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Dispersion and migration of agricultural particles in a variable-amplitude screen box based on the discrete element method

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ABSTRACT

Many relevant studies about screening of agriculture materials have been conducted from different perspectives such as mechanism design, optimization of parameters, and particle motion. Some studies suggest that a screen driven by parallel mechanisms is more adaptable than a traditional one while the traditional reciprocating screen still plays a positive role in agricultural production. Based on previous research regarding the variable-amplitude screening method, 4 indices of particle movement have been defined and computed in this paper to investigate the quantitative dispersion and migration characteristics of agricultural particles by using DEM (Discrete Element Method) simulation data. It shows that the turning angle of the front swing bar has a significant effect on the horizontal expansion coefficient $\delta_x(t)$, and the particles will be thin quickly at first and be stabilize within the next process. It also shows that the increase in the turning angle of the front swing bar leads to a negative stratification effect, but results in a positive migration effect of all particles on the screen. This research could provide a useful reference for solving the retention problem of agricultural particles in any position on the screen.

1. Introduction

Screening of materials is an important process in agricultural production. A traditional reciprocating screen is the most widely used instrument in all screening operations of agricultural materials, and many researchers have conducted important studies in this area. Shen (1984) optimized the amplitude and direction of acceleration, vibrating frequency, and airflow velocity of a given cleaning structure for cleaning quality by using a regression orthogonal design method. Cheng and Wang (1998) investigated the effects of structure and motion parameters of a given air-and-screen cleaning mechanism and optimized its main parameters based on a mathematical model, which was adopted in the current paper. Craessaerts et al. (2010) identified the optimum and non-optimum working conditions of traditional reciprocating screen based on experimental data and fuzzy modeling techniques.

In recent years, along with further research on parallel mechanisms, a large number of screening methods based on parallel mechanisms have been conducted by many researchers. Liu et al. (2008) studied a kinematics modeling method of a 2T–2R (two-translation and two-rotation) type parallel mechanism screen by using a conversion matrix and presented kinematic positive and inverse solutions of this mechanism. Wang et al. (2012) designed a multi-dimensional vibration test bench (3T-1R) by using a fully decoupled main excitation mechanism and a short driving chain based on parallel mechanisms and performed an experiment on typical agricultural materials. Deng et al. (2013) designed a parallel kinematic vibration sieve based on 1 DOF (Degree of Freedom) and a two-loop spatial mechanism with a non-planar screen and analyzed the topology structure of its main mechanism. These studies generally support the conclusion that multi-DOF vibration screens based on parallel mechanisms are more adaptable and efficient than the traditional reciprocating screens in appropriate conditions.

However, as stated earlier, the traditional reciprocating screen, which has not largely been replaced by the screen based on parallel mechanisms, continues to play a positive role in agricultural production. For example, the reciprocating cleaning screen is still used in almost all combine harvesters. This is because the screen based on parallel mechanisms is often more expensive and more complex, while agricultural machines often need to be simple, practical, and reliable. On the contrary, from a macro perspective, the particles often flow in a plane along a single direction within continuous materials screening processes, but particles on the multi-DOF screen often move along complex spatial trajectories and not in a single plane. Obviously, the traditional reciprocating

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screen is simple, reliable, and causes particles to move in a plane along a single direction.

The traditional reciprocating screen does have some disadvantages. It sieves all particles at different locations on the screen with a single and uniform pattern. Difference in positions and feed quantity of these particles is obviously ignored by this type of uniform pattern, which does not meet the increasing and sophisticated requirements of modern agricultural production. In order to improve this method, we developed a new type of variable-amplitude screening method and simulated particle movement by using DEM (Discrete Element Method) technology (Ma et al., 2015). This kind of variable-amplitude screening method could provide different amplitude in the front of the screen without changing the original state of the screen, which is conductive to meet the different needs in different positions on the screen.

With the rapid development of computing technology in recent years, the DEM method (Cundall and Strack, 1979) has more commonly been used to simulate particle motion and has proven to be effective and feasible. Such DEM simulation technology is not only used in industrial processes (Hongguang et al., 2008; Kawaguchi et al., 1998), but also applied in agricultural processes such as fertilizer spreading (Tijskens et al., 2003; Van Liedekerke et al., 2009), grain flow in silos (González-Montellano et al., 2011), manure handling, and land application equipment (Landry et al., 2006). Furthermore, Li et al. (2012) coupled the DEM and CFD (computational fluid dynamics) simulation technologies to study agricultural particle motion in the cleaning unit of a combine harvester. Kattenstroth et al. (2011) developed a discrete-element model for straw particles constructed using connected spheres and studied the alignment of the straw particles and cutting blades in the chopper section of a combine. Lenaerts et al. (2014) introduced changes into the DEM to construct segmented bendable straw particles in a DEMeter++ software environment and simulated the separation process of grain and straw particles.

