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Design and Testing of the Main Structure of a Deep Application Machine for Powder Organic Fertilizers

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Abstract

In order to address the problems of soil crusting and the lack of soil fertility produced by long-term planting of tobacco, an operation device integrated the functions of deep loosening, fertilizer application, and riding was proposed in this study. The agronomic requirements of tobacco planting and the ecological benefits of organic fertilizers and other advantages were considered during the design of the device. The device was consisted of the frame, deep loosening fertilizer shovel, and ridging part. ANSYS software was used to establish the finite element model of the frame and deep loosening fertilizer shovel, and the modal simulation experiment was conducted. Results show that, under the torsion and braking interaction, the stress change of the Frame is not obvious, and the stress of the shovel tip is mainly concentrated on the combination of shovel handle and shovel body, with the stress change of other areas being insignificant. The modal analysis of the Frame shows that its resonance frequency is 61.138 Hz, and the error rate between the modal simulation and the modal test is less than 10%, which verified the feasibility of the structural design. The results of this study provide technical references for the structural design of a device for improving deep soil characteristics.

Keywords: Soil nodulation, Deep pine fertilization, Finite element analysis, Light weight, Prototype development

1. Introduction

Since the 1980s, the development of urbanization and the illegal occupation of arable land have reduced the area of high-quality arable land, and the arable land has gradually shifted to areas with poorer ecological environment [1,2]. High-intensity agricultural cultivation results in a considerable decline in the content of organic matter in the soil. This condition makes the soil thin and hard, which causes its inability to provide sufficient nutrients for the growth of crops. Traditional shallow rotary tillage for surface soil operation leads to the thickening of the subsoil layer of the plough, and the root system of the crop cannot be deeply rooted to obtain nutrients. Year-round rotation of crops leads to the continuous reduction in nutrients in the arable land, which results in a low percentage of organic matter in the soil of only 1.86%. This amount is 50% of the level of the same type of soil in Europe. The insufficient quality of arable land seriously limits the development of agriculture.

Variety in soil fertilization machinery and its wider application play a role in the recovery of soil nutrients on arable land. At present, the mainstream soil fertilization machinery involves the application of fertilizers by spreading on the soil surface. This procedure is followed by deep plowing and turning operations, where the fertilizer is incorporated into the soil to achieve the purpose of soil fertilization. Another method involves deep plowing for furrowing operations, where fertilizers are manually or mechanically placed into furrows to accomplish soil fertilization. The abovementioned fertilization methods do not need consideration of terrain factors, and fertilization operations can be completed through the cooperation of mechanical operations. The mainstream soil fertilization machinery is highly efficient and has a significant cost-effectiveness ratio compared with manual work, especially for farms in the Great Plains. The deep application machine for powder organic fertilizers [3] combines the advantages of mainstream soil fertilizer application machinery, and it considers the operating environment of hilly small-area arable land. It is designed as a complete, multi-functional fertilizer application machinery for deep application of powdered organic fertilizers. Mechanical performance and the effectiveness of powder organic fertilizer are important performance parameters of deep application machinery for powder organic fertilizers. These parameters determine whether the machine can meet the standards for fertilizer application operations. The small land parcels in hilly areas and the thick plowing sublayer enhance the working resistance. Thus, the mechanical performance and working efficiency of the machine are strictly required. Simultaneously, these requirements pose a great challenge to the structural design of the deep application machine for powder organic fertilizers.

Researchers have considerably analyzed the structure of fertilizer application machinery suitable for hilly and mountainous areas [4]. However, most of the related works focused on the fertilizer application machinery for granular fertilizers, and few of them focused on the structure of fertilizer application machinery for powder organic fertilizers [5]. Moreover, given the widespread use of powder organic fertilizers in recent years, research on machinery for their applications has decreased. Therefore, designing a mechanical structure that can conduct deep application of powder organic fertilizers and investigating

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the mechanical properties of the structure when subjected to force, as well as the effects of fertilizer application during actual operation, are problems that need to be solved. In this study, a deep application machine for powder organic fertilizers was designed. The structural design of the machine was verified by investigating the mechanical properties of the Frame and the Deep loosening fertilizer shovel when subjected to force and the intrinsic frequency and vibration type of the Frame. This study can provide references for research on the integration of deep pine fertilizer application.

