DESIGN AND ANALYSIS OF A BIONIC PULL-TYPE SUBSOILER

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ABSTRACT: The performance of the subsoiler which serves as the main working part of subsoiling is one of the standards to evaluate subsoiling technology. Considering the conditions of soil and equipment in the province of Anhui, without changing any manufacturing materials, this article, based on the study of animal claw and arc subsoiler, applied the animal’s highly efficient digging skill to the structure design of subsoiler to effectively perform drag reduction and better subsoiling. The rationality of bionic subsoiler design was verified by Finite Element Analysis (FEA). The tillage resistance of the two types of subsoilers was compared by the Discrete Element Method, and the influence from working speed on the tillage resistance was analyzed.

KEYWORDS: Subsoiler, bionic design, finite element analysis, discrete element analysis, tillage Resistance.

1 INTRODUCTION

Subsoiling is one of the basics of conservation Agriculture (He et al., 2006). Subsoiler is the main working part of subsoiling, and it is also an important part of subsoiling machine. Therefore, the performance of subsoiler is a standard for evaluating subsoiling technology (Li, 2000). The subsoiler is composed of the shaft and the tip (Guo 2001). So far the subsoilers are classified as the vibrating type and the pull-type according to their modes of treatment on the soil; and the vertical type and the arc type according to the structures of their shafts. During the operation, the soil is cut, broken and loosened by the subsoiler. Therefore, the subsoiler’s structural shape greatly influences the resistance dragging the subsoiling components during soil tillage (Chen, 2010; Tamas et al., 2013).

There are many animal digging experts, for example, pangolin, house mouse, brown bear, etc. Their claws, toes and the other body parts have evolved into structures suitable for treating soil. The job of subsoilers is to loosen the soil and break the solid plow pan at the soil bottom, so as to better preserve the soil moisture and guarantee that the plant roots have proper conditions to grow. Therefore, to make the subsoiler an imitation of the claw toe will reduce the troublesome tillage resistance.

The object of this study is the pull-type subsoiler. Using claws of house mouse for reference, a bionic subsoiler is designed based on the arc type subsoiler. The 3D modeling is done for the arc type subsoiler and the bionic subsoiler by the 3D software, and the rationality of the design is evaluated through the Finite Element Analysis and the Discrete Element Method. All the above provides theoretical basis for the further optimization design. Meanwhile, a field trial has been carried out.

2 ARC TYPE SUBSOILER

The subsoiler is driven by the tractor to move with constant speed through the soil, at the same time, the soil is cut by the subsoiler tips and shafts. The tip is located at the front end of the subsoiler. During the operation, the tip touches the soil the first and then go deeper and deeper into the soil bottom. The shaft is fixed on the subsoiling machine using a U shaped fixing device. It works to immobilize the tip and bear its work load, and provides the power for the entire operation. When reaching certain depth, part of the shaft is also beginning to touch the soil and participate in the operation. Therefore, the subsoiling depth, range and the tillage resistance are influenced by the structure and the design parameters of the subsoiler as well as the soil conditions. So certain optimized design based on the soil structure parameters of the targeted field is needed when the operation is run in different regions.

The arc type subsoiler, featured by its shape which performs good subsoiling and few scrape of weeds, by far is the most widely used and recognized in China. The type is also good at cutting the upper soil, and its body is able to maintain a relatively stable subsoiling depth. The structure of the arc type mainly includes the shaft...
and the tip, Figure 1-1 and 1-2 are the arc subsoiler used in the province of Anhui, and its 3D image.

Figure 1-1. The Arc Type Subsoiler in Actual Use

Figure 1-2. The 3D Image of the Arc Type Subsoiler

3 DESIGN OF BIONIC SUBSOILER

During the operation, the soil is cut and dug by the shaft front part wedge blade and the tip of the subsoiler. This ensures the preservation of soil moisture, but the tillage resistance is remarkable. Consequently, the shaft's contact with the soil will affect the traction resistance of the subsoiler. This article provides a bionic subsoiler design in which the shaft cross section curve imitated the mice claw.

3.1 The bionic curve design of shovel handle

Scale up the fitting curve of the rat claw (Zhang et al., 2014) and take it as the ground breaking surface of the shaft of the subsoiler. Amplification coefficient is calculated in accordance with the working depth and the structural parameters of the design of working parts. Curve fitting equation of the rat claw is calculated by the amplification coefficient. The directrix equations are as follows (2-1), (2-2):

Inside directrix equation:
\[ y_1=3.320726-5.33522x+0.04263768x^2-0.000116x^3 \]  (2-1)

Outside directrix equation:
\[ y_1=-80.272217-1.946185x+0.01718x^2 \]
\[ -0.000056625x^3 \]  (2-2)

SolidWorks is used to draw the bionic model of the shaft, as shown in figure 2-1. At the same time, considering the influence of the structural parameters of the handle on the traction resistance, the width, thickness and depth ratio of the shaft are then determined.

