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Centrifugal fertiliser spreading: velocity and mass flow distribution measurement by image processing

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Abstract

This paper investigates the use of a new imaging system to measure the velocity and the mass flow distribution of fertiliser granules spread by a centrifugal device. The new acquisition system consists of a digital camera placed above the disc so that its view axis corresponds to the disc axle. This provides useful geometrical properties to develop a simple and efficient image processing. The technique provides a global estimation of the spreading characteristics for the whole fertiliser flow using a global analysis of an image rather than identifying individually each trajectory in the image. The new technique is compared to a previously assessed imaging method. Concerning the mass flow distribution, results deduced from both imaging methods are also compared to those deduced from a compartmented collection ring.

Keywords

Centrifugal fertiliser spreading, velocity, mass flow distribution, Hough transform, image acquisition

1. Introduction

In Europe, the application of mineral fertilisers is mainly performed by centrifugal spreaders because of their robustness, simplicity and low cost. The uniformity of the application rate in the field depends on the spreading width and on the overlaps resulting from the parallel passes. Consequently the quality of the spreading in the field depends on the outlet velocity and on the angular mass flow distribution around the spinning disc. In practice, the value of these parameters result from fertiliser physical properties and machine characteristics. Thus, the setting of the spreader with respect to the mechanical behaviour of the fertiliser is crucial for the quality of the spreading. Unfortunately, because of difficulties in adjusting the machines, major differences in the quality of the spread pattern deposition are observed in the field and numerous studies have reported a lack of fertiliser uniformity (Ziani and Rousselet, 1990; Sogaard and Kierkegaard, 1994; Tissot *et al.*, 1999; Leterme, 2000). This adversely affects not only the crops but also the environment (Tissot *et al.*, 2002), especially in the case of nitrogen-based fertilisers.

Nowadays, economic and environmental considerations call for improvements in the quality of fertiliser spreading and there is a need to better characterise centrifugal spreading and develop autonomous feedback systems for automatic uniformity control.

Some works addressed the problem of measuring the outlet velocity of fertiliser granules in the vicinity of the spinning disc. A technique based on the ultrasonic Doppler frequency shift was developed (Hofstee, 1994) using one transmitter and three receivers arranged in a three-dimensional configuration. The ultrasonic measurement cell opening was 20 × 20 mm. An optical sensor was developed (Grift and Hofstee, 1997) using two photosensitive arrays, placed perpendicularly to the radius of the disc. The radial component of the outlet velocity was derived from the time difference corresponding to a particle passing each sensor array. The orifice of the measurement unit was 3 cm. These techniques were limited to a narrow investigated space, and required the displacement of measuring cells in the material flow.

Another approach consists in using imaging systems. These systems have the advantage to cover the whole angular sector of spreading around the spinning disc, and avoid any contact with fertiliser granules. Nevertheless, PIV (Particle Image Velocimetry) techniques, or fast imaging systems are inadequate because they are expensive, complex and difficult to adapt to agricultural machines. Some stroboscopic imaging systems were proposed (Cointault and Vangeyte, 2005) to measure the outlet velocity in the case of a flat disc only. In contrast to the stroboscopic approach, a low-cost acquisition system and an automatic image processing were developed (Villette et al., 2006) to derive the outlet velocity from motion-blurred images on which granule trajectories appear as straight streaks. The technique was first available for flat discs, assuming that the particle trajectories were parallel to the image plane to avoid any bias on distance or angle measurements. Then, the technique was extended (Villette et al., 2008) to deduce the three-dimensional velocities from the horizontal outlet angle of fertiliser trajectories in the case of a concave disc. The main drawback of the method was that each trajectory has to be identified individually in the Hough space. This was time consuming and do not have the robustness of a global analysis of the whole image to provide a global outlet velocity estimation for the whole fertiliser flow.

Concerning the measurement of the angular distribution of the fertiliser mass flow around the spinning disc, the traditional method consists in placing a compartmented collection ring around the disc (Colin, 1997; Olieslagers, 1997; Reumers *et al.* 2003). Using this collection device the horizontal angular distribution of the fertiliser flow is deduced by weighing the amount of material collected by each box of the ring. At the present time, no imaging system is proposed in the literature to estimate the angular distribution of the fertiliser mass flow.

