Soil-cutting Simulation and Test of Oblique Rotary Tiller

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Abstract: A virtual prototype of oblique rotary tilling based on SPH(Smooth Particle Hydrodynamics) was developed. Digital simulation and field test of oblique rotary tilling were conducted. The digital simulation suggested that soil mainly was torn to failure during oblique rotary tilling. Therefore, oblique rotary tilling could save energy. The given power consumption comparison of digital simulation and indoors test verified the virtual prototype .The optimization value of oblique angle and phase angle was given when rotary velocity equals 200rpm and working velocity equals 0.4m/s based on simulation. By simulating throwing soil during rotary tilling, the result suggested that the velocity of soil thrown was not uniform but lean to tangent blade's direction. This simulation result should be taken into consideration while designing oblique rotary tiller. Furrow bottom shape was figured out by simulating, too. The convex height was about 9.6% of tilling depth. All of the research result suggested that oblique rotary tilling might be a very potential tilling method which could save tilling energy greatly.

Keywords: oblique rotary tilling; simulation; SPH; specified power consumption; throwing soil

1 Preface

In the oblique rotary tillage, there was a sub-movement which made edge of the sub-exercise to apply force to the soil along the axis in the lateral when rotary blade was around the axis of rotation.

If the soil in the certain width direction along with the lateral force completely or partially lifted constraints (had been cultivated), then lateral edge of a lateral tear of the role of the soil causing more soil would be broken due to tension. From this perspective, oblique rotary tillage may reduce energy consumption, coupled with a better performance off the grass, it may be a promising new cultivation. The structure of cultivated soil was complex and very different in time and space and the movement of oblique rotary blade was more complex, so it was difficult to quantitative study of soil oblique rotary tilling mechanism by physical prototype testing of soil causing great difficulties in the development of the relevant equipment.

2 The Research of Oblique Rotary Virtual Prototyping System

The soil, nonlinear material, was damaged in high-speed collision was involved in this process of oblique rotary tilling. Soil high-speed cutting process has been an important and difficult problem with the method computer simulation in the study of tillage mechanics. Because this involves cultivated soil which is multi-phase, loose and scattered in the working parts of soil failure under high speed and describes the state of soil movement after the destruction process. Theory of continuous physical and numerical solution (finite element method or boundary element method) are difficult to describe the process(such as finite element method for large deformation conditions mesh distortion occurs, leading to failure calculated).Therefore, traditional numerical simulation methods based on the continuous mechanics could not do high-speed cutting mechanism of the soil.

SPH (smoothed particle hydrodynamics) is without grid and no mesh distortion problems, so it could be dealt with under the Lagrange large deformation. Meanwhile, the method of SPH permits material interface, so you could simply and accurately get the complex constitutive behavior and the method of SPH also applies to materials at high loading rates of fracture and other issues.

SPH does not use discrete units, but use a fixed point of the movable mass particles or nodes. The quality is fixed on the particle's coordinate system, so that discretization is closer to the physical properties of cultivated soil. SPH do not use mesh and do not have mesh distortion problems, so it could be accurately described the object as well as destruction of nonlinear large deformation process. Hence, SPH is very suitable for the dynamic description of the process of farming.

By the basic equation of dynamic, we could get the acceleration of Lagrange particle volume of soil under stress.

$$\frac{d\dot{u}^{\alpha}}{dt} = -\frac{\partial}{\partial x^{\beta}}\left(\frac{\sigma^{\alpha\beta}}{\rho}\right) - \frac{\sigma^{\alpha\beta}}{\rho^{2}}\frac{\partial \rho}{\partial x^{\beta}} \tag{1}$$

In the formula: ρ is a relevant variable for the density, $\dot{u}^{\alpha}$ is velocity vector and $\sigma^{\alpha\beta}$ is stress tensor. The spatial coordinates x^{β} and time t were the independent variables. The acceleration of point x could be estimated by the formula (1) and the neighboring information. SPH's weight function w was multiplied on the right of the formula (1) and the result was integral in the domain of whole space.

$$\frac{d\dot{u}^{\alpha}}{dt} = -\frac{\partial}{\partial x^{\beta}}\int w\frac{\sigma^{\alpha\beta}(x')}{\rho(x')}dx' - \frac{\sigma^{\alpha\beta}(x)}{\rho(x)}\frac{\partial}{\partial x^{\beta}}\int w\rho(x')dx' \tag{2}$$

If the adjacent information was only valid in the discrete point j and the volume element was shown by $\frac{m_j}{\rho_j}$, then formula (2) could be got by formula (3).

$$\frac{d\dot{u}_i}{dt} = -\frac{\partial}{\partial x_i^{\beta}} \sum_j m_j \frac{\sigma_j^{\alpha\beta}}{\rho_j^2} w_{ij} - \frac{\sigma_j^{\alpha\beta}}{\rho_j} \frac{\partial}{\partial x_i^{\beta}} \sum m_j w_{ij} \tag{3}$$

A simple soil and crushable foam model was advanced by Krieg in 1972.If the yield stress was too low, this model feature was close to the fluid.

