \cdot \pi \cdot f)^2 \cdot \sin(\beta - \alpha)}{g \cdot \cos(\alpha)} \qquad \text{(Eq. 1)}$$

Contrary to the linear sieve movement, where grain is conveyed in direction of the sieve oscillation, the movement of the grain-MOG-mixture on a circularly oscillating sieve at the point of detachment is tangential to the sieve movement. The angle of detachment ϕ describes the point where the grain-MOG-mixture detaches from the sieve and depends on the flight number (Figure 1). A higher flight number causes an earlier point of detachment and therefore a lager angle of detachment. This results in a large proportion of the vertical acceleration, which directly influences the conveying and segregation process. The angle of the sieve oscillation and therefore the angle of detachment on an elliptically oscillating sieve depends on the rotation of the elliptical orbit, which means the angle between the sieve and the minor axis. The rotation of the elliptical sieve movement colored in red in Figure 1 is chosen in a way that the point of detachment is equal to the circular sieve movement.

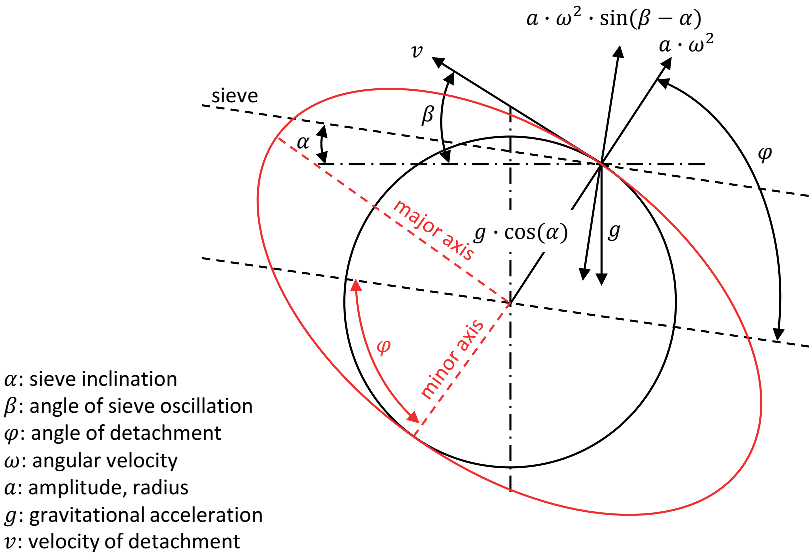

Figure 1: Dependency of the flight number *Fr* on the angle of detachment of the grain-MOG-mixture on a circular and an elliptical sieve movement (Rothaug et al. 2003)

The maximal accelerations on a circular oscillating sieve in vertical and horizontal direction are inevitably equal. Whereby it is presumed that the horizontal acceleration mainly characterizes the conveying process and the movements in the mixture layer. The vertical acceleration defines the separation forces (Bernhardt 2015, Damm 1971). Equal accelerations in horizontal and vertical direction do not need to cause an optimal functioning of the cleaning unit. With elliptical sieve movements, the maximal accelerations in vertical and horizontal direction can be adjusted independently. This additional degree of freedom can have a positive effect on the segregation and separation (Bernhardt 2015).

Test rig to investigate different sieve movements

To investigate elliptical sieve movements, the combine cleaning unit test rig of the Institute of Agricultural Engineering was modified with a special drive to enable linear, circular and elliptical sieve movements with different drive parameters. To reduce the amount of grain and MOG the effective sieve width is 0.23 m. In contrast to state of the art combine harvesters, the test rig has only one sieve. The air velocity of the air flow which is initiated through the sieve can be adjusted individually. With this set-up, it is possible to investigate and analyze sub-processes in more detail. The basic structure of the test rig is shown in Figure 2 (Meyer 2015).