The objective of the work is to develop cheap, fast and robust vision systems to measure the outlet velocity and the angular distribution of the fertiliser mass flow around a spinning disc. This article compares two imaging systems based on the use of motion-blurred images. It presents developments to provide a global estimation of the spreading characteristics for the whole fertiliser flow using a global analysis of an image rather than identifying individually each trajectory in the image. The study investigates an imaging system in which the camera is placed above the disc so that its view axis corresponds to the disc axle.

2. Materials and methods

2.1. Experimental arrangement

The study is carried out in laboratory conditions using an experimental spreading device made up of elements similar to those found in a traditional centrifugal spreader. The disc is driven by an asynchronous AC motor and a programmable power supply. Fertiliser granules are stored in a hopper at the bottom of which a shutter sets the fertiliser flow. Under the shutter, a delivery pipe adjusts the feeding point of the granules onto the disc Fig. 1.

An imaging system was developed to capture an image of the trajectories followed by the fertiliser granules in the vicinity of a spinning disc. The system is made up of a monochrome digital camera placed vertically at approximately 1 m above the spinning disc or above the fertiliser flow in the vicinity of the disc (Fig. 1). The disc rotational axle and the camera optical axis are vertical. A particular acquisition situation is obtained when the camera view axis corresponds to the disc rotation axle.

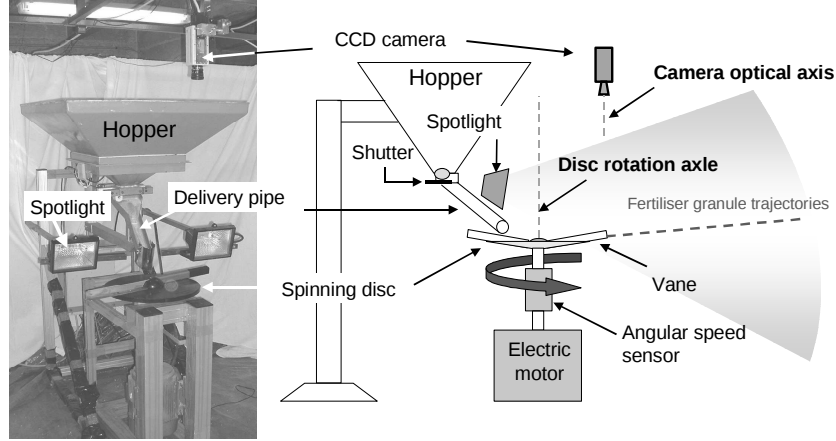


Fig. 1: Experimental arrangement

The camera is equipped with a 8.5-mm-focal-length lens that provides a field-of-view of approximately $1 \times 1 \text{ m}^2$ to capture a wide angular range of spreading. Two spotlights are used to illuminate the granule lengthways during their motion at the beginning of their ballistic flight. The camera exposure is set long enough (e.g. 35 ms) so that images are composed of streaks associated to the motion of fertiliser granules after their ejection from the disc (Fig. 3). These images, called ‘motion-blurred images’, show the trajectories of fertiliser granules in the vicinity of the spinning disc.