Figure 2-1. Three dimensional image of the shaft of the bionic subsoiler

The depth ratio has significant influence on the working performance and resistance of the shaft. On the basis of the existing theories (Guo, 2000; Gong, 2013), the depth ratio(L/D), namely the ratio between the horizontal length of the longitudinal part in the working depth range L and the working depth D, maintains at 0.68-1.0. The subsoiler effectively reduced the tillage resistance. When the depth ratio is 0.8, the tillage resistance is the minimum. Therefore, the depth ratio of the bionic subsoiler in this paper is 0.8.

The width and thickness of the subsoiler directly determines its structural strength and is also the main factor affecting tillage resistance. The larger the width or the thickness of the shaft is, the larger the structural strength and the safety coefficient are. However, the increasing contact surface may increase friction and adhesion, and the tillage resistance will become larger. If the width or thickness is too small, the shaft may be deformed or sheared off when the tillage resistance increases sharply when working at the bottom of the soil or touching the stones. In this paper, the tilling depth of the subsoiler is 30-35cm. Take the subsoiling effect and the local soil environment as consideration, and according to the mechanical industry standard design requirements, the width and the thickness of the bionic shaft are 55mm and 25mm respectively.

3.2 Force analysis of the shaft

In the operation, the section of the shaft is used to cut the soil. The whole surface of the shaft which contacts the soil is not taken into consideration. Force analysis is carried out on the working surface. The force analysis is based on the method proposed by Kostritsyn, which regards the whole shaft as knife-shaped right-angled slice, and regards the cutting edge at the front of the shaft as the wedge blade, and the parallel blade as the side shovel. The force analysis of the shaft is shown in figure 2-2:
The force balance equation in the horizontal direction of the shaft is obtained from the force analysis shown in the diagram:

\[ F_2 = 2(N_3 \sin \frac{\delta}{2} + N_4 \mu_1 \cos \frac{\delta}{2} + N_4 \mu_2) \]  

(2-3)

N3 is the normal force on wedge blade. N4 is the normal force on the side shovel, which is relevant to the deformation resistance of the soil; \( \delta \) is the angle of the wedge blade, which is 60°.

\[ N_3 = K_1 S_2 \]  

(2-4)

\[ N_4 = K_2 S_3 \]  

(2-5)

K1 is the specific resistance of soil deformation; S2 is the area of the wedge blade, which is 7.57×10^{-3} m²; K2 is the specific pressure of soil; S3 is the area of the side edge, which is 0.0149 m².

According to (2-3), (2-4), (2-5):

\[ F_2 = 2K_1 S_2 (\sin \frac{\delta}{2} + \mu_1 \cos \frac{\delta}{2}) + 2K_2 S_3 \mu_2 \]  

(2-6)

In the upper form (2-5), only K1 and K2 are unknown. When the subsoiler is working, the deformation caused by cutting soil will produce specific pressure and specific resistance:

\[ K_1 = K_{el} + K_{pl} \]  

(2-7)

Type: \( K_{el} \) is the stress produced by the elastic deformation of soil; \( K_{pl} \) is the stress produced by the plastic deformation of soil. When shaft is working, the specific pressure is only produced in elastic deformation, the ratio of which can be:

\[ K_{el} = K_2 \frac{1}{\cos \frac{\delta}{2}} \]  

(2-8)

The current study (Yu et al., 2007) shows that when the width of the shaft is greater than 0.3 cm, \( K_e \) is close to 4500 N/m². The function relationship between \( K_{pl} \) and the width of the shaft is shown in Hyperbolic form in the axis. \( K_{pl} = k/L_0 \), where k is a constant, and its value is 200; \( L_0 \) is value of the average soil deformation, the calculation formula is as follows:

\[ L_0 = \frac{w}{4 \cos (\frac{\delta}{2} + \delta_1)} = 0.025 m \]  

(2-9)

In the formula, \( \delta_1 \) is the friction angle between soil and metal, which is 40°. Therefore, according to the above formula, \( K_{el} = 3897 \text{N/m}^2 \), \( K_{pl} = 8000 \text{N/m}^2 \), \( K_{pl} = 12055 \text{N/m}^2 \).