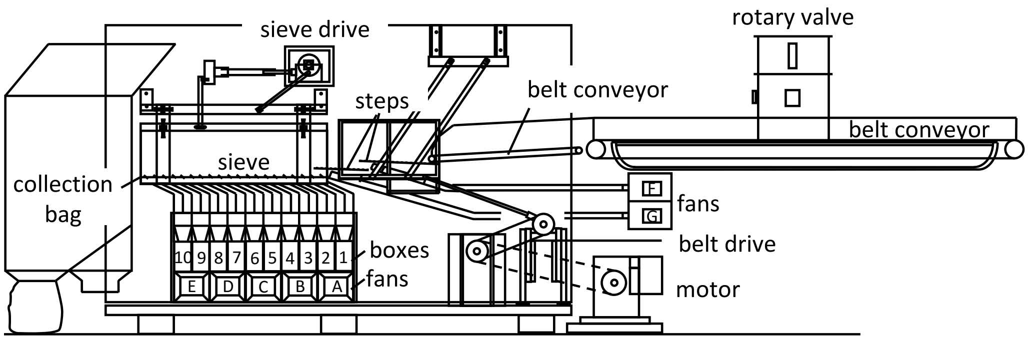

Figure 2: Combine cleaning unit test rig to investigate linear, circular and elliptical sieve movements (Beckmann et al. 2016)

To supply the grain and MOG for the investigations MOG is evenly distributed on a 10 m-long belt conveyor. The belt speed of 0.5 m/s causes a test duration of 20 s and allows to neglect unsteady conditions at the beginning and at the end of the experiment because the amount is relatively small (Zhao 2002). A rotary valve evenly dispenses grain above the straw layer during the experiment. The throughput is adjusted by the amount of MOG, which is distributed on the belt conveyor, and the speed of the rotary valve. A second belt conveyor conveys the grain-MOG-mixture to the preparation pan of the cleaning unit test rig. The preparation pan is driven by a separate electric motor and a belt drive and executes an approximately linear movement. Behind the preparation pan and the two winnowing steps, the mixture reaches the air-ventilated sieve that can execute different movements. Due to the conveying, segregation and separation processes the grain is separated through the sieve in the boxes 1–10, the unseparated grain is conveyed over the sieve to the collection bag. The determination of the grain loss V_{grain}, the grain purity R_{grain}, die separation length l_{80} and the grain separation rate

A_{grain} allows the evaluation of the functioning of the cleaning unit. In the following, mainly the grain loss is used to assess the functioning. It is defined by the quotient of the unseparated grain mass $m_{grain,loss}$ and the total amount of grain $m_{grain,ges}$.

$$V_{grain} = \frac{m_{grain,loss}}{m_{grain,ges}} \cdot 100\ \% \qquad \text{(Eq. 2)}$$

The grain purity is a measure of the amount of impurities of the separated grain and is defined as the ratio between the separated grain mass $m_{grain,cleaning}$ and the entire separated components $m_{ges,cleaning}$. The entire separated components $m_{ges,cleaning}$ consists of the separated grain mass $m_{grain,cleaning}$ and the separated MOG mass $m_{MOG,cleaning}$.

$$R_{grain} = \frac{m_{grain,cleaning}}{m_{grain,cleaning} + m_{MOG,cleaning}} = \frac{m_{grain,cleaning}}{m_{ges,cleaning}} \qquad \text{(Eq. 3)}$$

The separation length l_{80} is the length, which is necessary to separate 80 % of the grain. The separation rate A_{grain} defines the percentage separation over the sieve. The fans A-E initiate air flows through the sieve in the mixture and fans F-G in the winnowing steps. The air velocity for the related sieve regions can be adjusted by the pressure drop of the fans. The implementation of different sieve movements is realized by superimposed horizontal and vertical oscillations. Therefore, the main-frame is firmly attached with the test rig foundation on the one hand and via linear bearings with a vertical oscillation frame on the other hand. A horizontally oscillating frame is mounted via linear bearings to the vertically oscillating frame and the sieve is attached to the horizontal frame. This assembly enables an independent horizontal and vertical oscillation of the sieve. The drive consists of an electric motor and two crank drives which are connected by a distribution gear and a multi-plate clutch, as shown in Figure 3 (Meyer 2015).