2. State of the art

In recent years, experts and scholars at the word have conducted considerable research on the structural design of deep pine fertilizer applicator and have achieved certain results. In terms of drag reduction of the deep pine shovel, M. N. Richard et al. [6] established a discrete element model of the soil and set up a bonding key for the discrete element particles to act as cohesive forces between the soil particles. They also studied the horizontal and vertical soil resistance of deep pine shovel at different depths and speeds through simulation. A. K. Atta et al. [7] constructed a discrete element model of the soil and used the hysteresis spring contact model and linear cohesion model as the contact model. In addition, they verified the effects of the rake angle of the furrow opener, the chamfer of the cutting edge of the furrow rake, and the furrow rake shank on the performance of the furrow rake through testing. The accuracy of the test was found to be related to the consistency of the constructed model, and the linear cohesion model was not applicable to soil layers with more serious sloughing. D. L. Larson et al. [8] reduced the resistance by forming a water film on the shovel surface, and the test results showed that the resistance could be reduced by 10%. However, the test was applicable to cultivated lands with high moisture content, and it had no reference value to dry land with low moisture content. Jiang [9] established a mathematical model to calculate the traction and resistance forces on the prediction curve of deep loosening. The mathematical model was practical, but it was mainly used for prediction calculations with insufficient accuracy. Li et al. [10] simulated the tillage of winged and wingless deep loading shovels based on a discrete element model of the soil. They analyzed and obtained the working depth bands and forward tilt angles of each of the two types of deep loading shovels. They derived the tillage resistance of the deep loading shovels at different working depths with distinct forward tilt angles. E. Awuah et al. [11] calculated the optimal set of parameters using response surface experimental design to determine the effects of operating factors of vibratory deep pine shovels on resistance, wear, and tear of deep pine. J. C. Niziolomski et al. [12] investigated the mechanical properties of different types of shovels at varying operating depths and the effect of deep loosening operation based on the soil groove test. However, the modified soil grooves cannot completely simulate the real conditions of plowing and subsoiling on cultivated land. Q. Rashid et al. [13] designed a flexible deep loosening shovel by optimizing the structure of the shovel. The shovel could reduce the amount of soil cohesion by 15.85%, but it was unsuitable for cultivated soils with compacted and hard soils. R. L. Raper et al. [14] found that different shovel blades exhibited varying degrees of resistance to deep loosening, as obtained through the use of a three-dimensional tensiometer and portable tillage profilers. Zhang et al. [15] improved the structure of the deep pine shovel based on the principle of bionics through studying animal paws to reduce its working resistance. However, the main shape of the shovel was based on a chisel shovel, which had a singular function and could not conduct fertilizer operations in deep soil. In the research on the deep pine fertilizer applicator, I. Patuk et al. [16] focused on the fertilizer needs of soybean planting. They used simulation test means, specifically simulating the deep-buried fertilizer applicator through static simulation. This approach involved calculating stress, strain, and displacement. However, their research method was singular, not combined with actual field tests. The accuracy requirements for the model drawing in simulation experiments were high, which led to large errors in the test results. M. Kumar et al. [17] developed a deep pine fertilizer application device that included a V-shaped deep pine shovel and a fertilizer application device attached to the inverted T-shaped furrow opener. However, the design of the device was complex, and its strength was not sufficient to meet the demands of plowing the hard bottom layer of the soil. K. Kathirvel et al. [18] designed a fertilizer applicator for addressing the fertilizer shortage in deep soil. The applicator ensured the guaranteed spreading of organic fertilizers in terms of rate and depth. The effect of fertilizer application was assessed by setting up a control group and comparing parameters such as plant height, rate of bell formation, root length, root spread, root volume, and yield. However, this lacked the ability for deep pine operation.