According to equation (3), combined with the pressure - volume deformation relationship, it's easy to calculate the force between soil particles.

Because this test was mainly carried out in indoor soil, SPH model of the soil was established according to indoor soil tank model.

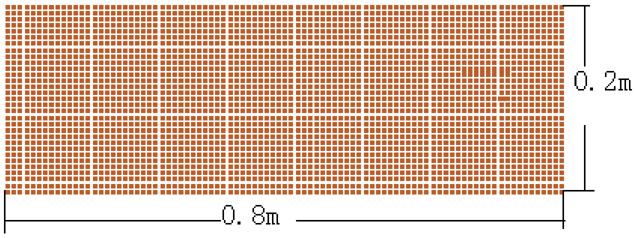

Fig.1. Saltus curve the SPH model of soil

In this paper, soil and crushable foam model is as a soil model. The mechanical model about the tool contacting with soil was shown in Figure 2.Virtual prototyping system of oblique rotary was developed was shown in Figure 3. Rotary blade shaft was consists of three cutter head and each cutter head install two rotary cutter blade, so a total of six rotary blade was installed on the cutter shaft. Variables contains tillage depth, oblique angle, phase angle could be controlled in virtual prototyping system.

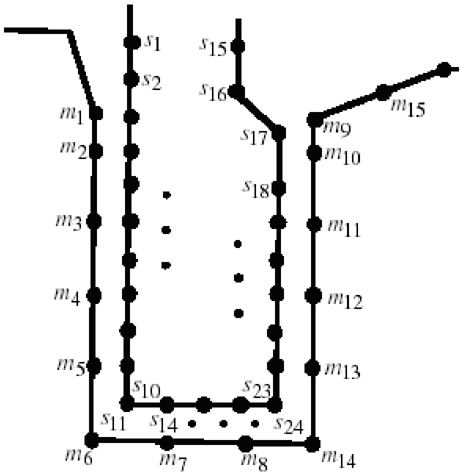

Fig. 2. Saltus curve the contact mechanical model between soil and cutter

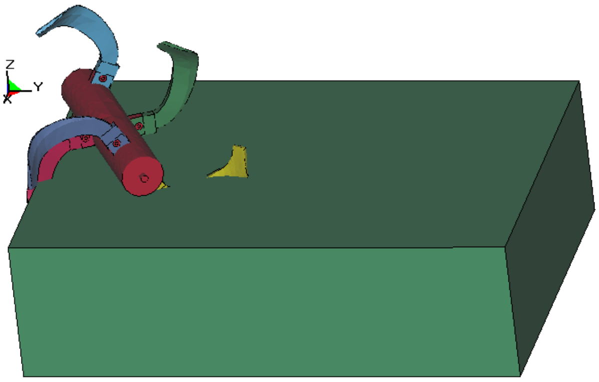

Fig. 3. Virtual Prototype of oblique rotary tilling

3 Numerical Simulation about the Process of Oblique Rotary Tilling Soil

Because the structure of soil which has time and space diversity is extremely complex, it is difficult to observe the process of cutting soil by Oblique rotary in the physical prototype test. The numerical simulation could accurately describe the damage process of cutting soil by Oblique rotary and the force of machine, and then the mechanism of Oblique rotary tilling soil could be revealed.

3.1 The Research on Lateral Tear of Soil

Tillage machinery approach to design was best "destroyed pull" and followed by "destroyed by cutting" and avoided "was destroyed by pressure" as far as possible to reduce energy consumption and improve the economy. In Oblique rotary, the soil was torn lateral that was possible main reason for oblique rotary saving energy. Through the physical prototype of lateral tear of the lateral edge effects on soil was more difficult, but the numerical simulation could be more clearly reveal the process. The particle of soil no.166,544 which was to be cutting by the rotary blade was selected (Figure 4) .The coordinates of x, y, z were 0.045, 0.226, -0.05 and unit forward speed was 0.5m / s and rotate speed was 200 rpm,then the acceleration in X direction was shown in Figure 5.