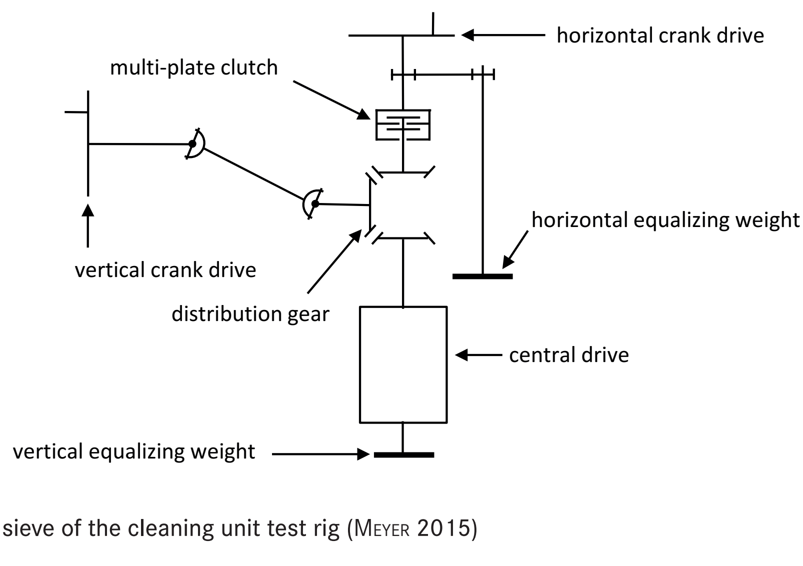

Figure 3: Drive of the sieve of the cleaning unit test rig (Meyer 2015)

The connection of the crank drives with the respective frames enables a sinusoidally oscillating movement. The amplitudes are continuously adjustable. The distribution gear has a transmission ratio of 1 : 1 and allows to adjust the oscillating frequency of the crank drives directly with the rotational speed of the electric motor. The phase angle of the two crank drives can be configured by the multi-plate clutch, Figure 4. To execute a linear sieve movement the crank amplitudes are set to a desired value depending on the resulting amplitude and angle of the linear oscillation. The phase angle is adjusted to 0°. Due to the sinusoidal movement of the frames, the sieve executes a linear oscillation. A circular sieve movement is realized by setting the phase angle to 90° and the horizontal and vertical amplitude of the crank drives to the same value, which defines the radius of the circle. Elliptical sieve movements can be realized by adjusting the phase angle between 0° and 90°, depending on the desired angle of oscillation. This configuration allows to investigate the influence of the sieve movement on the functioning of the combine cleaning unit in detail.

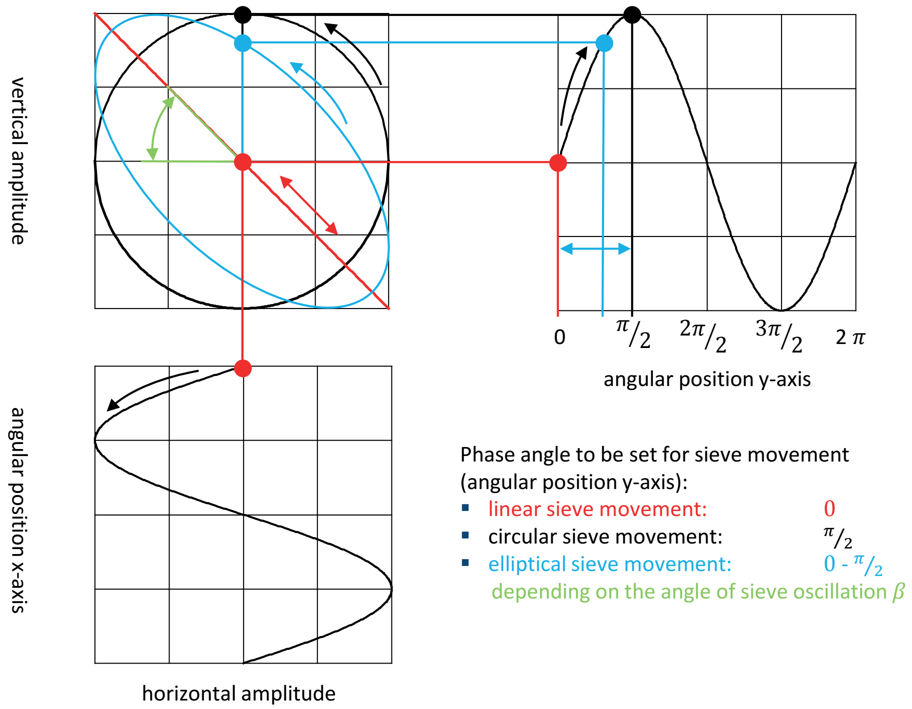

Figure 4: Adjustment of the linear (red), circular (black) and elliptical (blue) sieve movement with the phase angle, angle setting horizontal und vertical axis in radians