There has been a great deal of studies on the drag reduction of the deep pine shovel, which was a key component of implements. The research focused on analyzing structural reasonableness and mechanical properties through simulation and soil groove tests. At the same time, research was less on the design of deep pine fertilizer machinery, which was mainly conducted through finite element analysis and field tests. However, experimental research predominantly concentrated on the fertilizer application effect of implements, with less emphasis on the requirements for the ability of deep pine operation. In addition, few implements with good fertilizer application ability and deep pine operation ability are available in the market. Thus, this study was based on finite element analysis [19], modal analysis [20,21], and real field tests to design a multi-functional shovel that can simultaneously conduct deep pine fertilizer application. The study included in-depth mechanical characterization, modal tests, and field tests on the Deep loosening fertilizer shovel and Frame. The aim is to provide references and guidance for the research on the Deep loosening fertilizer shovel.

The remainder of the study is organized as follows. Section III conducts the structural design, finite element modeling, and analysis of the Frame and Deep loosening fertilizer shovel. Section IV performs modal simulation experiments on the Frame through modal simulation tests to compare its intrinsic frequency and vibration pattern. It verifies the structural reasonableness of the design of the Deep loosening fertilizer shovel through field tests. Section V summarizes the entire study and provides the conclusion.

3. Methodology

ANSYS Workbench, which is a finite element analysis software developed by the U.S. company ANSYS, is widely applied in mechanical design, the automotive industry, electronic technology, and many other industries. The software is simple to operate and can be set according to the working environment of the machine related to the simulation of computer work results. It is widely utilized as computer aided engineering software. This software can import models from other software, set material parameters in the preprocessing tasks of the software, calibrate model properties and connections in the analysis and calculation model, perform mesh division, and then apply loads and post-processing. In this machine design, the primary focus is on structural static analysis of the Frame and the Deep loosening fertilizer shovel, as well as modal analysis of the Frame.

3.1 Overall structural design and modeling of the deep application machine for powder organic fertilizers

The design of this machine is based on the actual needs of tobacco agriculture planting. It aims to design a multi-functional tobacco planting and fertilizing machine capable of conducting multiple operations in a single working stroke. The Deep loosening fertilizer shovel performs deep pine operation while simultaneously spreading powder organic fertilizer in the deep soil to increase organic matter content in the soil of the tobacco planting area. The device is mainly composed of the Frame, the Deep loosening fertilizer shovel, the precision fertilizer application system, and the ridge operation device.

3.2 Structural design of Deep loosening fertilizer shovel

Machine tools perform deep pine operations simultaneously with deep fertilization operations. Therefore, the shovel body of the Deep loosening fertilizer shovel is designed to be hollow. The front is equipped with a double-wing type shovel design to facilitate deep pine, and the rear section of the shovel body has a wedge-shaped surface design to prevent soil from entering the upper part of the shovel during operation. The lower part of the shovel body has a flat plate closure to prevent the upward extrusion of the soil at the bottom of the shovel body. The size of the fertilizer discharge port matches the maximum width required for fertilizer operations.

3.3 Force analysis of Deep loosening fertilizer shovel

The Deep loosening fertilizer shovel is a key component of the precision deep application machine for powder organic fertilizers. It is mainly composed of the shovel tip, shovel body, and shovel handle. Its tillage resistance is an important source of resistance for the entire machine. The tillage resistance of the Deep loosening fertilizer shovel mainly comes from two parts: one is the soil-breaking resistance of the positive surface of the shovel tip, and the other is the adhesion and friction between the two sides of the shovel body and the soil. The main structure of the force surface is shown in Fig. 1.

The forward resistance of the Deep loosening fertilizer shovel in the soil is calculated using the soil working part resistance model. The total mass of the soil particle on the front surface of the shovel tip is M, F_V denotes the force acting on the shove in vertical direction, and the soil-breaking resistance F_H of the Deep loosening fertilizer shovel mainly comes from two aspects: the soil-breaking resistance F_{H1} on the front surface of the shovel tip and the working resistance F_{H2} on the flank surface of the shovel body. This process is simplified into a two-sided wedge force model according to the force on the front surface of the shovel tip of the Deep loosening fertilizer shovel. The specific force analysis is shown in Fig. 2.

