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Research Status and Future Trends of DEM in Seed Metering Process of Seeders

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Abstract: *This paper reviews the current research status and future development trends of the discrete element method (DEM) in the seed metering process of seeders. The basic principles of DEM and its application in the field of agricultural machinery are first introduced, with a focus on the research progress in model construction, simulation analysis, experimental verification, and parameter calibration in the seed metering process. The limitations of current research, such as model simplification errors, insufficient multi-physical-field coupling, and the absence of parameter standardization, are analyzed. Future directions in technological breakthroughs and application expansion are explored, including multi-method coupling simulation, high-performance computing and machine-learning applications, adaptive seed metering systems, development of new materials and structures, and standardization database construction. Finally, challenges and strategies for dealing with complex working conditions, deepening the integration of field tests and simulations, and cross-disciplinary talent cultivation are proposed. The results show that DEM has significant potential in optimizing seed metering design and improving sowing accuracy and efficiency, but further overcoming technological bottlenecks is needed to promote its widespread application in precision agriculture.*

Keywords: *Discrete element method (DEM); Seeder; Seed metering process; Simulation analysis; Future trends*

1. Introduction

1.1. Research Background

With the advancement of agricultural modernization, agricultural mechanization has put forward higher requirements for sowing accuracy and efficiency. Sowing, as the primary link in agricultural production, directly affects crop growth and yield. Traditional seed metering design and testing methods have many limitations, such as high costs and long cycles, and it is difficult to accurately simulate the complex motion behavior of seeds in the seed metering process. These methods usually rely on a large number of physical tests, which are not only time-consuming and labor-intensive but also fail to conduct in-depth analysis of the microscopic interactions between seeds and seed metering devices. For example, traditional testing methods find it hard to accurately measure the collision, friction, and flow characteristics of seeds during the seed metering process, which limits the optimization of seed metering device design.

The discrete element method (DEM), as a granular system simulation technology, has significant advantages in simulating seed motion and seed metering device performance. DEM can accurately simulate the granular motion, collision, and friction behavior of seeds, providing strong technical support for the design and optimization of seed metering devices. Through DEM, researchers can conduct virtual tests on computers to quickly evaluate the impact of different design parameters on seed metering performance, thereby significantly reducing testing costs and shortening the research and development cycle. Moreover, DEM can provide detailed microscopic mechanical information, helping researchers gain a better understanding of the interaction mechanism between seeds and seed metering devices, and further optimize the design of seed metering devices.

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1.2. Research Significance

The discrete element method (DEM) plays an important role in optimizing seed metering device design, reducing seed damage, and improving sowing uniformity. By accurately simulating the motion and collision behavior of seeds, DEM can help design more efficient seed metering structures, reduce mechanical damage to seeds during the seed metering process, and increase seed survival rates. At the same time, DEM can also optimize the working parameters of seed metering devices, such as rotational speed and vibration frequency, thereby improving the uniformity and consistency of sowing. These optimization measures can not only improve sowing quality but also significantly enhance the efficiency and benefits of agricultural production.

Moreover, the application of DEM is of great significance for the development of precision agriculture and intelligent agricultural machinery. Precision agriculture emphasizes precise agricultural operations based on soil conditions, crop requirements, and environmental factors, and DEM can provide theoretical support and technical guarantees for precision sowing. Combined with intelligent agricultural machinery technology, DEM can achieve adaptive control of seed metering devices, automatically adjusting seed metering parameters according to real-time monitoring data to achieve precision sowing. The widespread application of this technology will greatly improve the technological level of agricultural production and promote the development of agriculture towards intelligence and precision.