Design of experiments

In order to reduce the amount of experiments, only the sieve movement and the throughput rate are altered. The constant parameters of the air flows, the mechanical excitation of the preparation pan and the sieve inclination were determined on the basis of selected reference experiments with linear and circular sieve movements from the literature (Zhao 2002, Rothaug et al. 2006). The grain-MOG-mass ratio of the reference experiments from literature is 70 : 30 (grain : MOG). The grain-MOG-mass ratio in these experiments is changed to 75 : 25 (grain : MOG) due to different material properties of the grain and MOG used in these experiments. Also 33 % of the test material used in the experiment is replaced by new material. An overview of the test parameters is shown in Table 1. In addition to investigations with linear and circular sieve movements to analyze the functioning of the test rig after the installation of the new sieve drive, a detailed investigation of elliptical sieve movements takes place to determine the influence to the functioning of the combine cleaning unit. To identify parameter settings where the grain loss is low with a minimum number of experiments, a fractional factorial experimental plan was developed using the Software Cornerstone from camLine. Based on a statistic regression using the results of the experiments, it is possible to investigate non-measured parameter settings. For this purpose, a quadratic regression approach was chosen because the dependency of the grain loss and the grain purity from the throughput can be described best with a quadratic function. The usage of a statistic experimental plan reduces the number of experiments to 31. Due to the statistical regression, the evaluation is always in a probability range. In order to obtain more robust results, a full factorial experimental plan was followed in the region of low grain loss.

Table 1: Test parameters

Parameter	**Movement**		
	1. linear	**2. circular**	**3. elliptical**
Amplitude	30 mm		
Angle of sieve oscillation	34°		
Diameter of circle		40 mm	
Horizontal amplitude			10–30 mm
Vertical amplitude			10–30 mm
Phase angle			0–90°
Throughput	1–5 kg/(sm)		
Frequency	4 Hz		
Sieve opening (lamella sieve)	10 mm		
Air velocity Winnowing step	1. WS 5 m/s 2. WS: 5 m/s		
Air velocity sieve	In the region of box 1 to 4: 4.5 m/s In the region of box 5 to 6: 3 m/s In the region of box 7 to 10: 2 m/s		
Direction of air flow	30°		
Sieve inclination	1°		
Mass ratio	Grain 75 % : MOG 25 %		
Crop type	Wheat		

Results

The grain losses with a linear and circular sieve movement show the same qualitative course as the experiments based on literature (Zhao 2002, Rothaug et al. 2006). The average grain loss is slightly higher, which is due to differences in the material properties. Thus, the test rig is suitable for examining the elliptical sieve movement (Beckmann et al. 2016).

The analysis of the influence of the horizontal amplitude a_h, the vertical amplitude a_v and the angle of oscillation β is possible by means of the experiments from the fractional factorial experimental plan and the regression analysis (Figure 5). The interpolation parameters as well as the corrected coefficients of determination for Figures 5–8 are given in Table 3.