According to formula (2-6), the actual size of the design is taken into account, and the force of the shaft can be obtained \( F_2 = 256 \text{N} \).

### 4 FINITE ELEMENT ANALYSIS OF SUBSOILER

#### 4.1 Meshing and loading of the shaft

The 3D model of bionic subsoiler shaft and arc type subsoiler shaft are transformed into x_t format file by Solidworks software and imported into ANSYS Workbench. The materials of the two kinds of subsoilers are 65Mn rigid attributes, and then meshing and loading are applied. The unit size of the mesh is 3m; the load stress is on the basis of the stress analysis of the last section. The shafts of the arc type subsoiler and the bionic subsoiler are similar in terms of two dimensions. Therefore, the stress on the shaft of the arc type subsoiler will also adopt the above figures so that to ensure the conditions in which the results are analyzed are the same. The resultant force of the shaft is 256N, the direction of which is perpendicular to the surface of the shaft. The resultant force of the tip is 876N, the direction of which is perpendicular to the front of the shaft. The degree of freedom of the hole on the connecting section of the tip and the upper part of the shaft is fixed. The meshing and loading of the two types of subsoilers are shown in figure 3-1, 3-2, 3-3, and 3-4.
4.2 Results analysis and comparison

After analyzing two kinds of shafts, and get the stress-strain diagram of the shaft through post-processing module. The deformation amount, stress concentration and stress magnitude of the shaft can be seen from the stress-strain diagram.

Results analysis: according to Fig. 3-5 and 3-6, the most severe deformation of the bionic subsoiler is in the middle of the shaft, and the maximum deformation is 1.35×10^-3 mm. The deformation of the circular shaft is at the tip of the shaft, and the maximum deformation is 1.63×10^-3 mm. The results show that the deformation of bionic subsoiler is relatively small, but the deformation is easy to occur in the middle. The backwards inclination of the curve of the shaft of the bionic subsoiler is larger than that of the arc type subsoiler, which can be installed with protection device.
The results of the 3-7 and 3-8 diagrams show that the stresses of the bionic and arc type subsoiler are concentrated at the connecting hole that connects the front of the shaft and the tip of the subsoiler. The maximum stress of bionic subsoiler is 4.49MPa. The maximum deformation of the shaft of the arc type subsoiler is 7.96MPa.

Static analysis is carried out on the shaft of the bionic and arc type subsoiler. The result is obtained by post-processing. According to the analysis on the result, the deformation and maximum stress of bionic shaft are smaller than that of the circular shaft, which improves the feasibility of the design.

5 DISCRETE ELEMENT ANALYSIS OF TILLAGE RESISTANCE OF SUBSOILER

5.1 Analysis model and parameter determination

Based on the theoretical content of Hertz-Mindlin analysis, a subsoiler- particle contacting model (Li, 2016; Zheng and He, 2016) was established. The model is built in Solidworks 3D design software and then is converted to x_t format and then output to EDEM software. The material of the subsoiler in simulation is the same as that in reality, which is 65Mn. The material is defined as 65 manganese steel. The Poisson ratio of the subsoiler is 0.3 and the elastic modulus is 2.06 x 1011Pa. According to the relevant formula of mechanics of materials (4-1):

\[
G = \frac{E}{2(1+\mu)} = 7.9 \times 10^{10} Pa
\]

G-- shear modulus; E-- elastic modulus; \(\mu\)--Poisson ratio.

The parameters of the soil in the model are in accordance with relevant literatures, and the parameters are shown in table 4-1. The particle radius is 0.01m, and the gravity acceleration is 9.81m/s.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson's ratio of soil particles</td>
<td>0.4</td>
</tr>
<tr>
<td>Density of soil particles</td>
<td>2600Kg/m3</td>
</tr>
<tr>
<td>Shear modulus of soil particles</td>
<td>6.43+06Pa</td>
</tr>
<tr>
<td>Restitution coefficient between</td>
<td>0.2</td>
</tr>
<tr>
<td>particles</td>
<td></td>
</tr>
<tr>
<td>Dynamic friction coefficient between</td>
<td>0.3</td>
</tr>
<tr>
<td>particles</td>
<td></td>
</tr>
</tbody>
</table>

