Integrated approach for prediction of centrifugal fertilizer spread patterns

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Abstract: The present paper proposes a numerical approach for prediction of the behavior of those fertilizers spreaders based on centrifugal disc functioning. Particular results from finite element multi-body simulations provided by a commercial software are used to define boundary conditions of field tests carried out concurrently. Results are then integrated into a mathematical model to rapidly generate distribution charts and distribution diagrams. Such an integrated approach can be implemented to effectively calibrate a theoretical model which provides simulations on different machine settings conditions. Finally, simulations allow fast testing of different distribution conditions, helping defining those conditions which minimize the variability of the distribution itself.

Keywords: simulation, fertilizer, spreader, distribution

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1 Introduction

Aspects related to proper mineral fertilization are of primary importance for an appropriate management of crops. Either insufficient or excessively high fertilizer dose application, on a portion or over the entire soil crop surface, can result not only in different yield responses but also in toxicity phenomena or in a greater predisposition of the crops to diseases (Cillis et al., 2017). Uniform fertilizer distribution is then of primary importance to preserve crop growth and to limit impact on environment (Basso et al., 2016; and Pezzuolo et al., 2017).

Hence, in recent years the attention of many researchers has been focused on the study of solutions that can improve the performance and reduce the environmental impact of mineral fertilization. In particular mechanical controls and electronic devices mounted on spreaders or on tractors have been developed (Dubbini et al., 2017), aimed to improve fertilizer spreaders operations, while digital imaging systems have been proposed to deduce three-dimensional velocities of fertilizer particles and monitor the quality of the distribution (Villette et al., 2008; and Hijazi et al, 2010).

However, in order to make such improvements effective, accurate characterization of machines and fertilizer dynamic is needed. This is not a trivial task, mainly due to the amount of fertilizers types available in the market, each with different physical, geometrical and mechanical properties.

Some researchers have proposed solutions not only based on field measurements (Fulton et al., 2001), but also on mathematical modeling (Villette et al., 2005) or on discrete element methods (Van Liedekerke et al., 2009).

Physical tests have the limit to require time consuming and expensive spread hall measurements, to be repeated for different types of fertilizers (García-Ramos et al., 2012). Mathematical approach based on ballistic model is interesting, and typically can accurately describe particles flight and distribution (Cool et al., 2014). However, such approach is difficultly applied when highly packed granules, with continuous interactions and frequent collisions, are studied, as is the case of the passage from the hopper to the disc. Finally, finite element methods (FEMs) can also provide reliable

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results on particle dynamics, however computational times can increase dramatically when thousands granules are simulated.

It is in the belief of the authors that an integrated method is the optimal approach to exploit fertilizer machines characterization. Therefore, in the present work integration of finite element simulation with mathematical modeling carried out concurrently with field characterization is proposed for effective modeling of centrifugal fertilizer spreaders.

2 Materials and Methods

The present work proposes an integrated numerical approach for prediction of behavior of fertilizers spreaders based on centrifugal disc functioning. A schematic representation is reported in Figure 1.

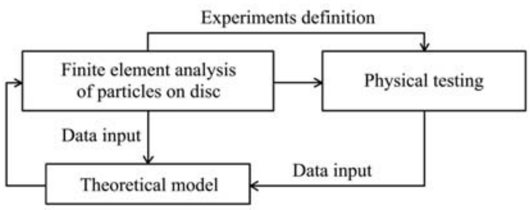

Figure 1 Schematic representation of an integrated approach for fertilizer spreaders behavior prediction

In the new approach, finite element simulations allow optimal definition of experiment conditions, making it possible to concentrate efforts on boundary conditions. Then, physical tests and finite element analyses give input data for the calibration of the theoretical model. Once the model is calibrated, it can be verified on the same boundary conditions as defined by the FEM or with intermediate settings.

As a consequence, detection of critical machine settings helps minimization of physical tests, and consequently reduction of investigation time and costs.