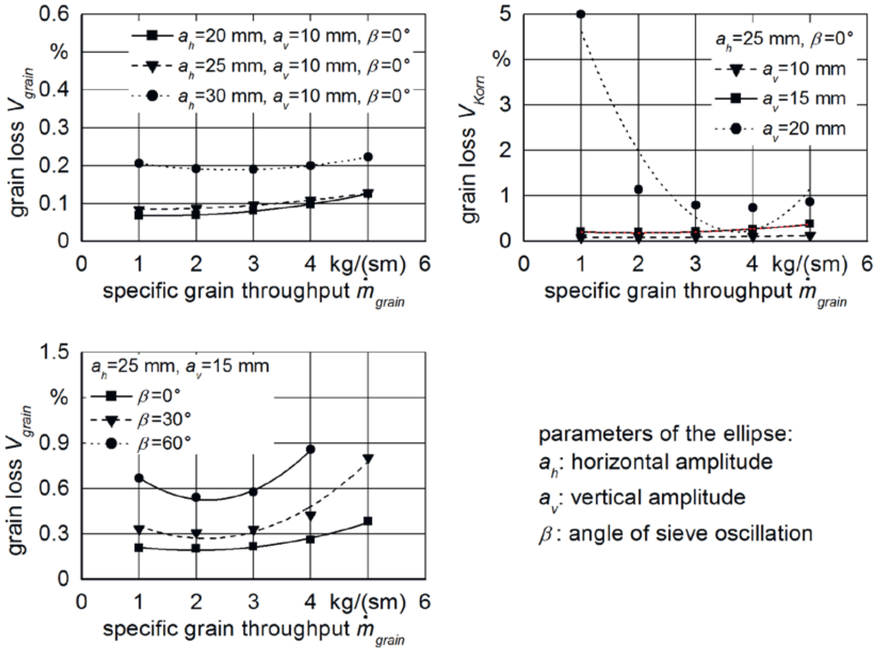

Figure 5: Influence of the horizontal and vertical amplitudes as well as the angle of oscillation on the grain loss based on a regression analysis with a quadratic regression approach

With a constant vertical amplitude of 10 mm and an angle of oscillation of 0° (lying ellipse), a lower horizontal amplitude causes a reduction in grain loss. A lower amplitude results in lower conveying speed and thus an increase of segregation and separation time. As can be seen in the diagram, the correlation between grain loss and horizontal amplitude is non-linear; a small increase in grain loss can be observed when the horizontal amplitude is increased from a_h = 20 mm to a_h = 25 mm. However, a further increase to a_h = 30 mm reveals a doubling of the grain loss. A further reduction of the horizontal amplitude is not reasonable, since a safe flow of material cannot be ensured at smaller amplitudes.

When reducing the vertical amplitude from a_v = 20 mm to a_v = 10 mm with a constant horizontal amplitude of 25 mm and a constant angle of oscillation of 0° (lying ellipse), the grain loss is also reduced. The lower accelerations vertical to the sieve cause a lower compression of the material layer, which has a positive effect on the segregation process (Bernhardt 2015). It was determined how the amplitudes interact to affect grain loss; a larger horizontal amplitude allows lower grain loss than a larger vertical amplitude. Bernhardt (2015) found similar results in the investigation of elliptical movement behaviors of straw walkers. The lowest grain loss could be determined at an angle of oscillation of 0° (lying ellipse). Thus, the following values are obtained for a parameter set in which the grain loss is minimal:

- horizontal amplitude: 20–30 mm
- vertical amplitude 10–15 mm
- angle of oscillation: 0° (lying ellipse)

To verify the parameters calculated using the regression, a full factorial experimental series was carried out in a throughput range of 1–5 kg/(s · m) (Table 2).

Table 2: Parameter set of the full factorial experimental series, for which the grain loss is minimal

No.	Horizontal amplitude in mm	Verticale Amplitude in mm	Angle of oscillation in °
1	25	10	0
2	25	15	0
3	30	15	0

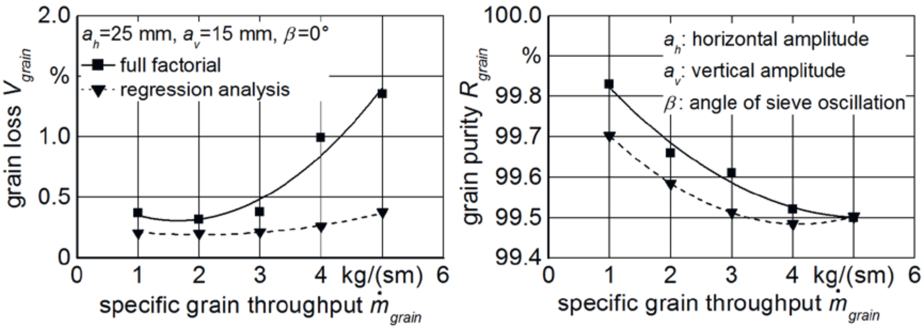

Figure 6: Comparison of grain loss and grain purity of a full factorial experimental series with the results from the regression analysis with a quadratic regression approach

A comparison of the results of the regression analysis with those of the full factorial experiments shows a nearly constant deviation in a throughput range of 1–3 kg/(s · m) (Figure 6). For higher throughputs, the differences are significantly larger, at a level of about 1 %. Due to a smaller number of experiments in the range of larger throughputs, the regression is carried out over longer intervals, resulting into larger interpolation errors. Over the entire throughput range, the grain purity determined in the full factorial experiments are higher than the values of the regression analysis. Due to these differences, the results of the regression analysis are only suitable for a qualitative evaluation. Experiments with the corresponding parameters of excitation must be carried out for a quantitative assessment. It is generally possible to increase the accuracy of the regression analysis by a higher number of experiments in the fractional factorial experimental plan and thus to reduce the interpolation uncertainty. However, the effort is similar to carrying out full factorial experimental series, therefore this procedure was not used.

