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RECENT RESULTS OF EXPERIMENTATION AND DEM MODELING OF CENTRIFUGAL FERTILIZER SPREADING

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Abstract – For the past few decades there has been a growing concern about the environmental implications associated with the use of soil fertilizers. In Europe, over 90% of fertilizer is distributed using spinning disc spreaders. The popularity of spinning disc spreaders lies with their relative low cost. However, the performance of these machines is highly dependent on the particle properties (e.g. friction coefficients, shape). This results in large differences in spread patterns depending on the fertilizer type as well as the prevailing weather conditions (e.g. air humidity). This dependence requires extensive experimental calibration of the spreader for each type of fertilizer. When a new spreader is designed this calibration work has to be largely repeated. DEM is believed to be the key to increase the understanding of the spreading process, the design of better spreaders and a drastic reduction of experimental calibration.

The paper reviews recent results in experimentation and modelling of an international research consortium running several industrial research projects on centrifugal fertilizer projects (Tijskens et al. 2005).

1. GENERAL

The centrifugal fertilizer spreader represents a very important spreader of choice for farmers worldwide. They are usually of the spinning disc type comprising two discs, spinning in opposite directions. The reasons for the popularity of these machines include their low price, easy maintenance and a large working width of up to 48m. So far, these spreaders have been predominantly used for (approximately) uniform fertilizer application on the field. However, nutrient maps and yield maps collected from fields always show substantial variations in the nutrient (N, P and K) demand across the fields. Owing to a growing concern for the environment and the natural desire by farmers to be economical, site-specific fertilizer application has become a very important topic in agricultural research. When fertilizer is applied according to site-specific requirements, leaching to ground and surface water is minimized while at the same time a significant amount of fertilizer is conserved. In addition, both over and under-dosage have been reported to lead to yield losses (Sögaard & Kierkegaard, 1994; Prummel & Datema, 1962). To effect site-specific application, there is a need for an automatic controlsystem which will adjust

spreading mass flow rates to the specific needs. Fertilizer demand maps could be used as input and various ways to accurately locate the machines in the field, such as the global positioning system (GPS), can be incorporated.

For such a control system to be designed, major improvements are necessary in the understanding of the spreading process with respect to the interplay of machine settings and the properties of the fertilizer granulate. These improvements require better experimental apparatus to probe the process as well as simulation models which are capable to account for intricate interactions in the moving granulate.

The paper concentrates on three topics for which recently significant improvements have been made: Image analysis of particle trajectories, experimental evaluation of spatial and transverse distributions for centrifugal fertilizer spreaders, and DEM modeling of centrifugal fertilizer spreading

1. IMAGE ANALYSIS OF PARTICLE TRAJECTORIES

In order to predict the spreading pattern, that is, the distribution of fertilizer particles in the field, it is necessary to obtain information about the motion of the particles when they leave the spinning disc. This information provides the input data for ballistic flight models in order to compute the landing points of the fertilizer particles and thus to predict spread pattern.

In order to measure the velocity and the direction of the fertilizer particles in the vicinity of the disc, various methods have been elaborated based on traditional photography^{1,2,3}, Doppler frequency shift⁴, photo sensitive sensors⁵, high speed video¹ or various stroboscopic methods^{6,7}. The aim of our work is to develop automatic processing to provide velocities and directions of fertilizer granules by using a robust and simple imaging system, especially as concerns the scene lighting.

Our approach involves the use of a CCD camera whose location and lens are chosen to cover a wide field of view in the vicinity of the spinning disc. Thus the imaging system does not need to rotate around the disc to sample the whole angular range of spreading.

A set-up was specifically constructed to develop and assess this device in an enclosed space, as shown in figure 1. The first part, the mechanical apparatus, is made up of elements similar to those included in a common broadcaster. The second part of the set-up consists of a black and white camera unit and two simple spotlights placed just above the disc to illuminate the granules lengthways during their motion.

Since camera exposure was long enough (i.e. 35 ms), fertilizer particles flying in the vicinity of the disc appear as streaks across a motion blurred image.