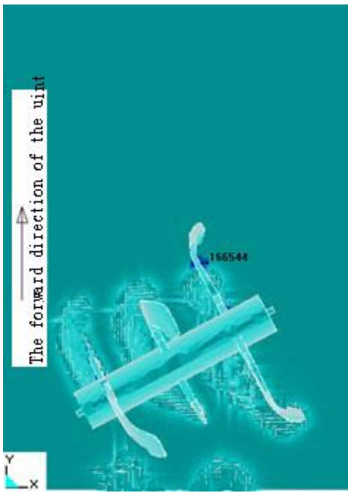

Fig. 4. The location of soil element no.166544

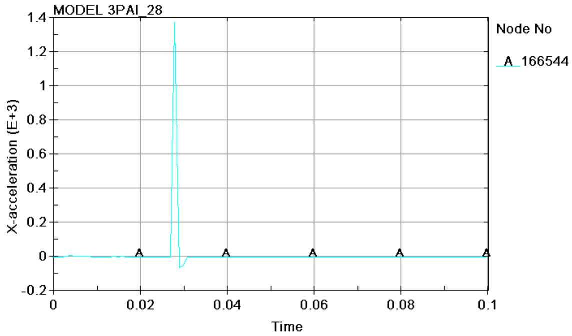

Fig. 5. The acceleration of soil element no.166544

Soil particle no.166,544 generated acceleration of 1370m/s^2 in the X positive, that was to say, the lateral movement of rotary blade torn soil along the positive of X when rotary blade was cutting soil in the soil near the particle no.166,544. Because the rotary cutter blade lateral torn the lateral effect to the soil, the soil was destroyed by “pull" was verified from the perspective of numerical simulation. From this perspective, oblique rotary tillage could greatly reduce energy consumption.

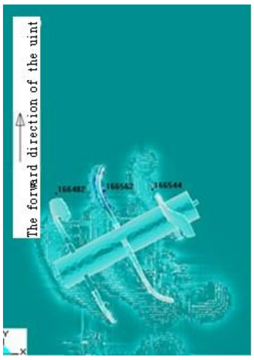

Fig. 6. The location of soil element no.166562

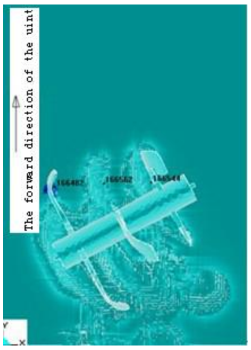

Fig. 7. The location of soil element no.166482

The soil particles no.166562 (Figure 6) and no.166482 (Figure 7) which were near the two other lateral edge cutters were chosen. Soil particles no.166,562, and no.166,482 had the same coordinates of the no.166 544 in Y, Z directions and its acceleration in X direction was shown in Figure 8.

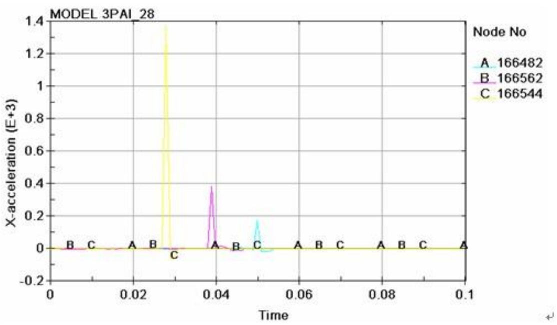

Fig. 8. The acceleration of soil element no.166544, 166562,166482

It could be seen from Figure 8:

Soil particles no.166544, no.166562, and no.166482 all had a instantaneous acceleration in the same direction which was along lateral edge of the direction of lateral movement indicating that the soil near the three cutter disc cutter were destroyed by the lateral movement of soil caused by tearing.

Soil particles no.166544, no.166562, and no.166482 of the coordinate of Y were consistent, but the failure time was not the same. This was because the tool axis was inclined to make that the soil produced ordered cut.

The tensile strength of soil particles no.166544, no.166562, no.166,482 reduced in correct order. This is because the tool axis was inclined, cutter head near soil particles no.166544, no.166562 and no.166482 cut soil in proper order to make the follow-up sword plate achieve all or part of the unconfined cut. From the literature, we could get that, unconfined soil strength is much smaller than confined soil strength. The cutter head near the soil particles no.166,544 first cut soil was confined soil cutting, so the tensile strength of it was more larger than the other two cutter heads. On the contrary point of view from the numerical simulation, the correctness of the theory of the side of the limit on soil strength which was introduced in the literature 4 was proved.

3.2 The Research of Specified Power Consumption

The specified power consumption was important parameter to measure the performance of a rotavator. To the oblique rotary tiller, the computing formula of specified power consumption is:

$$N_s = \frac{N}{(B\cos\alpha + 2R\sin\alpha)Av_m} \tag{4}$$

In the formula (4): N- output (N.m) B- width (cm) α- Oblique angle (°) R-Rolling radius of the blade. In the Figure 9,connection in specified power consumption, phase angle and oblique angle were obtained through laboratory test when the rotational speed was n = 200rpm and V = 0.4m / s.

