Research on Simulation Analysis of Soil Cutting Process by Ditcher

Zihan Zhang¹, Yuepeng Song¹*, Longlong Ren¹,²*, Hongmei Zhang¹

¹College of Mechanical and Electronic Engineering, Shandong Agricultural University, Tai’an, 271018, Shandong, China
²Institute of Vibration, Shock and Noise, State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai, 200240, China

*Corresponding author: uptonsong@163.com, renlonglong@sdau.edu.cn

Abstract. Ditching and fertilizing is the important components of the orchard working. In order to achieve modern agricultural requirements for energy saving and drag reduction, the mechanism of ditching blade on soil during soil cutting process was studied, and the tool structure and parameters were optimized. This paper numerically simulated the soil cutting process of disc type ditcher blade based on SPH method by ANSYS /LS-DYNA. Simulation result showed that the SPH method can directly simulate the whole process of cutting the soil with the ditch cutter. The maximum Von Mises stress and cutting force are 4 MPa and 350N. The Von Mises stress of soil and cutting force had small fluctuation, so that the cutting is stable. The power consumption was approximately 0.35 kW at steady state, and the cutting consumption obtained by theoretical analysis is similar to the simulation result. By theoretical analysis, the viability of SPH method on simulating the soil cutting process of disc type ditcher blade was verified.

1. Introduction
At present, the disc type ditcher has been applied to the orchard trenching and fertilizing work due to its advantages of uniform ditching and good reliability. But owing to the lack of research on soil cutting process of the disc ditcher theoretical analysis, problems such as high power consumption and low efficiency had appear in the actual application[1-5]. The design and research of agricultural machinery mainly adopts the field test method currently. This method is intuitive and reliable, but it is limited by many factors such as test land, equipment, season, weather and agricultural time[6-9]. In recent years, Many scholars have used the method of finite element analysis especially smooth particle fluid dynamics (SPH) method to study the interaction between agricultural machinery and soil[9-11]. Lu Caiyun et al. verified the viability of SPH method on simulating the soil cutting process of plane blade implement. Simulation result showed the of cutting stability during soil cutting process and the simulation error was not more than 0.05 compared with theoretical analysis and experiment[12]. Kang Jianming et al. investigate the general rule of soil conditions and working parameters on power consumption of disc type ditcher[13]. They concluded that soil firmness, rotation speed of cutting disk and ditching depth had a larger effect on power consumption and verified the conclusion through the soil trough test.

Numerous studies have fully proved that SPH has great advantages in dealing with soil cutting. However, at present, the research on the process of cutting the soil is limited to the ditching process.
There is a gap between the actual working statuses, ignoring the process of the ditching blade into the soil.

Based on this, this paper numerically simulated the soil cutting process of disc type ditcher, which include process of the ditching blade into the soil and ditching process, based on SPH method by ANSYS/LS_DYNA software. So as to verified the viability of SPH method on simulating the soil cutting process of disc type ditcher blade thorough the analysis of Von Mises stress, cutting force and power consumption and provide simulation model of soil cutting process.

2. Ditching blade and soil model establishment

2.1. Disc type ditcher finite element model

The structure of the Disc type ditcher is complicated. Therefore the model was built in Solidworks software imported into the ANSYA software. In order to shorten the simulation time and maintain the accuracy of the simulation, the secondary parts of the disc type ditcher are simplified.

The element type and material model disc type ditcher model is SOLID 164 and Rigid. The material is defined as 65Mn, the material has a modulus of elasticity of \(2.07 \times 10^{11}\) Pa, a density of \(7850\) kg/m\(^3\), a Poisson's ratio of 0.3. The mesh size is set to 11 mm.