To obtain as much prior knowledge as possible before image processing, the motion of a single particle sliding along a vane was first analysed for the case of a flat spinning disc equipped with radial or pitched straight vanes. It is shown that the outlet angle of the granule is a bounded value and that its measurement provides the outlet velocity of the particle.

Since the aim of our imaging system is to extract metric information, and since image acquisition is not a perfect perspective transformation between object space and image space, each image was

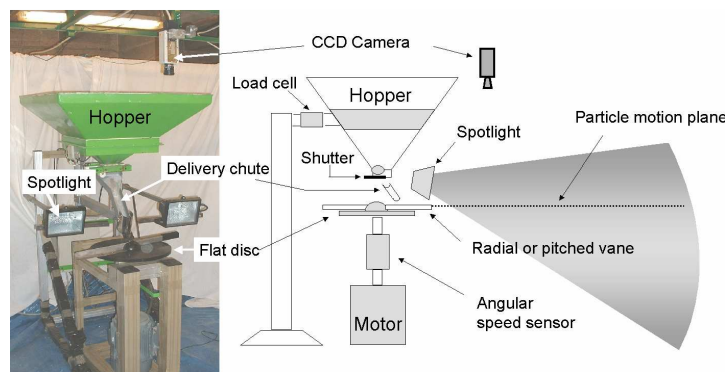


Fig. 1: Mechanical and imaging set-up

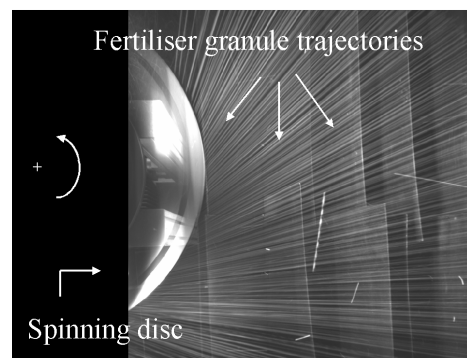


Fig. 2: Example of spreading image

corrected by using a pinhole camera and fourth order lens distortion models.

Low level processing is then carried out on the grey level image to highlight trajectories and to obtain binary images. Angular information is extracted using the Hough Transform which is specifically optimised in order to analyse these streaks and to measure the motion of the particles. Our automatic image processing was assessed on various simulated images and used on real spreading images to characterise fertilizer particle trajectories.

The velocity values deduced from the outlet angle have also been compared with the velocity values measured by the stroboscopic method. The causes of bias in both methods are examined.

The technique has also been used to feature the behaviour of fertilizer particles in the vicinity of the disc. The analysis of trajectories extracted from spreading images does not show any significant trend in the outlet angle with respect to the angular location of the vane during spreading. This finding contrasts with the decrease in the outlet angle for increasing angular position suggested by other authors^{1,3}. Examining the locations of trajectory pixels with respect to the identified axis of each extracted trajectory shows that the horizontal motion of the granules can be considered as straight lines in the vicinity of the disc.

Using this simplified mechanical analysis, some global values of friction coefficients between the particles and the vane are deduced from the outlet angle measurements.

Extensions of this measurement system towards the use of concave (common in centrifugal spreaders) rather than flat discs are underway. Also it is investigated how information can be extracted about the number of particles flying away in each direction.

2. EXPERIMENTAL EVALUATION OF SPATIAL AND TRANSVERSE DISTRIBUTIONS

The spatial distribution pattern is defined as the particle density distribution obtained on the ground when the spreader is in a fixed position, normalized for a certain amount of spread fertilizer. This distribution is two-dimensional. The transversal distribution is defined as the particle density distribution obtained along a line when the spreader is moving perpendicular to that line, again, normalized for a certain amount of spread fertilizer, and for a given driving velocity. This distribution is one-dimensional. The relation between these distributions is depicted in figure 2.

Several techniques have been developed to measure distribution patterns. The most realistic method is the placement of a row of collection trays in the field, perpendicular to the driving direction of the spreader. The captured particles are weighed and the transverse distribution is obtained. Owing to uncontrollable external factors, such as wind and field conditions, it is impossible to compare the performances of different combinations of spreader and fertilizer type.

