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Experimental determination of the segregation process using computer tomography

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Modelling methods such as DEM and CFD are increasingly used for developing high efficient combine cleaning systems. For this purpose it is necessary to verify the complex segregation and separation processes in the combine cleaning system. One way is to determine the segregation and separation function using 3D computer tomography (CT). This method makes it possible to visualize and analyse the movement behaviour of the components of the mixture during the segregation and separation process as well as the derivation of descriptive process parameters. A mechanically excited miniature test rig was designed and built at the company CLAAS Selbstfahrende Erntemaschinen GmbH to achieve this aim. The investigations were carried out at the Fraunhofer Institute for Integrated Circuits IIS. Through the evaluation of the recorded images the segregation process is described visually. A more detailed analysis enabled the development of segregation and separation function based on the different densities of grain and material other than grain.

Keywords
combine cleaning system, combine harvester, computer tomography, segregation, separation

Simulations have become an indispensable analytical tool in the process technologies of combine harvesters. It enables time and cost efficient function development. Often these simulations are composed of various complex numerical methods. An insight into these methods and an overview of the application areas of simulation in agricultural technology are provided by Korn and Herlitzius (2014). To reduce the procedural complexity of the processes the validation of the applied simulation models is frequently carried out using simplified test rigs (Pförtner and Böttinger 2013, Pförtner et al. 2014). Due to the complex metrological recording of the processes in a combine cleaning system the validation of modelling approaches to simulate the segregation and separation system is difficult. The effect of various influencing parameters such as oscillation amplitude, etc. on the segregation process has been adequately investigated (Freye 1980, Rochell 1975, Timofeev 2013, Zehme 1972, Böttinger and Timofeev 2010). The segregation and separation process is usually described using the penetration time (Beck 1992). Here the grain at the beginning and in the end of the experiment are considered. A consideration of the movement of the grain inside the layer of material during the segregation process is not possible. Due to the currently available measurement techniques, information about the detailed movement behaviour of grain and MOG (Material Other than Grain) during the segregation process is not available. Using photographic methods of measurement the movement behaviour of the mixture components can be determined near surfaces (Weis et al. 2013). However, these were only

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partially useful due to the neglect of the third dimension. With the knowledge of the three-dimensional movement behaviour, the segregation process can be described in detail and a connection to the physical properties of the components of the mixture (friction, elasticity, etc.) can be concluded. Therefore, this knowledge would improve the opportunity to validate DEM and CFD models. Below, studies are presented in which the movement behaviour of grain in a grain-MOG-mixture is analysed using contactless 3D x-ray computer tomography (CT).

Theoretical examination

In order to generate a deeper understanding of the segregation process the movement behaviour of the grain in a grain-MOG-mixture during the segregation process will be examined. Using a time-dependent position monitoring, the trajectory of each individual particle of the mixture is determined and this data is used to calculate the segregation and separation function. CT provides a way of contactless detection of the movement behaviour of grain in the mixture. Recording in a micrometer range makes sufficiently accurate measurements possible. The measuring principle is based on x-rays (Figure 1).