1.3. Existing Problems in Current Research

Despite the significant progress made in the study of seed metering devices using the discrete element method (DEM), there are still some pressing issues that need to be resolved. First, there is a discrepancy between model simplification and the actual behavior of seeds. In the actual seed metering process, seeds may undergo deformation, and environmental factors such as humidity can also affect the mechanical behavior of seeds. However, current discrete element models often ignore these factors. Although this simplification can reduce the complexity of the model, it may also lead to deviations between simulation results and actual conditions. For example, when Zhang et al. [1] studied the air-suction seed metering device, they obtained relatively accurate results through discrete element simulation, but in actual application, changes in seed humidity may cause differences in suction performance, and this factor was not fully considered in the model.

Second, the balance between computational efficiency and accuracy is also an important challenge in current research. DEM simulations usually require a large amount of computational resources, especially when dealing with large-scale seed populations and complex working conditions, the computational time may be very long. Although high-performance computing and GPU acceleration technologies have alleviated this problem to some extent, how to improve computational efficiency while ensuring computational accuracy in practical applications remains an urgent issue to be solved. For example, Zhang et al. [2] significantly improved the simulation efficiency of corn seeds by optimizing the adhesive model, but further integration of high-performance computing technology is still needed to shorten the simulation cycle.

Finally, the insufficient simulation of multi-factor coupling is also an important limitation of current research. In the seed metering process, there are not only mechanical interactions between seeds and seed metering device components but also possible couplings of multiple physical fields such as airflow and vibration. However, there are still technological bottlenecks in the multi-physical-field coupling simulation of DEM, making it difficult to accurately simulate these complex physical phenomena. For example, Zhao et al. [3] analyzed the suction dynamics of rice seeds using CFD-DEM coupling, but the dynamic matching problem between the turbulence model and particle motion has not been completely solved. This technological bottleneck limits the application scope of DEM in seed metering device design and affects its adaptability to complex working conditions.

2. Basic Principles and Application Overview of Discrete Element Method (DEM)

2.1. Basic Theoretical Framework of DEM

The basic theoretical framework of the discrete element method (DEM) is based on the granular motion equation, contact mechanics model, time-integration algorithm, and boundary condition setting. The granular motion equation usually uses the Newton-Euler equation to describe the motion state of seeds, including translation and rotation. The contact mechanics model is used to describe the interaction between seeds and seed metering device components, and common models include the Hertz-Mindlin model and viscoelastic model. These models can accurately simulate the mechanical behavior of seeds during collision and friction processes, providing a solid theoretical basis for DEM simulation. For example, Zhang et al. [4] constructed a mung bean seed model using the Hertz-Mindlin adhesive model and calibrated its contact parameters with organic glass and resin materials. The error between the simulated and measured angle of repose was less than 5%.

The time-integration algorithm is a key part of DEM simulation. It solves the granular motion equation through numerical methods to achieve dynamic simulation of the seed motion process. Common integration algorithms include explicit and implicit integration. Choosing the appropriate integration algorithm is crucial for improving the stability and efficiency of the simulation. In addition, the setting of boundary conditions also has an important impact on the accuracy of DEM simulation results. Boundary conditions include the motion state of seed metering device components, the initial position and velocity of seeds, etc. By reasonably setting boundary conditions, the simulation process can be highly consistent with the actual seed metering process. For example, Sun et al. [5] used a discrete element design analysis method based on a CAD boundary model to establish a joint model of precision seed metering device components and seed groups, and conducted dynamic simulation analysis of the soybean precision seed metering process.

2.2. Application Status of DEM in the Field of Agricultural Machinery

The application of the discrete element method (DEM) in the field of agricultural machinery has achieved significant results, especially in typical application scenarios such as sowing, fertilizing, and harvesting. In the sowing process, DEM can accurately simulate the motion behavior of seeds in the seed metering device, including granular flow, collision, and friction and other complex phenomena. For example, Zhang et al. [2] used DEM to simulate the motion law of corn seed population and studied the influence of vibration parameters on the suction performance of air-suction seed metering devices. They concluded that the best suction performance is achieved when the vibration frequency is 15 Hz and the amplitude is 6 mm. Similarly, Liu et al. [6] optimized the working parameters of air-suction seed metering devices through simulation, and concluded the best range of parameters such as stirring wheel speed, vibration frequency, and amplitude, further proving the effectiveness of DEM in the performance analysis of air-suction seed metering devices.