2.1 Finite element analysis

Finite elements analyses are firstly carried out in order to define spreading conditions which are most critical, in particular for what relates fertilizer particles interactions. Indeed, one of the most critical aspects on fertilizer spreading operations is the mass of the granules, which quadratically influences the spreading distance. Given a certain fertilizer type, whose density in most of cases can exhibit only negligible bulk density variations, the mass of a particle is determined only by its average diameter. Unfortunately, the size of a particle is not constant from the hopper to the disc exit: indeed, due to impacts and friction phenomena deformation or breaking may occur. Crushing strength is typically known for different fertilizers; conversely, predicting maximum loads acting on granules during spreading is very difficult due to the multiplicity and complexity of interactions acting on particles after they flow from the hopper to the disc. Finite element simulations can help fertilizer dynamics understanding, allowing determination of forces acting on particles, in particular when the vanes hit and convey the flow (Figure 2).

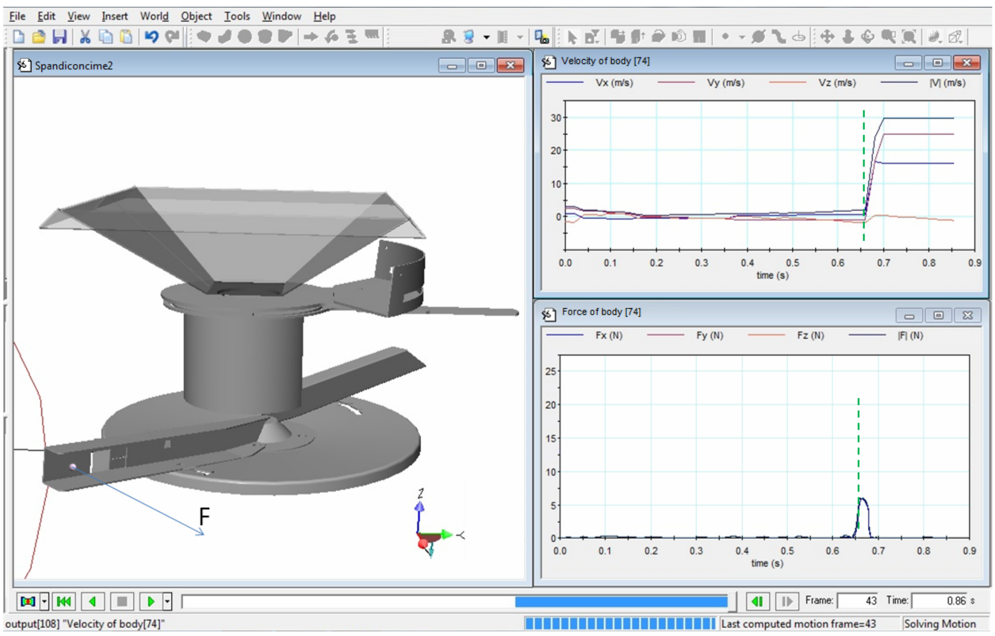

Figure 2 Example of finite element simulations, by means of SimWise 4D software

2.2 Theoretical model

A complete mathematical model for fertilizer particles moving on a spinning disc with vanes was proposed in recent years (Villette et al., 2005).

The central point of the model lies on the speed definition of the particle exiting the disc. This can be expressed by:

$$v = \frac{x_{vo} - K}{2\delta}(\delta + \mu\cos\Omega)(\delta - \mu\cos\Omega)\omega \quad (1)$$
$$(\exp((\delta - \mu\cos\Omega)\omega t) - \exp(-(\delta + \mu\cos\Omega)\omega t))$$

being,

$$K = \frac{\mu g\cos\Omega + gsen\Omega - \mu r_P\omega^2}{\omega^2\cos\Omega(\cos\Omega - \mu sen\Omega)} \quad (2)$$

and

$$\delta = \sqrt{\cos^2\Omega(\mu^2 + 1) - \mu sen\Omega\cos\Omega} \quad (3)$$

where, x_{vo} is the initial radial position of the particle on the disc; Ω and r_P are geometrical parameters of the vanes on the discl ω is angular velocity; g is the acceleration due to gravity; t is the time needed by the particle to exit the disc and μ is friction coefficient of the particles along the vane. Since the time t is directly correlated to the length of the vane, the only parameters which is difficulty estimated is the friction coefficient of the particles along the vane.