The results of the full factorial experimental series with the excitation parameters from Table 2 confirm the qualitative evaluation of the regression analysis (Figure 7). In analogy to the regression analysis from the fractional factorial experimental plan, the interpolation is also carried out with a quadratic approach. The parameter set with a horizontal amplitude of 25 mm and a vertical amplitude of 10 mm is the one with the lowest grain loss over a throughput range of 1–4 kg/(s · m). The grain purity of these excitation parameters is highest over the entire throughput range. The grain loss of the parameter set with the horizontal amplitude of 30 mm and the vertical amplitude of 15 mm is the lowest in a throughput range of 4–5 kg/(s · m). Due to the higher throughput, the layer height of the mixture increases. Thus, for an optimal segregation process a higher mechanical excitation is necessary. This means that the excitation parameters with the lowest grain loss must be defined in context of a given throughput. The grain loss of the parameter set with a_h = 30 mm and a_v = 15 mm is smaller for larger throughputs than the grain loss of the curve with a_h = 25 mm and a_v = 15 mm, which confirms the requirement of a larger horizontal amplitude.

A comparison of the parameter sets with a_h = 25 mm and a_v = 15 mm or a_v = 10 mm reveals lower grain loss at smaller vertical amplitudes. This confirms the evaluation of the improvement of the segregation and separation process by a lower compression of the material layer.

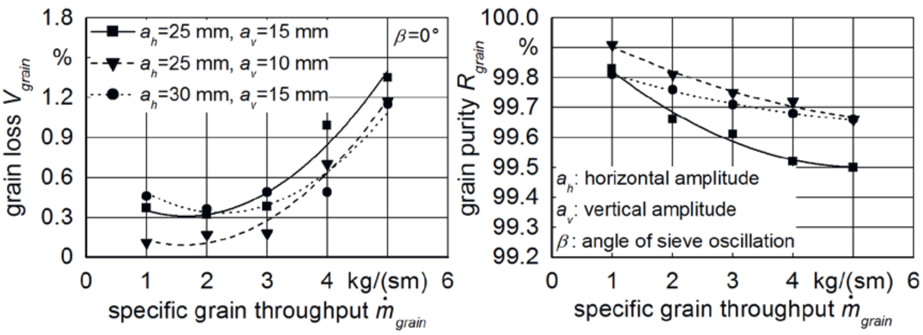

Figure 7: Comparison of the elliptical sieve movement with different parameter sets

The advantage of the elliptical sieve movement in a throughput range of 1–3.5 kg/(s · m) becomes clear from the comparison of the elliptical sieve movement with a_h = 25 mm and a_v = 10 mm with the reference experiments of the linear and circular sieve movement (Figure 8). In comparison with the linear sieve movement, the grain loss of the elliptical sieve movement increases with an increasing throughput but remains slightly lower over the entire throughput range. The grain loss of the circular sieve movement is the lowest at very high throughputs, due to the low throughput sensitivity of the circular movement. In contrast to the linear and circular sieve movement, the elliptical sieve movement shows a higher grain purity over the entire throughput range. It should be noted that it could also be possible to reduce the grain loss and increase the grain purity with linear and circular