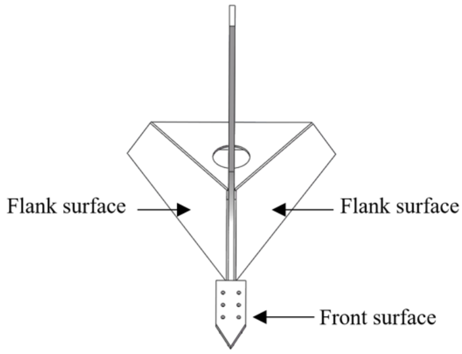


Fig. 1. Illustration of the force surfaces of the Deep loosening fertilizer shovel

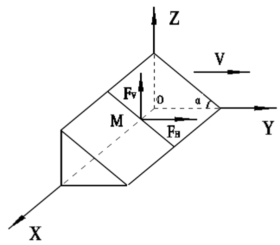


Fig. 2. Two-sided wedge force model on the front surface of Deep loosening fertilizer shovel

The total mass of the soil particle mass point on the front surface of the shovel tip is calibrated to be m1, and the terminal velocity Vt of the soil particle mass point after Δt is proportional to the shovel velocity V, that is, Vt ∝ V. The front surface of the shovel tip is a two-sided wedge when the shovel is used for deep-polishing operation. According to Newton's third law, the horizontal force on the wedge surface of the two-sided wedge by the soil particle mass M is equal in magnitude to F_{H1}. Thus, the horizontal force on the wedge surface by the soil particle mass in a certain time Δt is

$$F_{H1} = \frac{m_1(V_t - V_0)}{\Delta t} \quad (1)$$

In the formula,
V_0—initial velocity of the measured soil particle mass point during its movement;
V_t—end velocity of the measured soil particle mass point after time Δt;
Δt—time required for the movement of the soil particle mass point.

The flank surface side of the Deep loosening fertilizer shovel body is inclined and can be simplified into a three-sided wedge model, as shown in Fig. 3. The calibration of forces on the three-sided wedge model is performed based on the actual force situation, where F_Y denotes part of the forces on the model perpendicular to F_H and F_V.

The shape of the side wing surface of the Deep loosening fertilizer shovel body is similar to that of the biplane shovel, and the three-sided wedge mathematical model and the horizontal direction resistance formula are introduced. According to the actual working condition of the side wing surface of the Deep loosening fertilizer shovel body in the soil, the three-sided wedge model advances along the direction of x-axis in the soil, and the horizontal direction resistance suffered by the side wing surface is obtained as

$$F_{H2} = (N\sin\alpha + N\tan\varphi\cos\alpha)\quad(\sin^2\gamma + \frac{\sin(2\gamma)}{2}\tan\varphi)$$
$$= \frac{m_2(v_t - v_0)}{\Delta t}(\sin^2\gamma + \frac{\sin(2\gamma)}{2}\tan\varphi) \qquad (2)$$

The organization is

$$F_{H2} = \frac{2m_2(v_t - v_0)}{\Delta t}(\sin^2\gamma + \frac{\sin(2\gamma)}{2}\tan\varphi) \qquad (3)$$

In the formula,
N—the positive force on the Deep loosening fertilizer shovel body;
α, β, γ—wedge surface angel between the wedge face and X, Y, Z axis;
φ—the friction angle;
m_2—the total mass of soil particle passing through a single flanking surface of the shovel body in Δt time.

As a result, the force F_H in the forward direction during the operation of the Deep loosening fertilizer shovel is the sum of the forces on the front and flank surfaces:

$$F_H = F_{H1} + F_{H2} \qquad (4)$$

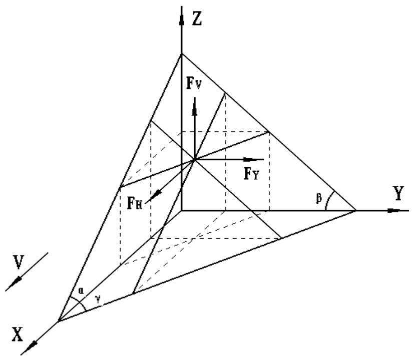
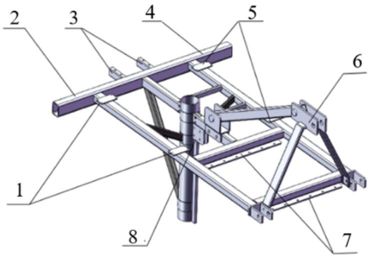