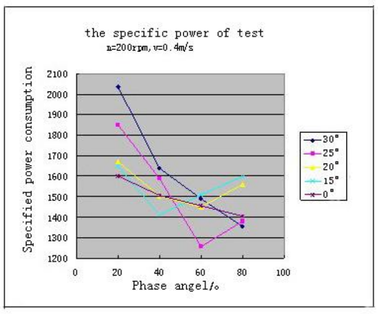

Fig.9. The specific power of test

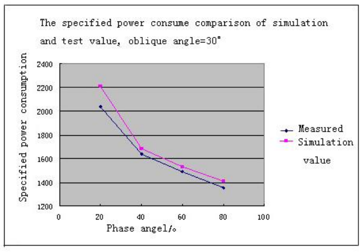

Fig.10. The specified power consume comparison of simulation and test value, oblique angle=30°

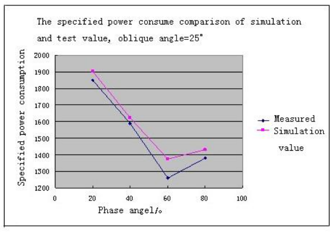

Fig.11. The specified power consume comparison of simulation and test value, oblique angle=25°

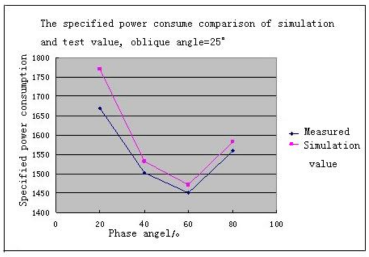

Fig.12. The specified power consume comparison of simulation and test value, oblique angle=15°

Figure 10, Figure 11 and Figure 12 showed the contrast between measured value and simulated values at different oblique angle and phase angle when the rotational speed was n = 200rpm and V = 0.4m / s.

It could be seen from these figures:

Measured and simulated values were basically the same and the maximum relative prediction error is 6% indicating that the accuracy of the virtual prototype system could meet the analysis requirements.

Whether actual or simulated results showed that when the phase angle was 60° and oblique angle was 25°, the specified power consumption was minimum when speed was n = 200rpm and V = 0.4m / s. It could be used as design reference designing oblique rotary tiller.

3.3 The Analysis of Oblique Rotary Tillage Throwing Soil and the Shape of the Ditch after Plow

Throwing soil simulation image was shown in Figure 13 when unit forward speed was 0.5m / s and oblique angle was 25°and rotate speed was 200 rpm and deep tillage was 25 cm. By the statistics of thrown SPH soil particles, the sub-speed X of 93.4% of the thrown soil particles were greater than zero. That was the same as the lateral edge of the axial speed indicating that the velocity of soil thrown was not uniform but lean to tangent blade's direction by simulating throwing soil. We should fully consider the factors when design shell oblique rotary equipment. The shape of ditch after plowing was shown in Figure 14.

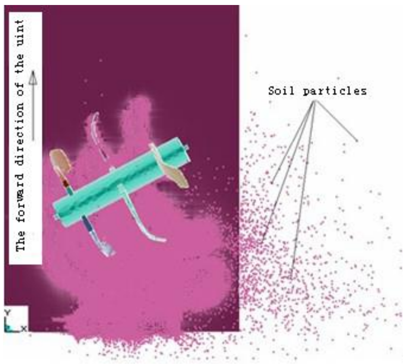

Fig.13. Throwing Soil simulation of oblique rotary tilling

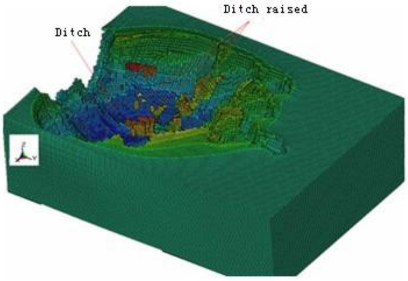

Fig.14. Furrow bottom shape

As could be seen from Figure 14: when forward speed of the unit was 0.5m / s and oblique angle was 25°and rotate speed was 200 rpm and deep tillage was 25 cm, the maximum raised height was 2.4 cm which was 9.6% of the tillage depth and it was accounting for 7.1% of the whole ditch area indicating that after oblique rotary ditch was basic level could meet the farming requirements.

Conclusion:

Through this study, we could obtain the following conclusions:

The result of digital simulation indicates that soil mainly was torn to be destroyed during oblique rotary tilling. The failure modes made more soil "destroyed pull" significant savings in energy work. This could also explain the phenomenon that oblique rotary tilling soil was easier in testing process.

The correctness of the simulation system was verified by the comparison of the test of oblique rotary tilling in specified power consumption between indoor and numerical simulation. At the same time, the best oblique angle and the optimum phase angle was given when the speed was n = 200rpm and V = 0.4m / s.

By simulating throwing soil, the velocity of soil thrown was not uniform but lean to tangent blade's direction. We should fully consider the factors when design shell oblique rotary equipment.

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