In the fertilizing process, DEM also plays an important role. For example, Yuan et al. [7] designed a spoon-wheel type furrow fertilizer-placing seed metering device and tested its furrow-making performance and the uniformity of fertilizer application per furrow through DEM simulation technology. Their research results show that optimizing the structural parameters of the seed metering device can significantly improve the uniformity and stability of fertilization. In the harvesting process, DEM can also simulate the movement and separation of crop granules in the harvester, providing a theoretical basis for the design and optimization of harvesters.

However, the seed metering process of seeders has its particularities. The granular flow, collision, and friction behavior of seeds are more complex, which puts higher requirements on the application of DEM. In the actual seed metering process, seeds are not only subject to the mechanical action of seed metering device components but also to the influence of multiple factors such as airflow and vibration. Therefore, how to accurately simulate these complex phenomena through DEM is still an important direction for current research. For example, Zhao et al. [3] analyzed the suction dynamics of rice seeds using CFD-DEM coupling, providing theoretical support for the design of air-suction seed metering devices, but the dynamic matching problem between the turbulence model and granular motion has not been completely solved. In the future, with the development of multi-physical-field coupling technology, DEM will play a greater role in the research of the seed metering process of seeders.

3. Research Status of Discrete Element Method in the Seed Metering Process of Seeders

In recent years, the application of the discrete element method (DEM) in the design and optimization of seed metering devices in seeders has made significant progress. Research has mainly focused on model construction, simulation analysis, experimental verification, and parameter calibration, involving various types of crop seeds and seed metering devices. The research status is summarized from four dimensions: model construction, simulation analysis, experimental verification, and parameter calibration.

3.1. Discrete Element Model Construction

The accuracy of the discrete element model directly affects the reliability of the simulation results. Researchers have established refined models for different crop seeds based on their physical properties (such as shape, size, friction coefficient, and restitution coefficient). For example, Zhang et al. [4] constructed a mung bean seed model using the Hertz-Mindlin adhesive model and calibrated its contact parameters with organic glass and resin materials. The error between the simulated and measured angle of repose was less than 5%. Shi et al. [8] constructed an ellipsoid and irregular-shaped model of potato seed tubers through reverse engineering and slicing, with an error of only 1.33% between the simulated and tested angle of repose. For small-grain seeds, Li et al. [9] used EDEM to establish a wheat seed model for the external groove-wheel seed metering device and optimized the structural parameters of the groove-wheel through orthogonal experiments, achieving a seed metering uniformity coefficient of 90.15%. In addition, the modeling technology of complex boundary conditions has also developed. Sun et al. [5] constructed a joint model of soybean seed metering device and seeds based on a CAD boundary model and found that the range of the seed-metering wheel's filling angle and the seed friction coefficient significantly affected the seed metering performance. Ji et al. [10] constructed a combined arc model of corn seeds through AutoCAD secondary development and analyzed the influence of seed-metering wheel angular velocity on the seed-clearing angle.

3.2. Simulation Analysis of Seed Metering Process

Through discrete element simulation, researchers have revealed the quantitative relationship between the working parameters of seed metering devices (such as rotational speed, vibration frequency, and amplitude) and seed metering performance (uniformity, breakage rate, and seed-missing rate). For example, Liu et al. [6] simulated an air-suction seed metering device and found that when the stirring wheel speed was lower than 18.5 r/min and the amplitude was less than 5 mm, the average suction rate increased by 7.1%-8.9%. Chen et al. [11] simulated the impact of vibration on large-grain soybean seed population and found that the average velocity of the seed population was linearly related to the amplitude, with the best seed-clearing effect achieved at an amplitude of 2 mm. Guo et al. [12] simulated a sunflower seed metering device and found that the seed metering quantity was positively correlated with the rotational speed, while the seed-metering port angle and seed variety were negatively correlated, with the best rotational speed being 20 rpm.