When the particle exits the disc, the horizontal distance from the exit point of the disc and the final granule position on the soil x_k is achieved nulling the equation of the vertical trajectory:

$$y = g\left(\frac{4\rho_p d}{3\rho_a C_r v}\right)^2\left(\exp\left(\frac{3\rho_a C_r}{4\rho_p d}x_k\right) - \frac{3\rho_a C_r}{4\rho_p d}x_k - 1\right) \quad (4)$$

where, ρ_p and ρ_p are respectively the densities of the particle and of air; C_r is the air resistance coefficient and d is the particle diameter.

A part from geometrical parameters (which can be directly measured on the machine) and fertilizer density (which can be realistically considered constant for a given fertilizer), the final distribution is determined mainly by the diameter of the particles d and by their coefficient of friction μ (which is in turn influenced by particles size). Coefficient μ can be estimated by comparing theoretical with the actual particle exit angle. Indeed, the angle formed by the fertilizer particles with the vane when exiting the disc is directly proportional to their exiting speed v. Knowing other variables, the friction coefficient μ can be directly estimated inverting equation (1). However, it is worth noting that such coefficient is sensitive to particles diameter, and can undergo variations when different settings of the machine (in terms of angular velocity of the disc, position of the vanes or of the orifice, etc.) cause different solicitations on fertilizer particles. As already mentioned in the previous paragraph, each fertilizer type is characterized by a specific crushing strength, therefore resulting in generation of different levels of dust and fines. Therefore, in order to understand and foresee fertilizer distribution, it is very important to test machines at boundary conditions: such conditions can be defined more straightforwardly taking advantage of finite elements simulations.

3 Results and Discussion

3.1 Test on a commercial spreading machine

Specifically, for the present study a commercial software tool (SimWise 4D) was implemented. Such software tool allows three dimensional kinematic and dynamic motion reconstruction, of both machine and fertilizer particles together with their interaction, then providing a description of the distribution phenomenon. A screenshot of the working software is reported in Figure 2: graphs monitor velocity and forces variations for the granules as a function of time for a selected granule. By modifying the vanes or the orifice position and changing disc angular speed, variations in interaction forces can be recognized. Boundary conditions are corresponding to those machine settings which minimize or maximize the loads acting on the particles.

For the present study, 3 main parameters were identified and varied during physical tests, in order to collect actual data for theoretical model calibration, as reported in Table 1: 16 different conditions with two repetitions. Further details of selected fertilizers are reported in Table 2.

Table 1 Physical tests conditions

Parameter	Conditions	Notes
Fertilizer	4 different fertilizers	Type a, b, c and e
Vane positions	2 positions	Radial position and maximum tilt position
Orifice position	2 positions	

Table 2 Physical properties of fertilizers

Type *	Fertilizer	Commercial name	Density, kg/m³	Average diameter, mm	Crushing strength, N	Notes
Type a	Complex f.	Nitrophoska (Eurochem agro)	1077	3.1	82	Granular
Type b	Urea	Entec 46 (Eurochem agro)	755	3.1	35	Granular
Type c	Urea	Vera (Yara)	791	3.1	47	Prilled
Type e	Complex f.	NPK 8-24-24 (K Adriatica)	997	3.7	57	Compacted

Note: * According to EN 13739-2 (2011).

Tests were carried out on an open space, in agreement with standards (EN 13739-2, 2011), keeping disc rotation speed constant. Data were collected from two series of containers (size 500×600 mm, with septa to minimize spillage). For spreading, a two discs machine available on the market was implemented (by Agrex SpA, Italy), operated at speeds comprised between 0.5 and 2 km/h, and with flow rates between 25 and 100 kg/min.

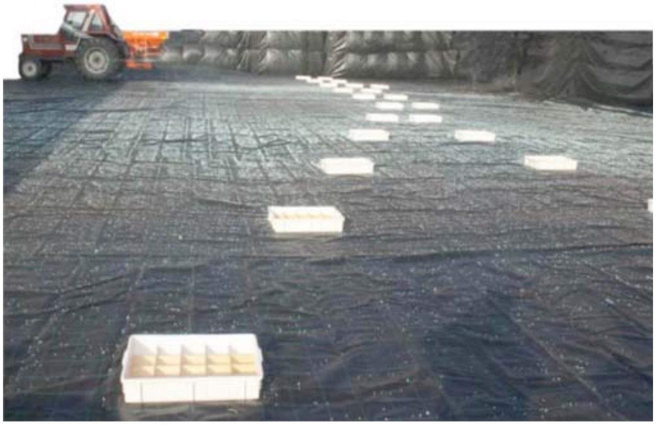

Figure 3 Physical tests carried out for determination of actual distribution at boundary conditions