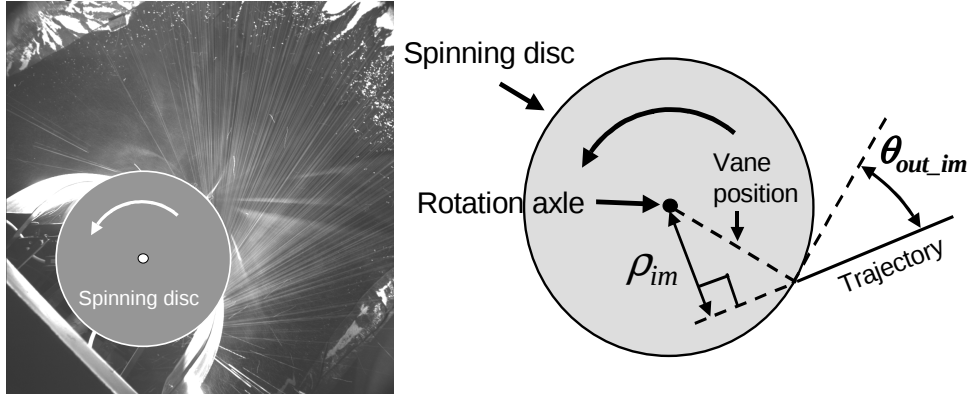


Fig. 3: Motion-blurred image (left) and geometric characteristics of a trajectory (right): ρ_{im} is the perpendicular distance of the trajectory from the disc axle; θ_{out_im} is the apparent outlet angle in the image.

2.2. Mechanical model

The velocity measurement is based on the analysis of fertiliser granule streaks observed in motion-blurred images (Fig. 3). The outlet velocity is deduced from the horizontal outlet angle θ_{out} which is the horizontal angle between the fertiliser granule trajectory and the tangent to the disc.

The cinematic analysis (Villette *et al.*, 2008) of the fertiliser motion on the spinning disc demonstrated that the three-dimensional components of the outlet velocity were deduced from the horizontal outlet angle θ_{out} as follows:

- radial component of the velocity:

$$v_R = \frac{r_{vane} \omega \tan \theta_{out}}{1 + \tan \theta_{out} \tan \alpha} \quad (1)$$

- tangential component of the velocity:

$$v_T = \frac{v_R}{\tan \theta_{out}} \quad (2)$$

- vertical component of the velocity:

$$v_k = \frac{v_R}{\cos \alpha} \tan \Omega \quad (3)$$

where r_{vane} is the radius of the vane, ω is the rotational speed of the disc, α is the horizontal angle of the vane and Ω is the vertical angle of the vane.

2.3 Geometric considerations concerning image acquisition

In the case of a concave disc, fertiliser granule trajectories are not parallel to the image plane and there is an angular bias ε between the apparent observed angle θ_{out_im} in the image and the real horizontal outlet angle θ_{out} . This angular difference ε increases with the distance between the trajectory and the view axis of the camera. Fig. 4 illustrates this phenomena and the influence of the distance between the view axis and the spinning disc centre in the image.

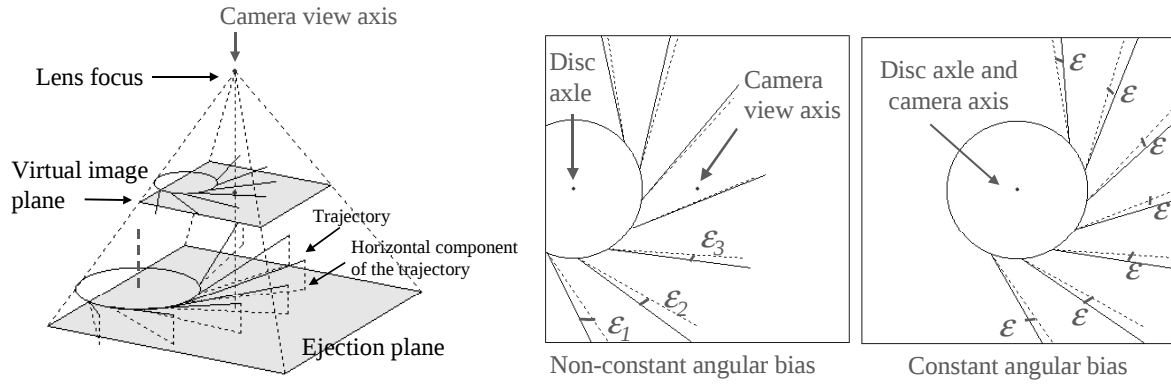


Fig. 4. Simulation of the three-dimensional scene and image acquisition (left); resulting image when the camera view axis does not correspond to the disc axle (middle) and when the camera view axis corresponds to the disc axle (right).

In the particular case where the view axis corresponds to the disc axle, the angular bias ε remains constant whatever the location (and the orientation) of the trajectory in the image assuming the vertical outlet angle is constant.