Optimization research on different types of seed metering devices has also made progress. For air-suction seed metering devices: Li et al. [13] simulated the seed population movement of the vibrating seed plate using a spring-damping model and found that high-frequency, low-amplitude vibration could effectively separate seeds, with a suction rate reaching 98%. For mechanical seed metering devices: Yuan et al. [14] optimized the rotational speed of the spoon-wheel type seed metering device to 10-13 r/min, with the best performance when the seed quantity was 1800-2100 grains. For centrifugal seed metering devices: Liao et al. [15] found that the seed quantity of the inner cone cylinder was negatively correlated with the critical rotational speed, and the total discharge increased linearly with the increase of rotational speed.

3.3. Co-Verification of Simulation and Experiment

To improve the credibility of the simulation, researchers have verified the model through high-speed photography, sensor measurement, and comparison with simulation results. For example, Zhang et al. [1] tested the vibration characteristics of the no-till seeder using a BK accelerometer and combined DEM to simulate the movement of corn seed population. They found that the best suction performance was achieved at an operating speed of 3-5 km/h and a vibration amplitude of 6 mm, with an error of less than 5% between the simulation and bench-test results. Liu et al. [16] simulated the influence of the seed-guiding tube height on seed metering uniformity using EDEM and determined the best height to be 500 mm, with a verification error of only 0.8%. Chen et al. [17] simulated a peanut seed metering device and found that the highest double-seed rate was achieved at a rotational speed of 38 rpm, which was consistent with the bench-test results. Parameter sensitivity analysis has become an important means of correcting the model. Li et al. [18] calibrated the contact parameters of sunflower seeds using the response surface method, with a simulated angle of repose error of only 0.78%. Li et al. [19] calibrated the parameters of Qianghu seeds in combination with heap-testing and EDEM, and the error between field tests and simulation was less than 5.6%.

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3.4. Limitations of Current Research

Despite the significant achievements, existing research still has the following shortcomings:

Model simplification error: Most studies ignore the influence of seed humidity, deformation, and surface roughness. For example, the linear spring-damping model used by Li et al. [13] did not consider the plastic deformation of seeds, leading to prediction deviations in seed population movement under high-frequency vibration.

Insufficient multi-physical-field coupling: The joint simulation of gas-solid coupling (such as the negative pressure field of air-suction seed metering devices) and fluid-solid coupling (such as the interaction between seeds and airflow in the seed-guiding tube) is still in the exploration stage. Although Zhao et al. [3] attempted to analyze the suction process of rice seeds using CFD-DEM coupling, they did not completely solve the dynamic matching problem between the turbulence model and granular motion.

Lack of parameter standardization: The calibration methods for seed mechanical parameters are diverse (such as the inclined plane method and free-fall method), and there is a lack of a unified database. Zhang et al. [20] pointed out that the static friction coefficient of soybean seeds with different materials varied significantly (0.408-0.474), and it is necessary to establish a parameter system for different crops and materials.

4. Future Development Trends and Research Directions

With the development of precision agriculture and intelligent agricultural machinery, the application of the discrete element method in the study of seed metering devices will deepen in the direction of multidisciplinary intersection, high-performance computing, and intelligence. The specific trends are as follows:

4.1. Breakthrough Directions in Technology

Multi-method coupling simulation. Gas-solid coupling: Zhao et al. [3] analyzed the suction dynamics of rice seeds using CFD-DEM. In the future, it is necessary to further optimize the real-time interaction algorithm between the turbulence model and granular motion. Fluid-solid coupling: Ding et al. [21] combined DEM-CFD to simulate the airflow field of the air-suction seed metering device for corn, providing new ideas for predicting the movement of seeds under high-speed operations. Structure-motion coupling: Liu et al. [22] used EDEM-FEM to jointly analyze the seed-throwing trajectory of the vertical seed metering device. In the future, it can be expanded to predict fatigue life.