4 Conclusions

Physical tests highlighted higher crushing phenomena in the case of type b fertilizer, confirmed by the estimation of a higher coefficient of friction (μ=0.38). Conversely the better performance of the Type a fertilizer with less dust and fines formation was reflected by a lower coefficient of friction (μ=0.34).

Fine calibration of the coefficient of friction, together with determination of the particles diameter distribution allows calibration of the theoretical model reported in 2.2.

The model can be then implemented for generation of distribution charts. In the example reported in Figure 4, the theoretical model is implemented to foresee the distribution of 10.000 fertilizer particles (randomized with respect to the diameter) and extrapolating distribution diagrams. In such a way, it is possible to repeat tests simulating different machine settings, allowing definition of those settings which minimize the variability of the distribution.

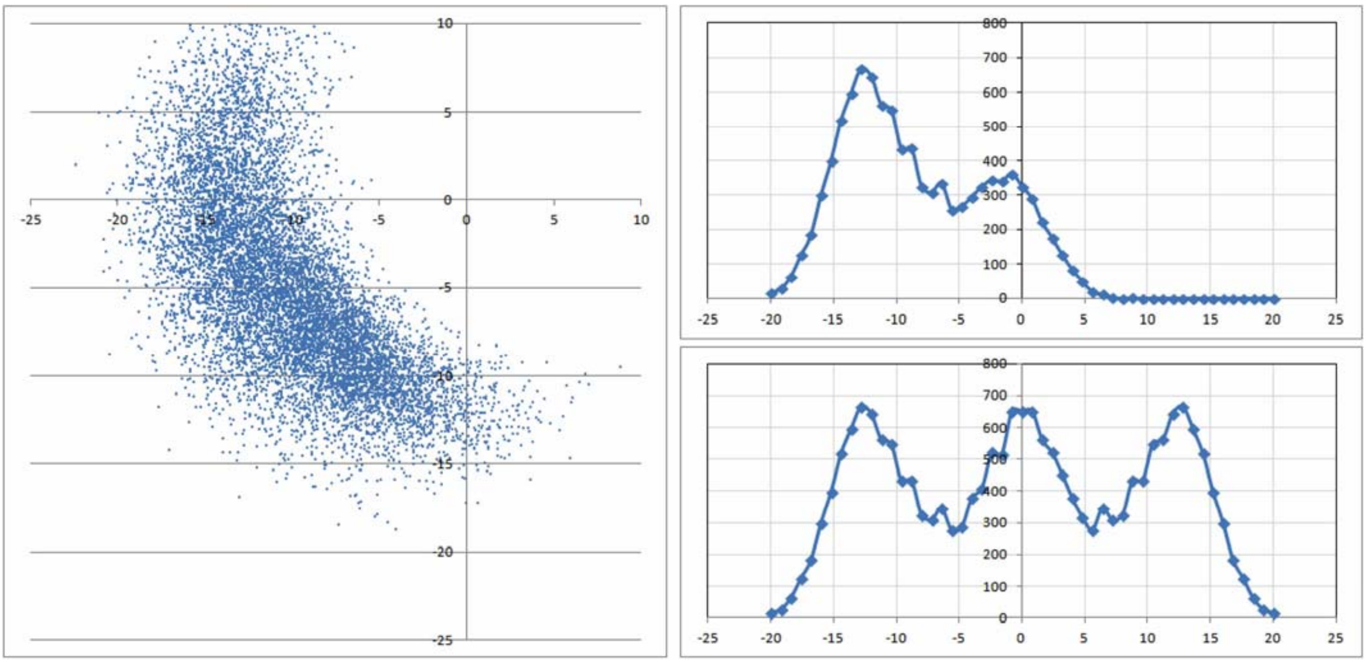

Figure 4 Example of charts generated after theoretical model calibration

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