Fig.3. Three-face wedge force model of flank surface of Deep loosening fertilizer shovel tip

3.4 Frame design

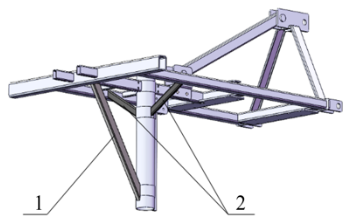
The Frame is the main force structure of the deep application machine for powder organic fertilizers, which is installed with the rotary tiller, fertilizer box, fertilizer pipe, Deep loosening fertilizer shovel, ridging plow, and three-point suspension structure, as shown in Fig. 4 The machine operating Frame mainly bears the upward tension when the three-point suspension is lifted and the downward pressure when it is working. It also supports the gravity of the fertilizer in the fertilizer box, the tillage resistance of the Deep loosening fertilizer shovel, and the torque of the starter plow on the Frame. Referring to the Mechanical Design Manual, under the premise of ensuring structural strength and working stability, and considering the overall lightness and practicality of the entire machine, the main frame of the Frame is finally selected to be made of Q235B rectangular steel with a thickness of 5 mm.



1. Fertilizer tank support fixing point 2. Ridging plow mounting point 3. Motor mounting position 4. Ridging plow mounting point 5. Fertilizer tank support fixing point 6. Three-point suspension point 7. Rotary tiller hanging point 8. Deep loosening fertilizer shovel mounting position
Fig. 4. Stress structure of the Frame

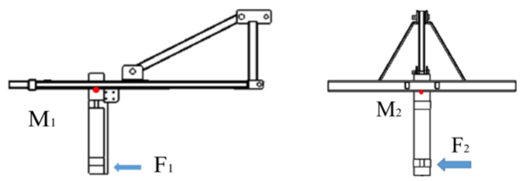
3.5 Design of diagonal braces

The operation of the Deep loosening fertilizer shovel in the deep application machine for power organic fertilizers, which breaks the soil, produces head-on resistance and lateral force. This condition can easily cause damage to the coaxiality of the fertilizer discharge winch and fertilizer pipe, which affects the normal operation of the machine. Thus, a diagonal brace is designed on the Frame, as shown in Fig. 5.



1. Rear diagonal brace 2. Side diagonal brace
Fig. 5. Diagram of diagonal bracing of the Frame

The forces on the fertilizer tube of the machine are shown in Fig. 6.



(a) Schematic diagram of the front force on the fertilizer tube of the Frame
(b) Schematic diagram of the side force on the fertilizer tube of the Frame
Fig. 6. Schematic diagram of the force on the fertilizer tube of the Frame

The connection between the Frame and the fertilizer pipe is taken as the point for force analysis, which needs to be kept in force equilibrium.

$$\begin{cases}\sum F_1 = 0\\ \sum M_1 = 0\end{cases} \qquad (5)$$

$$\begin{cases}\sum F_2 = 0\\ \sum M_2 = 0\end{cases} \qquad (6)$$

In the formula,
M_1—combined moment at force point 1, N/m;
M_2—combined moment at force point 2, N/m.
F_1—combined force at point 1, N;
F_2—combined moment at point 2, N.

Based on the analysis of the front and side forces of the fertilizer pipe, rear and side diagonal braces are designed on the Frame. A rectangular pipe made of Q235B is used to support the Frame behind the fertilizer pipe at an angle of about 60°. Similarly, the side brace and the Frame form an angle of about 30° to enhance the overall structural strength of the Frame.

3.6 Static simulation analysis of the Frame

The three-dimensional geometry of the Frame is transformed into a mathematical model that can be numerically calculated, and the model requires meshing. The cell size is set to 10 mm, the size adjustment transition is set to slow, and the center of the span angle is set to medium to improve the accuracy of the simulation results. The setup generates a total of 489,508 nodes and 118,605 cells. The specific grid division is shown in Fig. 7.