Using simulation software can not only observe the whole dynamic process, but also obtain a large number of micro motion data that cannot be measured in physical tests. By analyzing these data, researchers could investigate the same dynamic process and reveal the hidden rules from a quantitative angle. Particle motion simulations based on DEM technology could provide the kinematic parameters (such as displacement, velocity and acceleration) of all particles in the computational domain at any moment. By producing a specific formula according to statistics principle, a specific characteristic of a particle swarm could be calculated to reveal the potential rules. Alian et al. (2015) used the mean square of the axial and radial displacements of particles as particle motion parameters and calculated the mixing index as a function of the initial loading, rotational speed of the impeller, fill level, and particle size. Wen et al. (2015) analyzed all the common particle mixing indices and concluded that the neighbor distance method is the best choice. Zhao (2009) defined and computed the fluctuation coefficient of a particle's center of gravity in the simulation of particle motion on a vibrating plate by using DEM technology and depicted motion characteristics effectively.

In our previous study (Ma et al., 2015) we developed a new kind of screening mechanism (a variable-amplitude screen), and the particles' moving process on the screen was simulated in EDEM software (a widely used commercial software based on DEM method). In that study, the particles' moving process was analyzed just from macroscopic angle, so the potential and internal rules were not revealed. In order to analyze the process more quantitatively, 4 indices will be defined and computed by using these micro data in this paper to describe 4 kinds of specific dynamic characteristics of the particles on the variable-amplitude screen. It should be noted that this is a companion paper of our previous study (Ma et al., 2015), which based on the same simulation process with the same setting scheme. So the description of the simulation, such as the parameters and models, would be relatively concise in this paper.

2. Variable-amplitude screen

In previous studies (Ma et al., 2015), we developed a variable-amplitude screen based on the classical swing bar type reciprocating screen (similarly to that shown in Fig. 1). The front swing bar in this mechanism is able to rotate 45° around point A from O_2 to O_2' to change the position of the suspension point without changing the initial state of the screen. When the turning angle of the front swing bar changed from 0° (O_2A) to 45° ($O_2'A$), the amplitude of point A increased gradually to form a variable-amplitude effect.

Obviously, movement of the variable-amplitude screen is not the typical linear reciprocating movement, but rather a reciprocating motion with some rotation. In order to facilitate the simulation, a 3-DOF decomposition (2T-1R) was developed based on the analysis of the motion characteristics of the variable-amplitude screen (as shown in Fig. 2).

3. DEM simulations

3.1. Particle contact model

The universal DEM simulation software EDEM (DEM-Solutions, Edinburgh, UK) was used in this research. Considering the computational efficiency and the successful experience in related studies (Li et al., 2012), the popular Hertz–Mindlin contact model was selected for this study. This contact model type was developed based on the work of Mindlin (Cundall and Strack, 1979; Di Renzo et al., 2004), and its contact relationship is shown in Fig. 3:

F_n and F_t are the normal force and tangential force, respectively. R_i and R_j are the radii of particle i and j, respectively, and r_i and r_j are the position vectors of particle i and j, respectively. K_n and K_t are the normal stiffness and tangential stiffness, respectively, c_n and c_t are the normal damping and tangential damping, respectively, and μ is the friction coefficient.

3.2. Particle model

In this paper, rice particles (rice grain and rice straw) were selected as subjects for particle simulations (as shown in Fig. 4). The rice grain was designed as an ellipsoid with a 7.2-mm length and a 1.5-mm short axis. The rice straw was designed as an approximate cylinder with a length of 20 mm and a radius of 2.25 mm.

Mechanical and geometric parameters of the particles were adopted from the research of Li et al. (2012), and only a small

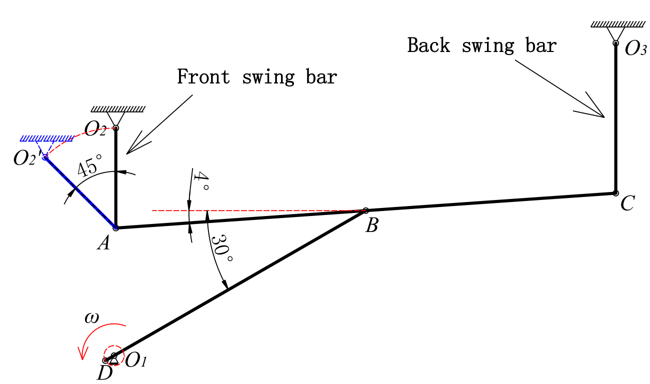

Fig. 1. Scheme of the variable-amplitude screen.