2.2. Soil finite element model

The soil element type defines SOLID164, and the soil material in this paper selects the MAT147 (*MAT_FHWA_SOLI) material model[14]. This model is in actual situation of the soil, and the simulation results are more accurate and credible. The main parameters of the soil material model are shown in Table 1.

| Soil parameter                      | Value       |
|-------------------------------------|-------------|
| RO (mass density / kg\(\cdot\)m\(^{-3}\)) | 2125        |
| SPGRAV (specific gravity of soil)   | 2.78        |
| K (bulk Modulus/Pa)                 | \(31 \times 10^7\) |
| G (shear modulus/Pa)                | \(19.6 \times 10^7\) |

The modeling method of soil is the same as that of the disc type ditcher. The soil model size is 1500x600x600 mm and the mesh size is 10 mm. The material and SPH model of solid are modified in the LS-PREPOST by the K file.

3. Boundary soil of cutting process simulation

The process of cutting the soil comprises two processes: the process of ditching and the process of the ditching blade into the soil. The process of the ditching blade into the soil contain the high-speed rotation \(\omega\) and the velocity of into the soil \((V_z)\), as shown in Fig. 1a. And the process of ditching contain the high-speed rotation \(\omega\) and the velocity of ditching \((V_x)\), as shown in Figure, 1b.

According to the cutting theory and preliminary design of the ditcher, the rotation speed is defined as 12 rad/s, \(V_z\) is 550 mm/s and \(V_x\) is 350 mm/s in the simulation. Defining the contact mode between the ditcher blade and the soil, static coefficient of friction and dynamic coefficient of friction is 0.2
and 0.18. The tone-mm-n-MPa unit system is used to the simulation and set simulation time to 1 s. All parameter such as boundary condition solid material model and SPH soil model are set in LS-PREPOST. The K file is generated and submitted to the LS-DYNA solver for calculation and simulated.

4. Results and analysis

4.1. The Von Mises stress of ditcher blade

Figure 2 shows the Von Mises stress of soil at different times during the process of the ditching blade into the soil. As the ditching blade into the soil, the initial position of the ditching blade is not in contact with the soil (t=0.02 s, showed in Fig. 3a). And then the disc ditcher rotates at \( \omega \) while moving downward at the speed \( V_Z \).

![Figure 2](image)

Figure 2. The Von Mises stress of ditcher blade during the process of blade into the soil

When times=0.05 s, the disc ditcher blade starts to contact with the soil. At this time, maximum Von Mises stress is 0.924 MPa, which appears in the disc ditcher blade bending (Fig.2b). With the movement of blade, the contact with the soil gradually increases. The soil began to be squeezed and sheared by the blade, and the maximum Von Mises stress increased significantly. Finally, solid material failure criteria achieved and the solid is destroyed.

Figure 2d, shows that when the No. 1 blade has not left the soil, the No. 2 blade begins to enter the soil, they complete the cutting of the soil at the same time from 0.09 s to 0.11 s. It can be seen that the continuous operation of the cutting of the soil is better, and the cutting process is relatively stable.

![Figure 3](image)

Figure 3. The Von Mises stress of ditcher blade during the ditching process

Figure 3 is the Von Mises stress of ditcher blade during the ditching process. As can be seen from Fig. 3a, the maximum Von Mises stress of the soil appears in the disc ditcher blade bending. The
maximum Von Mises stress of the soil is mostly concentrated in 1~1.7 MPa in the whole process of trenching, which shows that the Von Mises stress fluctuation of the soil is small, and the cutting process is relatively stable.

There are at least two blades cutting solid during the ditching process. In addition, the ditch depth can be stabilized at about 25 cm. It can be seen that the blade has better continuity and stability during the process of cutting solid.

4.2. Cutting force during the process of cutting solid

Figure 4 shows the change of cutting resistance with time in the process of cutting the soil with disc ditcher. It can be clearly seen from the figure that the cutting force gradually increases and tends to be stable over time. The disc ditcher has not been in contact with the soil, from 0~0.04 s. During this time, the cutting resistance is 0. During 0.04~0.4 s, disc ditcher enters the soil and the contact area between the disc ditcher and the soil gradually increases. The maximum cutting force is about 500 N.