2.4 Image processing

After filtering the original motion-blurred image, the binary image of trajectory axes is analyzed by identifying the location of peaks in a parameter space resulting from the Hough transform (Hough, 1962).

The method consisted in computing the Hough transform in polar coordinates (θ_H, ρ_H) (Duda and Hart, 1972) with respect to the disc rotation axle. Considering the normal representation of a line (i.e. $\rho_H = x \cos \theta_H + y \sin \theta_H$) each pixel (x, y) of the image is transformed into a sinusoidal curve in the (θ_H, ρ_H) -parameter space. When several pixels lie on the same line in the original image, they provide several curves passing through the same point in the Hough space. The location of this intersection point in the Hough space gives the polar parameters of the corresponding line in the image.

In order to optimize the method we chose the origin of the coordinate system at the disc centre. This reduces the range of relevant values that have to be considered for ρ_H and limits the

number of judicious pixels considered in the image (pixels lying on a ring centred on the disc centre are only considered).

Two methods have been developed to analyse the Hough space in order to characterise the spreading parameters (*i.e.* the horizontal outlet angle and the angular distribution of the mass flow around the disc).

Method 1: Iterative identification of individual peaks in the Hough space

When the camera axis does not correspond to the disc axle, a satisfying peak extraction from the Hough space requires an iterative process: identifying the global maximum, deducing the quantified values of the line parameters, adjusting the values with the real location of the trajectory in the image and subtracting from the Hough space the Hough transform of the corresponding segment (Villette *et al.*, 2006; Villette *et al.*, 2008). The apparent outlet angle was then deduced for each trajectory. Taking into account the location of the trajectory in the image, this angle was finally corrected to provide each horizontal outlet angle without bias. The angular distribution of the mass flow around the disc can be deduced from the location of each identified trajectory in the image.

This method has already been assessed (Villette *et al.*, 2008) to measure outlet angles and outlet velocities of fertiliser granules leaving a spinning disc. In this study, it is considered as a reference method for the measurement of outlet angles and outlet velocities.

Method 2 : Global analysis of the Hough space when the camera axle corresponds to the disc axis

In order to avoid individual identification of trajectories, the second method takes advantage of the geometrical properties that occur when the view axis of the camera corresponds to the disc rotation axle. In this situation, the angular bias ε measured in the image is constant (Fig. 4). Consequently, assuming that the mean value of the horizontal outlet angle of fertiliser granules remains constant for the whole angular sector of spreading, the radius parameter ρ_{im} (Fig. 3) of the trajectories (in the image) is also constant whatever the trajectory location around the disc. The hypothesis concerning the invariance of the mean outlet angle along the angular sector of spreading is supported by previous works (Villette *et al.*, 2008).

Thus, the horizontal outlet angle θ_{out} for the whole angular sector of spreading can be deduced from the mean value of the ρ_{im} -parameter deduced from the whole Hough space.

Combining the mechanical model, the pinhole camera model, and the specific location of the camera axis, the horizontal outlet angle is directly deduced from the radius parameter ρ_{im} as follows:

$$\theta_{out} = \arctan \left(\frac{\sqrt{(r_{vane} f_{conv})^2 - \rho_{im}^2}}{\rho_{im} \left(1 + r_{vane} f_{conv} \frac{\Delta p \tan \Omega}{f \cos \alpha} \right)} \right) \quad (4)$$

where f_{conv} is the meter per pixel conversion factor, Δp the pixel size and f the focal length.

The value ρ_{im} of the parameter that describes the best the outlet angle for the whole angular sector of spreading is deduced from the Hough space. This value corresponds to the maximum of the vote number (after filtering) projected on the ρ_H -axis. A robust and representative value of the outlet angle is then deduced for the whole spreading sector.

Assuming that the mass flow is proportional to the trajectory density in the image the angular distribution around the disc is also deduced from the Hough space very easily. Since the mean value of the ρ_{im} -parameter remains constant for all trajectories whatever their orientation in the image, the relevant peaks in the Hough space are approximately distributed along the line of the Hough space corresponding to $\rho_H = \rho_{im}$. Consequently, the angular distribution of the mass flow

is deduced from the angular location θ_H of not null values along the line defined by $\rho_H = \rho_{im}$ in the Hough space.