Standardised tests can be carried out in spreading halls, specifically designed for this purpose. In these halls, the principle of collection trays is applied as well, be it in a more sophisticated implementation. The external factors are eliminated as much as possible, so as to make experiments reproducible and comparable. The better halls are air-conditioned, so that a standard condition of the particles is guaranteed (Persson, 1998). In this way, unwanted variation between measurements because of the influence of humidity on the friction coefficient between particles and the disc, for example, is avoided. These halls suffer from a few important drawbacks: they are large and expensive. Performing tests is time consuming, especially for spatial distributions, and requires large amounts of fertilizer, which causes additional costs for purchase and transportation. After a spreading

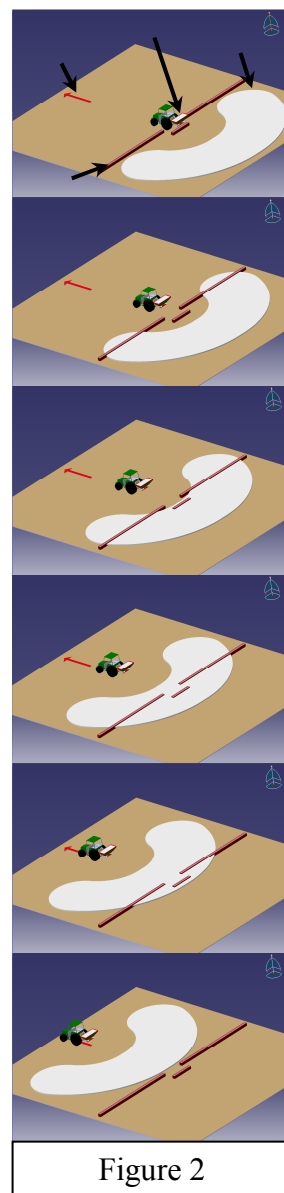
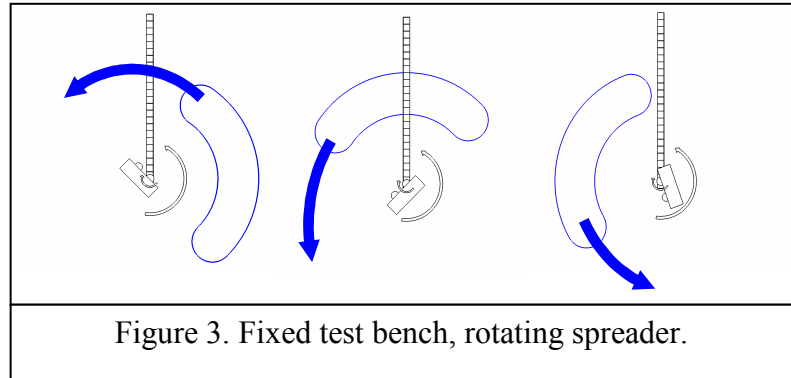


Figure 2

test, the market value of the use fertilizer is very low, due to damage and mixing of different products and often has to be treated as waste.

To overcome these problems, a new test device has been devised at CEMAGREF (Clermont-Ferrand) with the prime objective of providing characteristic spatial values of spreading. The configuration and operating method of this bench help cut down the size of the hall needed. Investment, maintenance and air conditioning costs are therefore greatly reduced.

Instead of an evaluation of the distribution in a Cartesian coordinate system, this patented method uses continuous weighing in a polar measurement system, which allows the evaluation of the spatial distribution on the ground of fertilizer broadcasted by a spreader. To limit the area to be covered and the required number of testing units, just one row of collection trays fitted with load cells (80 in all) is placed radially to the spreader. It is the spreader that rotates around itself during spreading (Figure 3). The duration of the spreading pattern evaluation is between 1 and 2 min. After a spatial treatment of the measured data, a regular Cartesian matrix of the amounts of fertilizer is obtained in the spreader referential. Characteristic values (range and angle) can then be extracted as well as standard transverse curves.