![Figure 4. Cutting force during the ditching process](image)

When times is 0.4~1 s, the disc ditcher is continuously move into the soil and leaving the soil, so the cutting force fluctuates within the range of 300 to 500 N and stable at around 350 N.

4.3. Power consumption during the process of cutting solid

The total energy consumption during the process of cutting the soil mainly includes two part: the kinetic energy by disc ditcher and the internal energy of the disc ditcher cutting solid. Figure 5(a) is a the total energy consumption of the process of cutting solid, and Figure 5(b) is the internal energy of cutting solid.

![Figure 5. The energy consumption during the process of cutting the soil](image)

As shown in Figure 5(a), when the disc ditcher begins to rotate (0~0.001 s), the kinetic energy of the disc ditcher increases linearly tends to be stable. During this process (t=0~0.04 s), the disc ditcher blade does not contact with the soil, and the internal energy is 0. After 0.04 s, the disc ditcher blade began to connect with the soil, the area of contact by disc ditcher blade and the soil gradually increases with time, so that the internal increases continuously. Obviously, the increase rate of process into the soil is higher than ditching process.
Figure 6. The power consumption during the process of cutting the soil

The power consumption is shown in Fig. 6. In \( t=0-0.04 \) s, there are no power consumption occurs. \( T=0.04-0.4 \) s, the contact area between the disc ditcher and the soil increases. Therefore, the power consumption increases remarkably. About \( t=0.2-0.3 \) s, mainly two blades are in contact with the soil, so the power consumption decreases slightly. After \( t=0.4 \) s, the disc ditcher is continuously move into the soil and leaving the soil, so the power consumption fluctuates around 0.35 kW, this regular also as shown in Fig. 4.

4.4. Theoretical analysis of power consumption

The simulation results are verified by empirical formulas of power consumption in the agricultural machinery design manual. The power consumption can refer to equation (1).

\[
P = 1 \times 10^{-5} K_\lambda \cdot h \cdot \nu \cdot B
\]

Where \( K_\lambda \) is the ditch resistance ratio in N/cm\(^2\), \( K_\lambda = K_g K_1 K_2 K_3 K_4 \), \( K_g \) is soil firmness in N/cm\(^2\); \( K_1 \) is the groove depth correction coefficient, \( K_2 \) is the soil water content correction coefficient, \( K_3 \) is the branch Dry leaf vegetation correction coefficient; \( K_4 \) is the operation mode correction coefficient, \( h \) is the ditch depth in mm; \( \nu \) is the speed in m/s, \( B \) is the ditch width in mm.

According to the simulation, \( h=250 \) mm, \( \nu=350 \) mm/s, \( B=100 \) mm. And based on the agricultural machinery manual and related literature, \( K_g=12 \) N/cm\(^2\), \( K_1=0.95, K_2=0.9, K_3=0.9, K_4=0.48 \). The power consumption \( P = 0.38 \) kW through calculations.

From the above results, it can be concluded that values of the empirical formula are agree well with that of simulation results.

5. Conclusion

This paper simulated the soil cutting process of disc type ditcher blade based on SPH method by ANSYS/LS_DYNA. From simulation results and theoretical analysis, the following conclusions can be drawn. The continuous operation of the cutting of the soil is better, and the cutting process is relatively stable. The ditch depth can be stabilized at about 25 cm. And the maximum Von Mises stress of the soil is mostly concentrated in 1~1.7 MPa in the whole process of trenching and appears in the disc ditcher blade bending. During the process of cutting the soil, the cutting force gradually increases and tends to be stable over time. The cutting force gradually increases during the process of blade into the soil. The cutting force fluctuates within the range of 300 to 500 N and stable at around 350N during ditching process. And the maximum cutting force is about 500 N. The power consumption increases remarkably with the contact area between the disc ditcher and the soil. And the power consumption fluctuates around 0.35 kW during ditching process. By theoretical analysis, the viability of SPH method on simulating the soil cutting process of disc type ditcher blade was verified.