3. Results

Both analysis methods (methods 1 and 2) have been compared on two sets of 25 images obtained with the same centrifugal disc and when the camera view axis corresponds to the disc axle. Two fertilisers have been used: ammonium nitrate and potassium chloride (KCl).

For an image of these sets, Fig. 6 presents the Hough space (after filtering), and its projection on the axis of the ρ_H -parameter. This projection is used to measure the relevant value of the ρ_{im} -parameter that characterise the whole motion-blurred image (Fig. 3) using the global analysis (method 2). The locations of the peaks individually detected by the iterative analysis (method 1) are also marked on the Hough space.

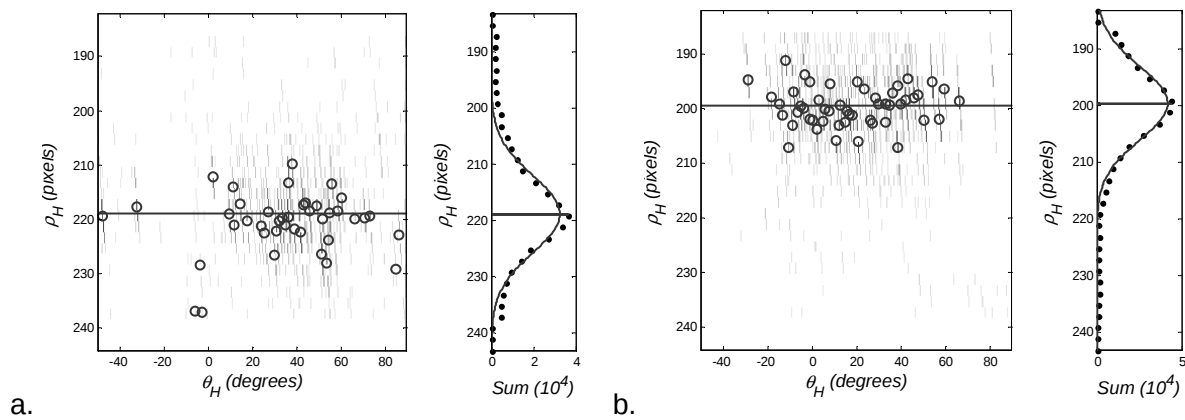


Fig. 6. Hough Space and its projection (right) on the ρ_H -axis for an image obtained for potassium chloride (a) or ammonium nitrate (b). The line parallel to the abscissa axis of the graphics corresponds to $\rho_H = \rho_{im}$. The locations of the peaks detected by the iterative analysis are indicated (O) on the Hough space.

3.1. Outlet velocity

For the two studied fertilisers, Table 1 provides the mean values of the outlet angles θ_{out} and the outlet velocities v_{out} calculated on the 25 images using the global analysis of the Hough Space and the iterative method based on individual peak identifications in the Hough space. Table 1 demonstrates that both methods provide very close results.

Table 1. Mean values of outlet angles and velocities for two different fertilisers: ammonium nitrate (Am. Nit.) and potassium chloride (KCl).

Fertiliser type	Global analysis of the Hough space		Iterative analysis of the Hough space	
	θ_{out}	v_{out} (m.s ⁻¹)	θ_{out}	v_{out} (m.s ⁻¹)
KCl	34.7°	33.1	34.2°	32.9
Am. Nit	40.5°	35.8	40.3°	35.7

3.2. Angular distribution of the mass flow

The reference method used for the measurement of the angular distribution of the mass flow consists in collecting fertiliser granules around the spinning disc using a compartmented ring divided into 22 adjacent compartments of 10° each. The fertiliser amount contained in each compartment is weighted to provide the angular distribution of the mass flow.

Figure 7 displays the histogram of the angular distribution of the mass flow deduced from the iterative analysis of the Hough space and from the reference method. The distributions are represented with respect to the angular position of the vane.