5.2 Simulation process and result analysis

The bionic soil box uses the Box model. The granule factory is hypothesized BOX. The size of the soil box is 1.5m x 0.5m x 0.5m. The depth of the subsoiler is 300mm. The speed is 4Km/h. It can be seen from Figure 4-1 that the subsoiler is on the right side of the soil box. It will move to the bionic soil box at a certain depth when the analysis begins. The interval between the simulation step and the data storage in the model is calculated through EDEM. The mesh size of this simulation analysis is 0.03mm, and the total motion time is 6s. In the simulation process, the particles are first generated for some time and accumulate at the bottom of the granule factory due to acceleration. The subsoiler will then move towards the bionic soil box until the time is over. The movement of the subsoiler in the soil box is shown in Figure 4-2.
5.2.1 Comparative Analysis of Resistance

After the simulation, the EDEM post processor will adjust the attributes, observe the movement process of each model, analyze changes of the data, and generate and export the simulation data. The resistance of the subsoiler during the simulation is displayed in Figure 4-3.

During the simulation analysis, the arc type and the bionic subsoiler will work under the same conditions, and the simulation analysis will be done to compare their respective resistance through the soil. The speed taken for the result analysis is 4km/h, for both subsoilers, for the same analysis the period with stable resistance is also taken. Given that the speed of the follow-up test is quite close to 4km/h, the resistance of the two subsoilers are obtained and shown in Figure 4-3 and 4-4. Figure 4-3 and 4-4 show that the resistance of the two types of subsoilers climbs over time and reaches a maximum value, then it decreases sharply with the end of the movement. The maximum resistance of bionic subsoiler is smaller than that of the arc subsoiler. The data tell us that the average resistance is 763.04N for bionic subsoiler and 907.41N for the arc type subsoiler, which makes the former 15.91% less than the latter. This indicates that the bionic subsoiler is better as to the resistance reduction design.

5.2.2 Resistance Changes with Different Subsoiler Working Speeds

In order to observe how resistance is changing with the subsoiler’s working speed, when running the preprocessor module, the speeds were loaded as 4 km/h, 4.5 km/h and 5 km/h. All status of the three speeds were analyzed and after the post-processing module, the results were obtained. We took the average values of resistance during the smooth movement and showed them in the following Table 4-2. The Table 4-2 tells us that the resistance of both subsoiler was increased as the working speed was increasing. However, the results also show that with all the three speeds the resistance of the arc subsoiler was greater than that of the bionic subsoiler, which theoretically supported the bionic design.

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Resistance Blocking the Bionic Subsoiler/N</th>
<th>Resistance Blocking the Arc Type Subsoiler/N</th>
<th>Rate of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>763.04</td>
<td>907.41</td>
<td>15.91</td>
</tr>
<tr>
<td>4.5</td>
<td>857.45</td>
<td>950.58</td>
<td>9.79</td>
</tr>
<tr>
<td>5</td>
<td>909.17</td>
<td>1101.17</td>
<td>17.43</td>
</tr>
</tbody>
</table>

The EDEM software was used to build the subsoiler-soil model, set the contact model and select the parameters, based on which the simulation analysis of subsoiler movement through the soil was completed. We have done comparative analysis on the average resistance of the two types of subsoilers during the simulation, and the results showed that the bionic subsoiler fought against 15.91% less of resistance than the arc type. Finally, on the basis of the above analysis, the simulations were run with three different working speeds, during which the influence from the working speed on the resistance was observed.

6 CONCLUSIONS

(1) Analyzing and modeling of the main working parts of subsoiling soil preparation machine, namely, the arc type subsoiler. The bionic contour curve of the claw of the house mouse was introduced to the design of the section of the arc type subsoiler. According to the optimization theory, a bionic subsoiler was designed in this paper.
(2) Finite element statics analysis was carried out for the shafts of bionic subsoiler and the arc type subsoiler. Through analysis, the maximum deformation of the shaft of bionic subsoiler is $1.35 \times 10^{-3}$ mm, and the maximum stress is 4.49 MPa. The maximum deformation of the shaft of the arc type subsoiler is $1.63 \times 10^{-3}$ mm, and the maximum stress is 7.96 MPa, which is slightly larger than that of the bionic subsoiler.

(3) Considering the traction resistance of bionic subsoiler and arc type subsoiler in the working process, simulation analysis was carried out under the same condition (certain tillage depth, operating speed), and the average working resistance of the bionic subsoiler is obtained by postprocessing, which is 763.04 N. The average resistance of arc type subsoiler is 907.41 N. The results show that the bionic subsoiler can reduce the resistance by 15.91%. According to comparison, the traction resistance is proportional to the increase of the speed.

7 REFERENCES

► Chen, K. (2010). The present situation and prospect of the research on the shovels in China and abroad. Agriculture and Technology, 30(3), 30-34.