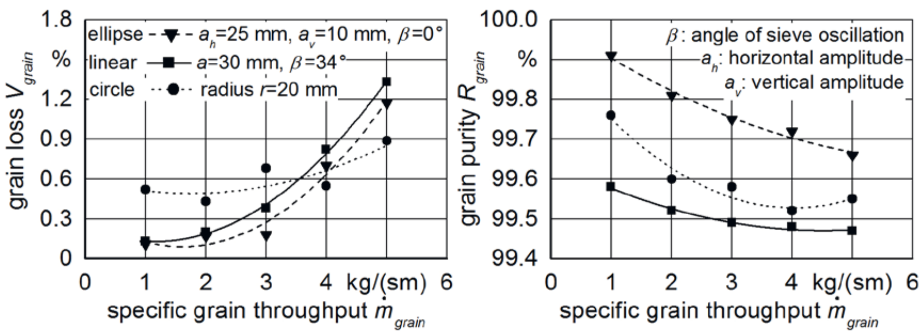

Figure 8: Comparison of the elliptical, circular and linear sieve movements

sieve movements using other parameter sets. The elliptical sieve movement enables small grain loss. However, compared to the circular sieve movement a lower throughput sensitivity could not be observed. Investigations with additional influencing parameters such as the pneumatic excitation and the sieve frequency must be carried out to further optimize the elliptical sieve movement.

For the regression analysis of the statistical experimental plan as well as for the interpolation of the full factorial experimental series a quadratic approach was chosen: $y = A + Bx + Cx^2$. The interpolation parameters A, B, C as well as the corrected coefficients of determination $\bar{R}^2$ can be seen in Table 3.

Table 3: Regression parameters and coefficients of determination

Description	a_h in mm	a_v in mm	ß in °	*A*	*B*	*C*	$\bar{R}^2$
Figure 5							
Grain loss	20	10	0	0.075	-0.011	0.004	0.997
Grain loss	25	10	0	0.086	-0.005	0.003	0.997
Grain loss	30	10	0	0.232	-0.032	0.006	0.999
Grain loss	25	15	0	0.272	0.080	0.020	0.968
Grain loss	25	20	0	8.438	-4.406	0.59	0.816
Grain loss	25	15	30	0.561	-0.270	0.063	0.930
Grain loss	25	15	60	1.019	-0.450	0.100	0.981
Figure 6							
Grain loss, full factorial	25	15	0	0.578	-0.324	0.098	0.919
Grain purity, full factorial	25	15	0	99.99	-0.191	0.019	0.963
Grain loss, regression analysis	25	15	0	0.270	-0.079	0.020	0.965
Grain purity, regression analysis	25	15	0	99.86	-0.186	0.0227	0.999
Figure 7							
Grain loss	25	15	0	0.578	-0.324	0.098	0.919
Grain purity	25	15	0	99.99	-0.191	0.019	0.963
Grain loss	25	10	0	0.336	-0.305	0.095	0.958
Grain purity	25	10	0	100	-0.106	0.008	0.970
Grain loss	30	15	0	0.832	-0.445	0.099	0.815
Grain purity	30	15	0	99.87	-0.072	0.006	0.997
Figure 8							
Ellipse, grain loss	25	10	0	0.336	-0.305	0.095	0.958
Ellipse, grain purity	25	10	0	100	-0.106	0.008	0.97
Linear, grain loss	*a* = 30 mm		34	0.236	-0.187	0.081	0.996
Linear, grain purity	*a* = 30 mm			99.65	-0.077	0.009	0.977
Circel, grain loss		radius *r* = 20 mm		0.596	-0.120	0.034	0.420
Circle, grain purity		radius *r* = 20 mm		99.92	-0.196	0.024	0.900

Simulation

Simultaneously conducted DEM-CFD-simulations allow a detailed investigation of the segregation and separation process. The CAD data of the cleaning unit test rig are used to represent the geometry. The DEM simulation was carried out with the software EDEM and the flow simulation with the software Ansys Fluent. Thereby a 1-way coupling was implemented in which the flow field was calculated in the center position of the unloaded oscillating lamella sieve. 1-way coupling means that the airflow has a force effect on the particles but they have no effect on the flow field. For a comparison between simulation and experiment, the experimental setup and procedure was also modelled in the simulation and the properties of the DEM particles were modeled according to the material properties of the grain and MOG used in the experiment (Beckmann et al. 2016). The simulation was calculated on a workstation computer with 8 cores and 16 GB RAM. The simulated test time is 16 s. At a throughput of 3 kg/(sm) in the stationary phase 105.650 particles are in the simulation environment.