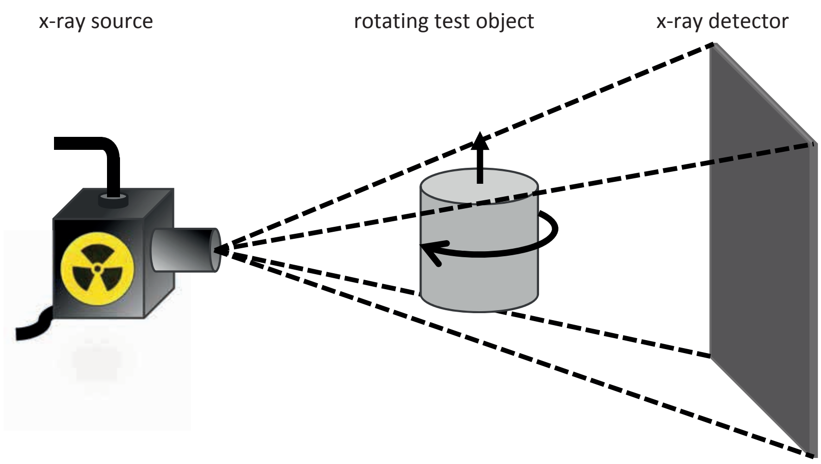

Figure 1: Schematic of an industrial computer tomography

The x-ray source generates x-rays and emits them in the direction of the test object, which is located on the sample plate. The absorption of the x-rays is, amongst others, dependent on the density of the test object. The radiation is transmitted in different magnitudes and the reaches the x-ray detector. Here, a digital 2D x-ray image is generated based on the radiation intensity. Because of the rotation of the test object during the measurement, 2D x-ray images are generated from different directions. Based on this batch of 2D x-ray images, three-dimensional images are then reconstructed. For this, x-ray images are used which were recorded during a half rotation of the test object. Because of the low data transmission rate of the x-ray detector the recording and processing of an image takes between 2 and 10 minutes. Therefore, the industrial computer tomography is mainly used for static investigations. The current focus of research in industrial computer tomography is to record dynamic processes. Thus, the Fraunhofer Institute for Integrated Circuits IIS developed a time-resolved, dynamic computer tomography method where a high-speed camera scans the x-ray detector system. This allows to produce recordings with a temporal resolution of up to 2000 x-ray images per second. The test object thereby rotates with a maximum speed of 0.35 1/s. With the time-resolved computer tomography, it is possible to visualize and analyse dynamic processes from the inside of the test object. Like in the static computer tomography, the structures of the test object are recorded in a completely contactless and non-destructive way. The dimensions of the x-ray detector and the high-speed camera system limit the maximum size of the examined test object. To investigate the segregation process with the dynamic computer tomography, a mechanically excited miniature test rig was developed at the company CLAAS Selbstfahrende Erntemaschinen GmbH. It has a geometry that allows the use in the dynamic CT and realise the excitation of the grain-MOG-mixture by vertical oscillation. The prerequisite for the reconstruction of 3D images during the segregation and separation process is that 2D x-ray images can be recorded at any time during a 180° rotation. At the beginning of the investigations, it was unclear if the technology allows the reconstruction due to the dynamic conditions of the processes. Therefore, an additional analysis based on the evaluation of the 2D x-ray images was performed.

Miniature test rig to produce the vertical oscillation and experimental setup

To achieve the lightest possible structure, the cylindrical container is made of acrylic glass. The inner diameter of the cylinder is 240 mm. In order to examine not only the segregation process but simultaneously also the penetration of the grain through the sieve, a sieve is inserted into the cylinder (Figure 2). The sieve mesh width is chosen so that grain and small components of MOG can pass the sieve.

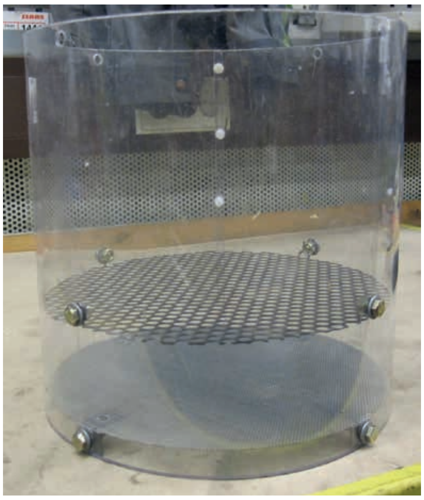

Figure 2: Container

Due to the rotation of the test object the necessary stationary power supply is realised using a battery. Furthermore, x-rays are ionizing radiation and pose a health risk at a certain dose, which is why all CT systems were set up in a radiopaque chamber. This chamber cannot be entered during recording.

The oscillation generated by the miniature test rig can be switched on and off through a remote control. A schematic of the CAD model and a kinematic diagram illistrate the generation of the vertical oscillation (Figure 3).