This new evaluation method allows to carry out research works on fertilizer characteristics (spreading capabilities for example), and on spreading systems. In a really short time, and with only a few measurements, the distribution laws of a typical fertilizer on the ground can be extracted in regard with the mechanical characteristics of the spreader. Researches and designed process are also faster and more efficient.

In addition, the device could be completed with additional sensors to allow spreading models validations (image processing could be for example a good way to get initial characteristics of ballistic flight of fertilizer granules just after the disc acceleration).

A comparison is done between the transverse distributions obtained first with the traditional method, and second with a prototype for the new radial system (Figure 4). For these tests all mechanical settings and the fertilizer type were the same. The results obtained with both methods are absolutely similar. However, the curve is less noise-affected with this measuring process using integration of spatial data. It also highlights the major characteristics of distribution, and is more representative of average spreading performed.



Figure 4.

The assembly requires a covered area of about 500 m² and short bay widths (10 m) compared with about 5000 m² and bays in the region of 60 m with the traditional method.

This method is also a palliative way in front of the continuous increase of spreaders working widths, but it also opens new real possibilities for the public and private researches. This bench should be operating at the end of 2005 at the Clermont-Ferrand center of Cemagref (Montoldre – Allier).

3. DISCRETE ELEMENT MODELING

In DEM, the contact deformation is represented as a single vector describing the deformation of the contact point in normal and tangential directions. This vector is related to contact forces by a contact force model. For the problem at hand, Van Liedekerke *et al.* (2004) have proposed a Hertz-Kuwabara-Kono model (Kuwabara and Kono, 1987; Brilliantov *et al.*, 1996; Schwager and Pöschel, 1996; Schäfer *et al.*; 1996) for the normal contact force, N :

$$N = \min\left(0, -\sqrt{|\delta_N|} \left(k_N \delta_N + c_N \dot{\delta}_N\right)\right) \mathbf{n}. \quad (1)$$

Here, k_N and c_N are the non-linear contact stiffness and damping parameter, respectively. The quantity δ_N is termed the *virtual overlap* of the contacting bodies. In the light of equation (1), its magnitude can be seen as a measure of the deformation in the normal direction and is therefore also termed the *normal contact displacement*. Note that, by convention, δ_N is taken to be negative in case of contact. For a detailed account of how δ_N is computed, the reader is referred to Van Liedekerke *et al.* (2004). The vector \mathbf{n} is a unit vector normal to the contact surface. In (1) the δ_N term is responsible for elastic storage of energy during impact, whereas the $\dot{\delta}_N$ term accounts for viscous dissipation. For the tangential contact force, \mathbf{T} , Van Liedekerke *et al.* (2004) propose a simple linear elastic contact force model augmented with dry Coulomb friction, which is formulated as an incremental expression:

$$\mathbf{T}_{t+\Delta t} = -\min\left(\left\|\mathbf{Q}_t^{t+\Delta t} \mathbf{T}_t + k_T \Delta \delta_T\right\|, \mu \left\|\mathbf{N}_{t+\Delta t}\right\|\right) \boldsymbol{\tau} \quad (2)$$

Here, the quantity $\Delta \delta_T$ is the incremental equivalent of δ_N in the normal contact force model and can be seen as a measure of the tangential deformation at the contact. For a detailed account of how $\Delta \delta_T$ is computed, the reader is again referred to Van Liedekerke *et al.* (2004). In equation (2) $\mathbf{Q}_t^{t+\Delta t}$ is a rotation matrix which maps the orientation of the particle at time step t to that at time step $t + \Delta t$ and accounts for the rotation of the contact plane and the tangential contact force during the time step. In equation (2) the min-operator implements the Coulomb friction limit with friction coefficient μ between the fertilizer particle and the stainless steel disc or vane:

