Research on Drag Reduction Mechanism of Bionic Rib Subsoiling Shovel Based on Discrete Element Method

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Abstract: In order to study the drag reduction mechanism of bionic ribbed subsoiler, this paper established a soil particle motion analysis model by using discrete element analysis software EDEM, simulated the three kinds of subsoilers at the same tillage depth, the same tillage angle and the same tillage speed, compared the microscopic normal force and tangential force between the subsoiler and soil particles from the microscopic angle, and explored the drag reduction reason of bionic ribbed subsoiler according to the particle motion velocity nephogram and the particle motion trajectory on the subsoiler on different ribbed surfaces.

1. Introduction
As the core technology of conservation tillage, subsoiling technology has been paid more and more attention. However, subsoiling machinery has many problems, such as high tillage resistance, serious wear and tear, and high energy consumption. Bionics puts forward the basic principle of drag reduction and desorption, from which many successful products have been designed, showing broad development prospects. Applying bionics to the design of subsoiling shovel will reduce the tillage resistance and prolong the service life of subsoiling shovel [1-3], but the drag reduction mechanism of bionic subsoiling shovel is still unclear and needs further research. Discrete element method is a new numerical method for solving and analyzing the motion laws and mechanical properties of complex discrete systems, and has also been applied in the field of agricultural engineering [4-6].

In this paper, EDEM software is used to establish a soil particle motion analysis model and analyze the interaction between soil and subsoiling shovel, so as to clarify the drag reduction mechanism of bionic subsoiling shovel.

2. Structure of Bionic Subsoiling Shovel
Taking Hawaiian shellfish as the research object, the data point cloud of its outer surface is obtained by using a three-dimensional laser scanner, and its typical characteristic curve is obtained. In this paper, Rakem Karat 9 subsoiling shovel is selected as the prototype to design the bionic subsoiling shovel. The characteristic curve of the outer surface of Hawaii shellfish is applied to the rib design of the bionic subsoiling shovel by using three-dimensional software. Combined with the movement form of the soil, the rib is optimized to a structure gradually thickened along the rising direction of the soil. Each rib is "V" shaped and symmetrical left and right. Not all shovel bodies are buried, and the shovel
tip is seriously worn. The bionic rib is designed into a symmetrical structure from top to bottom. After one end of the subsoiling shovel is worn, the shovel body can be exchanged for 180 degrees and then used continuously, thus prolonging the service life of the shovel body, as shown in Fig.1. This paper selects 0000 (smooth non-bionic subsoiling shovel), 30204 (30 degrees of rib angle, 20mm of rib width, 4 ribs, symmetrical left and right and up and down) and 45306 (45 degrees of rib angle, 30mm of rib width, 3 ribs, symmetrical left and right and up and down) for analysis.

![Fig.1 bionic subsoiling shovel](image)

3. Establishment of Simulation Model
Firstly, three models of subsoiling shovel 0000, 30204 and 45306 are modeled and imported into EDEM by using three-dimensional modeling software. Then, a 600×270×350mm boundary Box of the test soil model was established in EDEM and set to open the top cover to facilitate particle filling. Based on the comprehensive consideration of factors such as the actual particle radius of the soil in the test site and the size of the soil model, the average particle radius is set to 0.8mm, as shown in Fig.2.

![Fig.2 Soil model](image)

4. Simulation and Analysis of Subsoiling Shovel

4.1 Comparison on Stress of Soil Particles

Figs. 3 and 4 respectively show the normal force and the normal overlapping displacement generated by the contact between the particles and the subsoiling shovel during the time of 0.15s to 0.5s s. as can be seen from the figure, compared with the other two bionic subsoiling shovels, the normal force and the normal overlapping displacement of the 0000 model subsoiling shovel are both larger, while among the two bionic subsoiling shovels, the 45306 model has the smallest normal force and the smallest normal overlapping displacement.

Figs. 5 and 6 respectively show the tangential force and tangential overlapping displacement generated by the contact between particles and the subsoiling shovel during the time of 0.15s to 0.5s for the three types of subsoiling shovel and 0.15s to 0.5s for the three types of subsoiling shovel. From the figure, it can be seen that the trend is basically consistent with the tangential force and tangential overlapping displacement, which shows that the normal force between the bionic subsoiling shovel
and the particles is smaller in the burying stage and the stable tillage stage, and the 45306 has the best drag reduction effect.

![Fig. 3 Normal force of contact](image1)

![Fig. 4 Normal overlapping displacement](image2)

![Fig. 5 Tangential forces](image3)

![Fig. 6 Tangential overlapping displacement](image4)

4.2 Comparison of Transverse Soil Particles

The surface morphology of bionic ribbed subsoiler is the main feature of the subsoiler's shape. The change of this feature plays an important role in the dynamic behavior of soil particles. The subsoiler with different surface morphology has obvious difference in the law of soil dynamic change. Fig. 7 shows the influence of three types of subsoiling shovel on soil dynamic behavior at three consecutive times of 0.2s, 0.3s and 0.4s. For convenience of observation, two transverse soil layers are selected and marked with different colors. Comparing the dynamic behavior changes of soil layer between 0000 model subsoiler and two bionic subsoilers, we can find that the arching angle of soil layer at the front end of bionic subsoiler is obviously smaller than the fluctuation range of soil of original glossy surface subsoiler. This is because the ribbed surface of bionic subsoiler produces uneven fluctuation on soil particles at the front end of subsoiler, and the ribbed convex reduces the change of relative displacement of local soil particles between the two waves, thus making the arching angle of soil layer smaller.