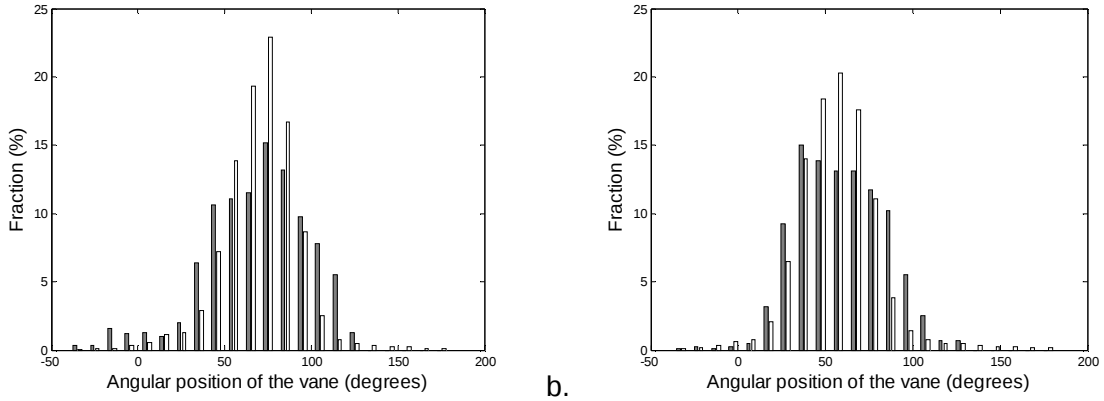


Fig. 7. Angular distribution of the mass flow deduced from the image by identifying each peak individually in the Hough space (grey) and collection ring (white) for potassium chloride (a) and ammonium nitrate (b).

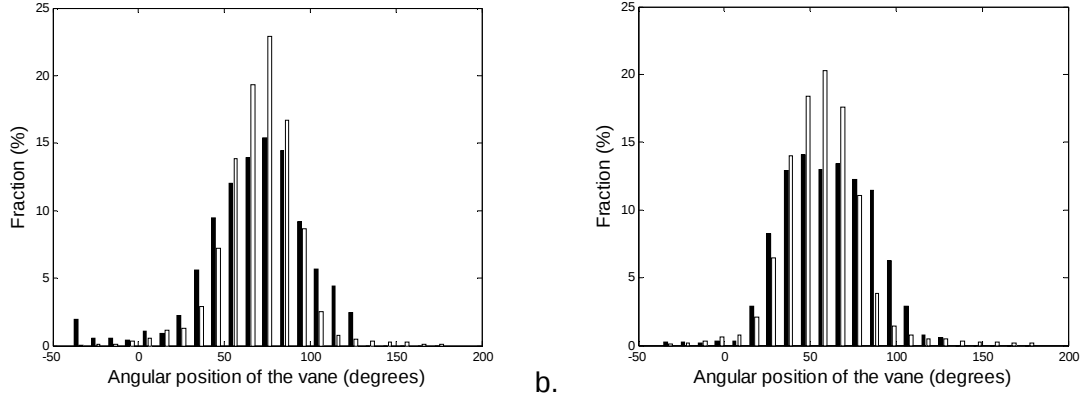


Fig. 8. Angular distribution of the mass flow deduced from the image by using the global analysis of the Hough Transform (black) and the collection ring (white) for potassium chloride (a) and ammonium nitrate (b).

Regarding the global location of the histograms it appears that the distributions deduced from the imaging methods are in agreement with those deduced from the compartmented ring.

Considering a Gaussian fitting of the distributions, the mean value θ_{flow} and the standard deviation σ_{flow} of the distributions are as provided in Table 2. Regarding the values of the distribution parameters (θ_{flow} and σ_{flow}) differences are enhanced between findings deduced from the imaging methods and the reference method. The main difference concerns the estimation of the standard deviation of the mass flow distribution that is overestimated using the imaging methods.

Table 2. Values of the distribution characteristic parameters deduced from the imaging methods and the reference method for ammonium nitrate (Am. Nit.) and potassium chloride (KCl).