$$\|\mathbf{T}\| \leq \mu \|\mathbf{N}\|, \quad (3)$$

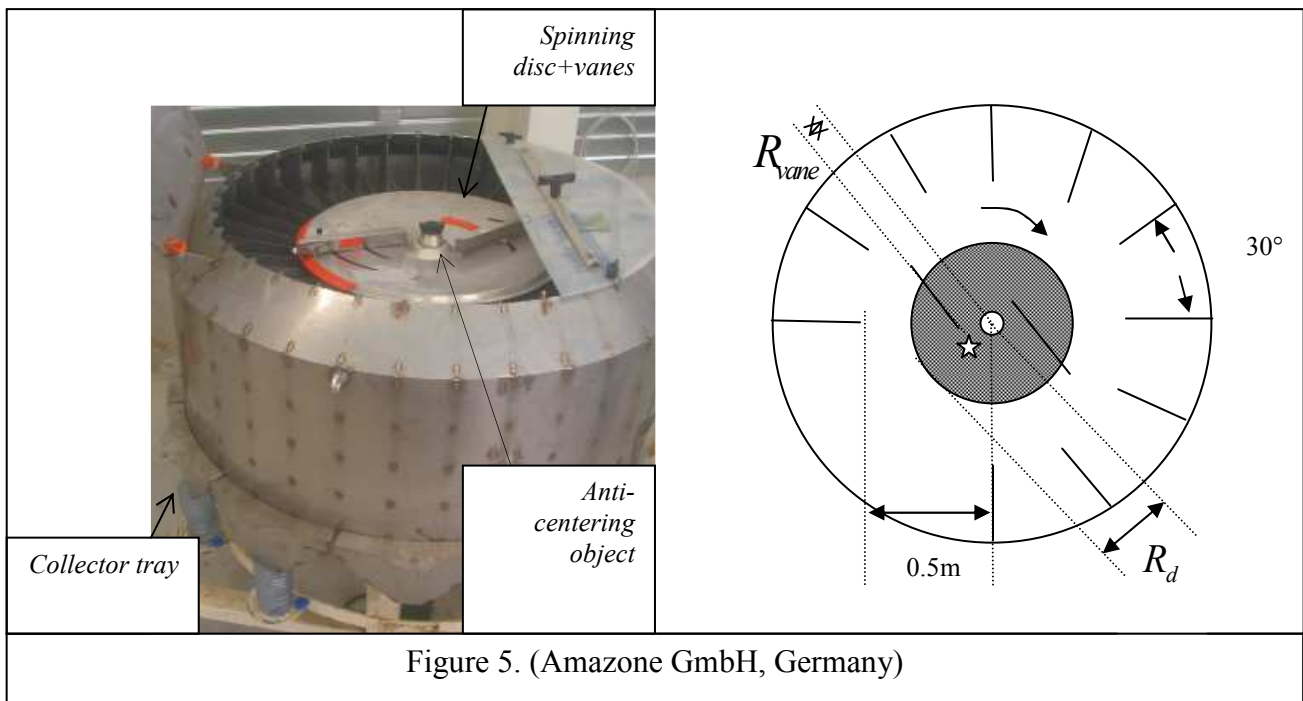


Figure 5. (Amazone GmbH, Germany)

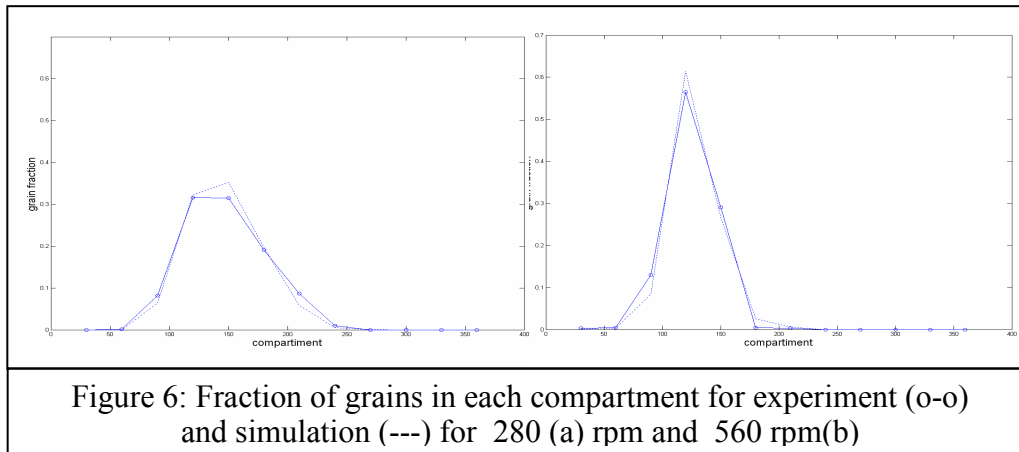


Figure 6: Fraction of grains in each compartment for experiment (o-o) and simulation (---) for 280 (a) rpm and 560 rpm(b)