A comparison of the grain separation rate A_{grain} and the separation length l_{80} between the simulation and the experiment for a linear sieve movement with a throughput of 4 kg/(s · m) and an elliptical sieve movement with a throughput of 3 kg/(s · m) reveals a mean deviation of a maximum of 6 % (Figure 9). In general, higher grain separation rates are observed in the experiment at a sieve length of 0.3 m. On the other hand, there is a higher grain separation rate in the simulation at a sieve length between 0.6–0.9 m. A comparison of the separation length l_{80} for linear sieve movements with different grain throughputs reveals larger deviations at smaller throughputs. Higher deviations are noticeable at smaller and larger throughputs with elliptical sieve movements, therefore the mean deviation is maximal here. The deviations between simulation and experiment are justified by the idealization of the particles in the simulation, but also by the limits of the 1-way coupling. However, the accuracy of the simulation is sufficient to evaluate results with different excitation parameters

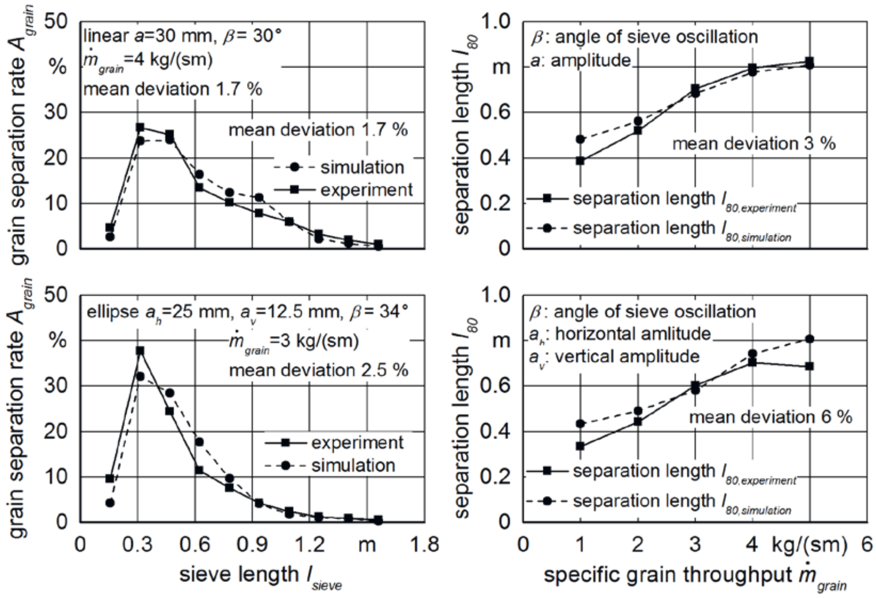

Figure 9: Comparison of the grain separation rate A_{grain} and the grain separation length l_{80} of simulation and experiment for linear (Beckmann et al. 2016) and elliptical sieve movements

using the grain separation rate and separation length in analogy to the experiment. Furthermore, the accuracy of the simulation is independent of the throughput or the sieve movement. For this reason, the simulation is suitable to support experimental investigations but also as a single examination method for the analysis of the elliptical sieve movement.

Conclusion

To investigate the functioning of the combine harvester for different sieve movements, the cleaning unit test rig at the Institute of Agricultural Engineering was extended with a sieve drive that enables the investigation of linear, circular and elliptical sieve movements with different amplitudes and frequencies. The elliptical sieve movement offers the possibility for different accelerations of the sieve in horizontal and vertical direction and thus a higher flexibility. A fractional factorial experimental plan was developed to reduce the maximal number of experiments and a regression analysis was used to determine the excitation parameters, which cause low grain loss. A subsequent full factorial experimental plan in the region of low grain loss enables a quantitative determination of grain loss and the grain purity as well as an estimation of the accuracy of the regression analysis. The potential of the elliptical sieve movement was found by comparing the results with the results of linear and circular reference movements. The optimal excitation parameters are always dependent on the throughput. Further investigations with additional influencing parameters such as the pneumatic excitation and the frequency of the sieve are necessary to further investigate the elliptical sieve movement.

Simultaneously performed DEM-CFD-simulations revealed a mean deviation in the grain separation rate and the separation length of a maximum of 6 %. These deviations are independent of the throughput and the sieve movement. Therefore, the simulation is suitable for investigating the functioning of the combine cleaning unit.

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