	Imaging methods				Reference method	
	Iterative analysis		Global analysis		Compartmented ring	
	θ_{flow}	σ_{flow}	θ_{flow}	σ_{flow}	θ_{flow}	σ_{flow}
KCl	72.6°	28.1°	71.1°	25.2°	70.3°	17.2°
Am. Nit.	57.7°	27.0°	60.2°	27.1°	56.5°	18.7°

4. Discussion

Concerning the outlet angle and the outlet velocity of the fertiliser granules when they leave the spinning disc, the values obtained with the global analysis of the Hough space are very similar to those obtained with the iterative analysis that can be considered as the reference method.

Concerning the characterisation of the angular distribution of the mass flow, the mean values of the distributions deduced from imaging methods are in agreement with those deduced from the compartmented ring. Nevertheless, differences appear for the estimation of the standard deviation of the distribution. Compared to the reference histograms (Fig. 7 and 8), histograms deduced from the Hough space show saturation in the central region of the spreading pattern. In this spreading sector, fertiliser granules actually leave the vane with an overlapping in the vertical plane. This leads to a saturation phenomenon. As the granule output flow is captured with a camera placed above the fertiliser flow, upper trajectories (associated to visible granules) are only counted while the downer ones are hidden. This yields to an over-estimation of the standard deviation when imaging methods are used. Future work will be devoted to improve the characterisation of the angular distribution.

Regarding the outlet velocity values and the angular mean values of the mass flow distribution, findings obtained with the vision system clearly show the differences in the mechanical behaviour between the fertiliser types used in this study. The outlet velocity and the outlet angle are higher for ammonium nitrate than for potassium chloride while the mean value of the angular distribution of the mass flow around the disc is higher for potassium chloride than for ammonium nitrate. The shape of the fertiliser granules could explain these observations. In the case of ammonium nitrate granules, which are rounded, the higher flowability of the fertiliser on the vane leads fertiliser granules to reach a higher velocity on the vane and be ejected more rapidly (*i.e.* at a lower angle value of the vane location). This demonstrates that the vision system presented in this article is of particular interest to characterise the spreading and adjust the machine setting with respect to the real mechanical behaviour of fertilisers.

Algorithms have been developed under Matlab v6.1 and run using a computer with an Intel Pentium III 4.3 GHz processor and one core. The computational times are: 3.7 s for the Hough space building (associated to an angular region of 150°, with a sampling step of 0.15° corresponding to a quantification step of 2 pixels); 21 s to analyse the Hough space based on the iterative method which identifies each trajectory and less than 0.2 s to analyse the Hough space using the global method described in this article. Increasing the sampling step and the space quantification can reduce the computational time of the Hough transform.

The imaging method based on the global analysis of the Hough space is not time-consuming and takes advantage of the global information provided by all the trajectories to improve the robustness of the outlet angle estimation. At the present time, the main drawback of this approach is that it requires placing the camera just above the spinning disc. This is possible for experimental spreading devices specifically built to study the centrifugal spreading process but this is not possible to measure spreading characteristics with a real spreader. Consequently, a

new approach is now being studied to make possible a global analysis of a specific parameter space although the view axis of the camera does not correspond to the disc rotation axle.

5. Conclusion

Two image acquisition and processing methods have been compared to deduce spreading parameters from “motion-blurred images” in which fertiliser granule trajectories appear as streaks. The study demonstrates that a simplified analysis can be used when the camera view axis corresponds to the rotation axle of the spinning disc. This geometrical situation provides useful advantages to improve the robustness of the image processing and reduce computational constraints. Concerning outlet velocities and the mass flow distributions, the study shows that findings deduced from the simplified analysis are similar to those deduced from the reference image analysis in which each trajectory is identified individually in the image. Concerning mass flow distributions, both imaging methods overestimate the standard deviations of the distributions with respect to values deduced from a traditional compartmented ring. At the present time, the main drawback of the simplified analysis method is that the method can only be used when the camera is placed above the disc. This camera position is possible for experimental spreading devices but is not possible for traditional centrifugal spreaders. Future work will be dedicated to improve the precision of the information related to the angular distribution of the granule flow and to adapt the imaging technique to the construction constraints of traditional centrifugal spreaders.

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