The contact forces, together with gravity, drive the motion of the particles, which is described by Newton's and Euler's equation of motion for each particle in the system (Arnold 1978; Haug, 1992):

$$m\ddot{\mathbf{x}} = \mathbf{F} ,$$

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega}) = \mathbf{M} . \quad (4)$$

Here, m and \mathbf{I} are the mass, resp. the inertia tensor of the particle, \mathbf{x} its position vector and $\boldsymbol{\omega}$ its angular velocity. The right hand sides \mathbf{F} and \mathbf{M} in these equations of motion represent the total force, resp. torque, acting on the particle.

The model was implemented using the DEMeter++ software framework a flexible C++ class library for the development of efficient particle based simulators (Tijssens et al., 2004).

The above model was validated against experimental tangential distribution patterns. The tangential distribution is defined as the particle density distribution of particles crossing a concentric cylinder around the disk. It is experimentally obtained by surrounding the disk with collection trays arranged on a concentric circle (see figure 5). This apparatus is called the *Karrussel*. The approach is practical but does not provide information about the velocity vector of the particles. Experimental results and DEM simulations are compared satisfactorily in Figure 6. The particles are fed to the *Karrussel* by removing the bottom of a small cylinder containing approximately 2000 fertiliser particles. In the simulations initial conditions for this feeding bin are generated by raining down particles in the cylinder (Figure 7). In this way, they are naturally placed in the bin, comparable to the experimental filling. The diameter of the particles follows a lognormal distribution. After the particles have come to rest, the positions are written to file to be used as initial conditions for the simulations of the spreader.

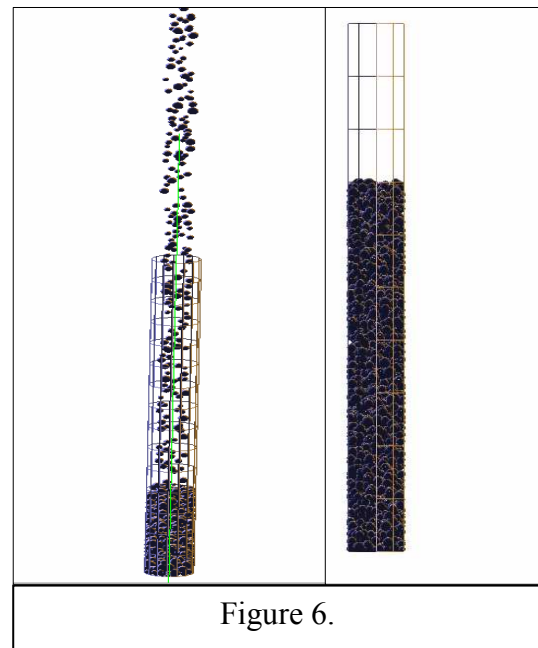


Figure 6.

Snapshots of the filling of the spreading process are given in Figure 8. The spatial distribution can be obtained from the simulation by recording the landing positions of the particles. The transverse pattern is obtained through integration of the spatial pattern. The tangential distribution is determined from the point where the particles pass through the opening of the collection trays of the *Karrussel*.

4. DISCUSSION

The paper reports about three recent developments that pave the way towards computer aided design of centrifugal fertilizer spreaders while taking the detailed physics of the spreading process into account. The experimental advances will allow for the development and validation of DEM-models which can be used to optimise the design. Recent developments of the Demeter++ software have made it possible to run simulations with 10^7 particles on parallel architectures, opening the way to the use of more realistic models for the physics and geometry of particles in DEM simulations.

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