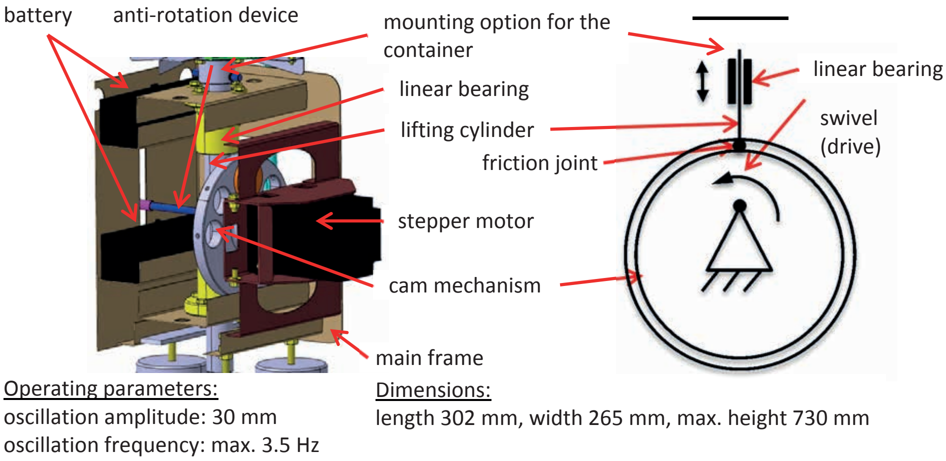

Figure 3: Miniature test rig to generate a vertical oscillation

A cam mechanism converts the rotational movement of the stepper motor into an approximate sinusoidal oscillation. A stepper motor is chosen here due to the ease of use. The speed can be infinitely adjusted from 0 to 3.5 1/s. The cam mechanism permits a fixed amplitude of the vertical oscillation of 30 mm. The mechanical excitation can be adjusted via the rotational speed of the stepper motor. The container is fixed on the lifting cylinder. The miniature test rig is designed so that it can be installed directly in the CT system (Figure 4).

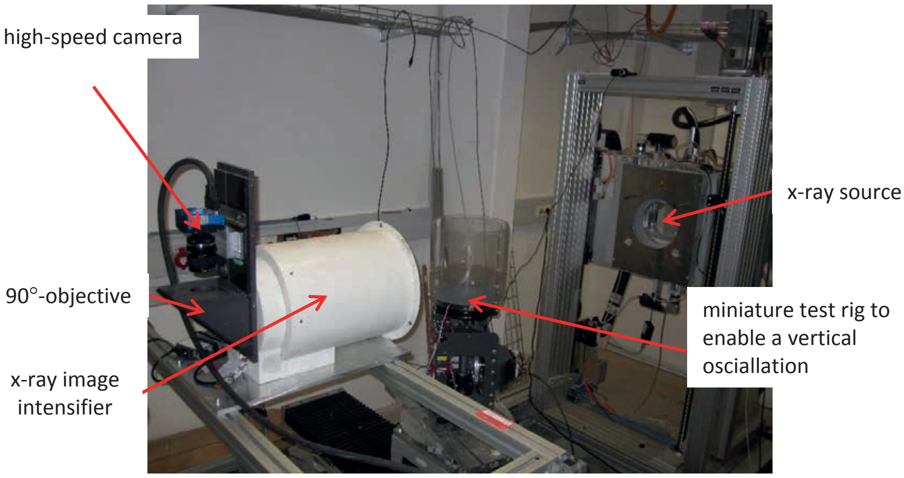

Figure 4: Miniature test rig installed in the CT system

For recording of the x-ray images, the voltage of the x-ray source was adjusted to 90 kV and the corresponding current to 12 mA. The exposure time of the camera is 500 µs. When displaying the 3D images using the software myVGL from Volume Graphics a value for a certain threshold of density can be chosen. All particles in the 3D image having a higher density than the threshold can be represented accordingly. In Figure 5 the threshold of density is set so that only the grain is displayed. In Figure 6 MOG can also be displayed due to the lower threshold. With a resolution of 200 µm, also the MOG structures are represented in detail. Furthermore, the 3D images can be sectioned at any level. Thus, not only the grain at the surface but also inside the grain-MOG-mixture can be analysed.

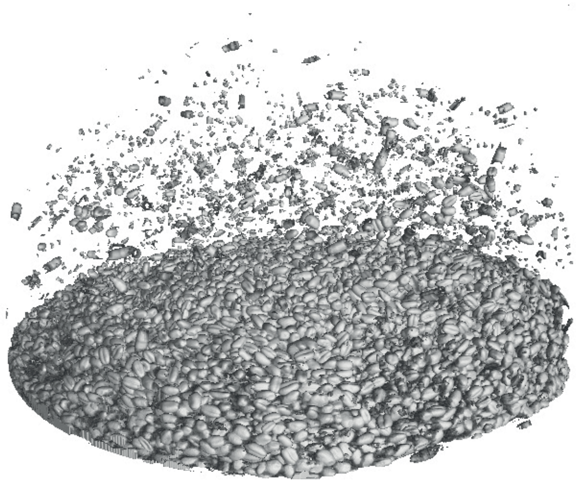

Figure 5: 3D image of a grain-MOG-mixture created with help of the computer tomography; only grain is displayed