When the working time of the subsoiling shovel is 0.2s, the soil particles at the front end of the subsoiling shovel are in a piling state. In this state, most of the soil climbs upward along the subsoiling shovel, while a small amount of dry soil moves forward under the squeezing action of the subsoiling shovel. At this time, the soil at the front end of the subsoiling shovel has a certain range of arching fluctuation. The arching angles of the 0000, 30204 and 45306 models of subsoiling shovels are successively decreased, respectively, by 25, 22 and 19. This arching fluctuation is the result of the upper soil squeezing the lower soil and some upper disturbed soil sliding down along the lower soil. When the working time of the subsoiling shovel is 0.3 seconds, the soil accumulation height before the shovel continues to increase, and the arching angles of 0000 model, 30204 model and 45306 model subsoiling shovels successively decrease to 35, 33 and 30 respectively, reaching a basically stable state, in which a part of soil at the front end of the subsoiling shovel slides upward along the shovel surface and falls to the rear end of the subsoiling shovel; A part of soil particles move forward under the squeezing action of the subsoiling shovel; There is also a part of upper disturbed soil particles sliding...
down along the lower soil particles. When the working time of the subsoiling shovel is 0.4s, the soil accumulation height before the shovel is basically stable, and the arching angles of 0000, 30204 and 45306 subsoiling shovels are still decreasing in sequence, reaching a stable cultivation state, respectively, 49, 39 and 36, and the cultivated soil falls backward overall, which also indicates that the movement form of the soil is consistent with the actual situation. Due to the different movement modes and positions of soil particles in each part, the local soil particles in the soil layer are slightly dislocated, which makes the overall dynamic behavior of soil change obviously. It can be seen from the white soil layer form in the figure that with the increase of working time, the internal structure of the soil layer changes in an arch shape, and the arch angle of the 45306 subsoiler is always the smallest. However, the larger the arching angle is, the more serious the accumulation of soil particles at the front end of the subsoiler at the same time, while the smaller the arching angle at the front end of the bionic ribbed subsoiler, the less the accumulation of soil particles. This shows that the bionic ribbed subsoiler has fewer disturbances to the soil, so the tillage resistance is smaller than that of the original smooth subsoiler under the premise set by this research.

4.3 Comparison of Longitudinal Soil Particles
In order to study the movement of soil particles on subsoiling shovel with different surface forms more intuitively, this paper studies the longitudinal soil layer of 20mm thick particles in the soil model and takes the perspective facing the front end of the subsoiling shovel. As shown in Fig.8, the streamlines of particle velocity distribution in the longitudinal soil layer of the soil model are obtained at 0.15s, 0.25s and 0.35s for 0000, 30204 and 45306 subsoilers respectively. The red line represents the larger particle velocity, the blue line represents the smaller particle velocity, the green line is between the two, and the curve represents the trajectory of the particle in 6 consecutive time steps. It can be seen that the soil particles at the front end of the subsoiling shovel show an overall upward trend at 0.15s, and the particle trajectory generated by the 0000 model subsoiling shovel is obviously denser and relatively longer than that of the bionic ribbed subsoiling shovel. At 0.25s, judging from the particle distribution, the particle distribution direction of the two bionic ribbed subsoilers is more disordered and shorter than that of 0000 model subsoiler, which is due to the "rolling effect" and guiding effect of the soil particles in contact with the ribbed subsoiler. When the soil particles are thrown out along with the ridge movement, they will collide and interfere with the impacting soil particles. At 0.35s, with the
passage of working time, the subsoiling shovel has passed through the longitudinal soil layer, most of the particles have been subsoiled and dropped, and a small number of particles are still present in the view. However, it is not difficult to find that the soil particles before the model 0000 subsoiling shovel are more denser, which indicates that the particle speed is higher than that of the other two bionic ribbed subsoiling shovels, and the speed of the soil particles before the model 45306 subsoiling shovel is the smallest.

![Fig. 8 Streamline cloud map of particle velocity distribution in longitudinal soil layer](image)

5. Conclusions
1) A soil particle motion analysis model of subsoiling shovel is established, and three types of subsoiling shovel are simulated under the same tillage depth, the same tillage angle and the same tillage speed.
   2) Normal force and normal overlapping displacement of 0000 smooth subsoiling shovel are larger, while that of 45306 bionic ribbed subsoiling shovel is the smallest, and its normal overlapping displacement is also the smallest.
   3) The disturbance of bionic ridge subsoiling shovel to soil is small, the soil particles are more dense before 0000 smooth subsoiling shovel, and the velocity of soil particles before 45306 bionic ridge subsoiling shovel is the smallest.

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