Acknowledgments

This work was supported by Funds of national key research and development for 13th year plan (2018YFD0700604, 2016YFD0701701), Innovation team fund for fruit industry of modern agricultural technology system in Shandong Province (SDAIT-06-12, SDAIT-06-1), Research project-2017 on intelligent agricultural mechanization equipment of Shandong Province(2017YF003) and Funds of Shandong “Double Tops” programs (SYL2017XTTD07), State Key Laboratory of
Mechanical System and Vibration (Grant No. MSV202002), Open Fund of Defense Key Disciplines Laboratory of Ship Equipment Noise and Vibration Control Technology (VSN201801).

References

[1] Salokhe V M and Ramalingam N 2002 Effect of rotation direction of a rotary tiller on draft and power requirements in a Bangkok clay soil Journal of Terramechanics 39 195-205

[2] Li M, Chen D, Zhang S and Tong J 2013 Biomimetic design of a stubble-cutting disc using finite element analysis Journal of Bionic Engineering 10 118-127

[3] Tong J, Moayad B Z, Ma Y H, Sun J Y, Chen D H, Jia H L and Ren L Q 2009 Effects of biomimetic surface designs on furrow opener performance Journal of Bionic Engineering 6 280–289.

[4] Fiaz A, Ding W, Ding Q, Mubshar H, Khawar J, and Rita G 2015 Forces and straw cutting performance of double disc furrow opener in no-till paddy soil Pls One 10 19648

[5] Karmakar S, Kushwaha R L and Lagu C 2007 Numerical modelling of soil stress and pressure distribution on a flat tillage tool using computational fluid dynamics Biosystems Engineering 97 407-414

[6] Gao J and Jin Y 2010 Soil-Cutting Simulation and Test of Oblique Rotary Tiller International Conference on Computer & Computing Technologies in Agriculture 6 140-150

[7] Mingjin Y, Po N, Bin P, Ling Y, Yunwu L, Xiaobing C and Zhuomin P 2015 Soil-cutting performance analysis of a handheld tiller's rotavator by finite element method (fem) INMATEH- Agricultural Engineering 47 13-20

[8] O Ate E and Rojek J 2004 Combination of discrete element and finite element methods for dynamic analysis of geomechanics problems Computer Methods in Applied Mechanics and Engineering 193 27-29

[9] Sonia FernándezMéndez, Bonet J and Huerta A 2005 Continuous blending of SPH with finite elements Computers and Structures 83 1448-1458

[10] Shoutai L, Xiaobing C, Wei C, Shiping Z, Yunwu L, Ling Y, Shouyong X and Mingjin Y 2018 Soil-cutting simulation and parameter optimization of handheld tiller's rotary blade by Smoothed Particle Hydrodynamics modelling and Taguchi method Journal of Cleaner Production 179 55-62.

[11] Jiang Z Xian Z, Jian Dong J and Zhang Feng Z 2012 Analysis of 3-D Numerical Simulation for Soil Cutting by Small Agricultural Machinery Advanced Materials Research 433 6182-6189

[12] Caiyun L, Jin H, Hongwen L, Qingjie W, Zhiqi Z and Xiangcai Z 2014 Simulation of soil cutting process by plane blade based on sph method Transactions of the Chinese Society for Agricultural Machinery 45 134-139

[13] Kang J, Li S, Yang X, Liu L and Liu X 2017 Design and experiment of ditching blade installed in close planting orchard ditching machinery Transactions of the Chinese Society for Agricultural Machinery 48 68-74

[14] Lewis B 2004 Manual for LS-DYNA Soil Material Model 147. Georgetown Turner- Fairbank Highway Research Center 5 256-280