Figure 6: 3D image of the grain-MOG-mixture created with help of the computer tomography; grain and MOG is displayed

Experimental procedure

Before beginning the experiment the examined grain-MOG-mixture is spread in layers in the container above the sieve. The layer height of MOG is h_{MOG} = 46 mm before spreading the grain on top of the MOG. The MOG is compressed by the grain, which has an idealized layer height of h_{grain} = 9 mm. Because of the vertical oscillation, it is expected that a segregation and separation process occurs and that the grain migrates through the MOG to the sieve and then penetrates through the sieve. For analysing these processes, the frequency of the stepper motor is adjusted so that a Froude number F_{RV} = 1 is reached. The Froude number F_{RV} is defined as the maximum acceleration of the grain experienced by the vertical oscillation in relation to the gravitational acceleration. At a threshold of F_{RV} = 1 the grain-MOG-mixture disengages from the sieve and executes a throwing motion. The duration of the CT scan is 6.6 seconds. In that time 6550 x-ray images are created. These images are available to reconstruct 3D images. A longer recording time has been omitted due to the large amounts of data.

Results

3D images can only be created of quasi-static processes that are not influenced by the rotational movement. Therefore, the analysis of the 2D x-ray images is described below (Figure 7). These images do not only represent the side view of the grain-MOG-mixture but also the third dimension using the different attenuation of the x-rays and thus the blackening of the x-ray images. For example, the blackening in the grain layer suggests large number of grain in the depth dimension.

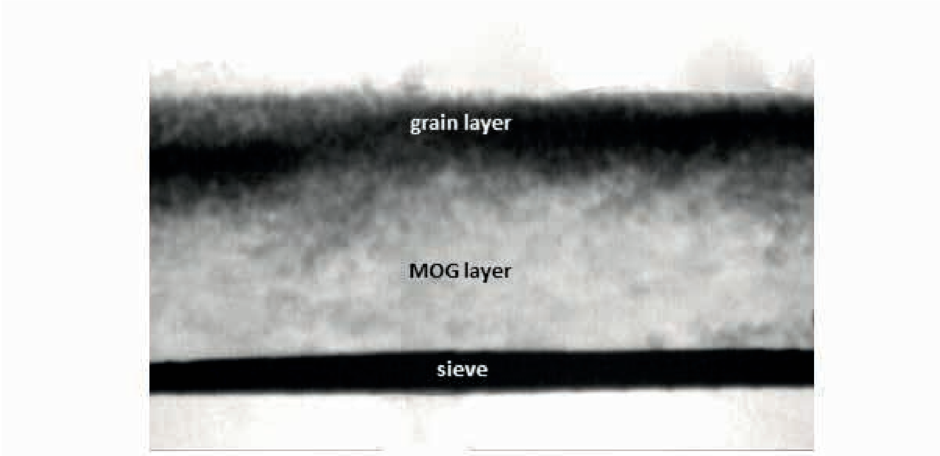

Figure 7: X-ray image of the grain-MOG-mixture at the beginning of the experiment

The sieve is shown very dark due to its very high density. The grain, displayed darker, lies on top of the MOG, displayed brighter. A video was created by stringing together a series of 2D x-ray images in which the segregation and separation process is shown. As expected the grain segregates through the MOG with different sinking rates and then penetrates through the sieve. To obtain further information about the segregation process, the distance between the grain layer and the sieve as well as the grain layer height at the bottom dead centre of the vertical oscillation are determined using the "Image Acquisition" and "Image Processing Toolbox" from Matlab. The aim is on one hand to get information about the sinking rate of the grain and on the other hand to determine the grain layer height as a function of time to get information about the variance of the sinking rate. Therefore, the 2D x-ray images are automatically converted into binary black-and-white images (Figure 8).