High-performance computing and GPU acceleration. Aiming at the bottleneck of low computational efficiency in large-scale population simulation, Zhang et al. [2] optimized the simulation efficiency of corn seeds using an adhesive granule model. In the future, it is necessary to combine GPU parallel computing technology (such as NVIDIA CUDA) to shorten the simulation cycle. Yuan et al. [23] proposed an optimization model for fertilizer blending uniformity based on RVM, providing an example for machine-learning-accelerated parameter calibration.

Machine learning and intelligent optimization. Parameter calibration: Li et al. [24] used the response surface method and genetic algorithm to optimize the contact parameters of coated corn seeds, with an error of less than 1%. Structural design: Liu et al. [22] realized the parametric design reuse of seed metering devices based on CBR (case-based reasoning) technology and verified the optimized solution with EDEM. Real-time control: Zeng et al. [25] optimized the seed metering parameters of small-grain seeds through discrete element simulation and realized the adaptive adjustment of suction positions in combination with PLC.

4.2. Expansion Directions in Application

Development of adaptive seed metering systems. Working condition perception: Cao et al. [26] analyzed the disturbance law of the concave-groove seed plate on corn seed population using EDEM. In the future, it is possible to integrate sensors to provide real-time feedback on the state of the seed population. Dynamic parameter adjustment: Liao et al. [27] designed a rapeseed centrifugal-type seed-collecting device that adjusts the seed-supply height and rotational speed to match the operating speed, laying the foundation for adaptive control.

Design of new materials and structures. Biomimetic surface: Hu et al. [28] designed a magnetic-adsorption plate-type seed metering device that uses permanent magnets to adsorb small-grain seeds, with a single-sowing rate of 89.57%. Lightweight materials: Yang et al. [29] optimized the structure of the hole-wheel through simulation, reducing the use of aluminum alloy materials by 20% while maintaining strength.

Construction of standardized database. Crop parameter library: Shi et al. [8] calibrated the rolling friction coefficient of flax seeds to 0.0415-0.0425. In the future, it is necessary to integrate the friction and restitution coefficients of crops such as corn, soybeans, and rice. Equipment-material interaction library: Zhang et al. [20] established a contact parameter comparison table for soybeans with seed metering discs and stirring wheels, which can be expanded to other crop and metal/plastic material combinations.

4.3. Challenges and Coping Strategies

Model robustness under complex working conditions: It is necessary to develop dynamic contact models that consider humidity and temperature changes. Li et al. [30] found that the increase in cotton seed moisture content led to a 15% increase in static friction coefficient. In the future, it is necessary to quantify the impact of environmental factors on simulation parameters.

Deep integration of field tests and simulations: Through Internet of Things technology, real-time field data (such as vibration spectrum, soil resistance) can be collected to correct the simulation model in reverse. Jiang et al. [31] combined EDEM simulation with rotary tillage and covering experiments and verified that the qualified rate of seedling-band distribution reached 95.1%.

Cross-disciplinary talent training: It is necessary to strengthen the cross-training of agricultural engineering, computational mechanics, and artificial intelligence to promote the innovative application of DEM in intelligent agricultural machinery.

5. Conclusion

The discrete element method (DEM) has made significant progress in the design and optimization of seed metering devices in seeders. Through refined model construction, in-depth simulation analysis, and rigorous experimental verification, it has provided strong support for improving seed metering accuracy and efficiency. However, current research still faces challenges such as model simplification errors, insufficient multi-physical-field coupling, and the lack of parameter standardization. In the future, with the continuous development of multi-method coupling simulation, high-performance computing, and machine-learning technologies, DEM will play a greater role in the adaptive design of seed metering devices, application of new materials, and construction of standardized databases. By coping with complex working conditions, deepening the integration of field tests and simulations, and strengthening cross-disciplinary talent training, DEM is expected to further promote the development of precision agriculture and intelligent agricultural machinery technologies and provide more efficient and precise sowing solutions for modern agricultural production.

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