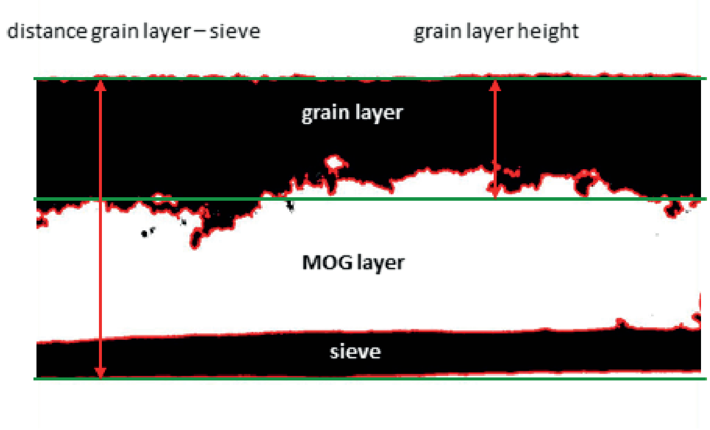

Figure 8: Binary image of the grain-MOG-mixture

The contrast is chosen so that the grain layer and the sieve are visible in black. An algorithm can then calculate the grain layer height as well as the distance between the grain layer and the bottom of the sieve. The boundary that defines the transition of the grain layer to the MOG layer is defined using the number of black and white pixels in the rows of the image. Looking at the pixels in every row of the image from the top to the bottom: The boundary between grain layer and MOG layer is defined when half of the pixels are white. The bottom of the sieve is selected as the reference for it because the algorithm can better identify the sieve bottom. The sieve thickness compared to the layer height is very small. The position of x-ray source and high-speed camera is angled horizontally through the middle of the container. Therefore, the camera records the sieve obliquely from above and consequently the sieve appears thicker in the x-ray image.

The grain layer height (Figure 9) increases during the segregation process because the grain sinks through the MOG layer with different sinking rates. Thus the grain layer expands. At the end of the experiment the majority of the grain has segregated through the MOG to the sieve; therefore the grain layer height decreases. The distance between the grain layer and the sieve over time describes a linear curve (Figure 10). This course indicates an average penetration of the grain through the MOG layer. The slope of the line represents the average segregation rate. It should be noted that in this evaluation the grain is always considered holistically. A separate analysis of each grain particle is not possible due to the undetermined movement behaviour for each particle.

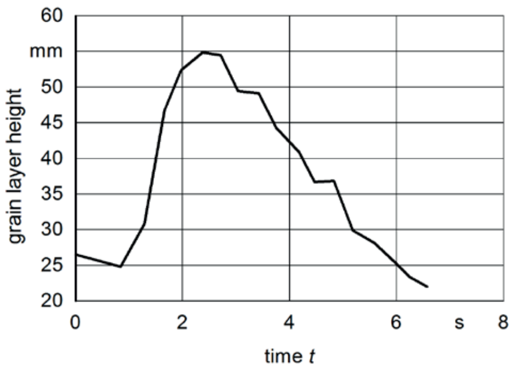

Figure 9: Grain layer height in a grain-MOG-mixture during a segregation process determined using the computer tomography

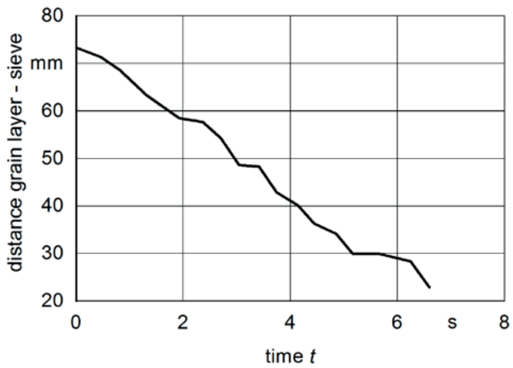

Figure 10: Distance grain layer – sieve in a grain-MOG-mixture during a segregation process determined using the computer tomography

Conclusion

Using the time-resolved computer tomography, the segregation and separation process of grain in a grain-MOG-mixture can be analysed in detail. While conventional high-speed cameras can only record images at the surface layer, the different attenuation of the x-rays indicates the third dimension in the x-ray images. The computer tomography allows to create 3D images from quasi-static processes and to analyse the internal structure of these processes. However, the required high speed rotation of the grain-MOG-mixture during the recording influences the segregation process. Based on 2D x-ray images a determination of the grain layer height and the distance between the grain layer and the sieve is possible. Unlike other methods to determine the segregation and separation process not only the initial conditions and the deposited grain mass over time is considered, but also the average movement behaviour of the grain can be visualized and analysed during segregation. In addition, these data are used for validation of DEM and CFD simulations because the average movement behaviour of the grain is visible in the entire volume and it is thus possible to reduce the influence of wall friction.

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