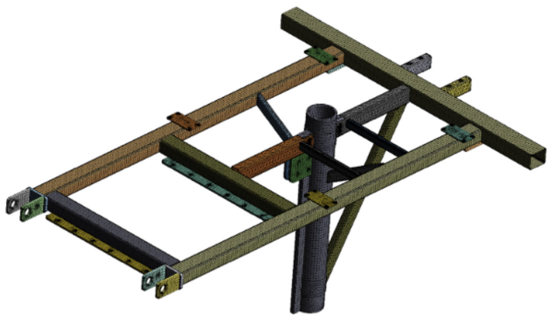


Fig. 7. Meshing of the Frame

The definition of boundary conditions and the application of loads are undertaken. The precision deep application machine for powder organizer fertilizers is connected to the tractor for operation through a three-point suspension device. Fixed constraints are imposed on the lower suspension point of the three-point suspension when defining the boundary conditions. A rotary tiller is mounted on the Frame, which needs the application of downward pressure generated by the rotary tiller operation to the Frame. The weight of the fertilizer tank when operating under full load also needs consideration and application to the Frame. In addition, the force exerted on the Frame by the Deep loosening fertilizer shovel during implement operation needs to be considered. This study comprehensively considers the force acting on the Frame under full working conditions. The frame forces are shown in Fig. 8.

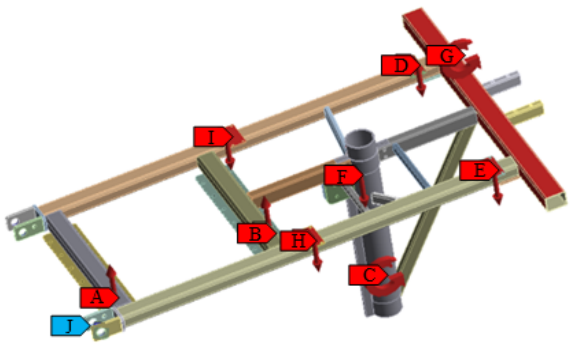


Fig. 8. Frame force diagram

3.7 Analysis of the results of the static simulation of the Frame

The total deformation, equivalent elastic strain, and equivalent stress are inserted into the solution module, and the solution for the calculation of Frame statics is initiated. After simulation calculation, the deformation of the Frame is shown in Fig. 9. The figure shows that the maximum deformation of the Frame is 6.20 mm. The maximum deformation of the Frame occurs at the installation position of the plow, which is subjected to the larger torque generated by the plow during operation. The equivalent elastic strain of the Frame is shown in Fig. 10. The maximum equivalent elastic strain is 6.70×10^{-4} mm/mm, which mainly occurs in the middle and rear Frame connections of the Frame. The equivalent stress cloud diagram of the Frame is shown in Fig. 11. The maximum equivalent stress is 140.44 MPa, which is mainly distributed in the rear half of the Frame where stress is concentrated.

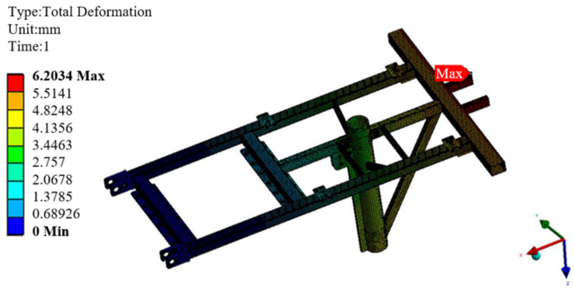


Fig. 9. Total deformation of the Frame

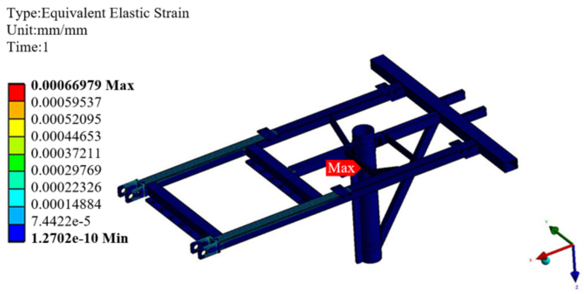


Fig. 10. Equivalent elastic strain of the Frame

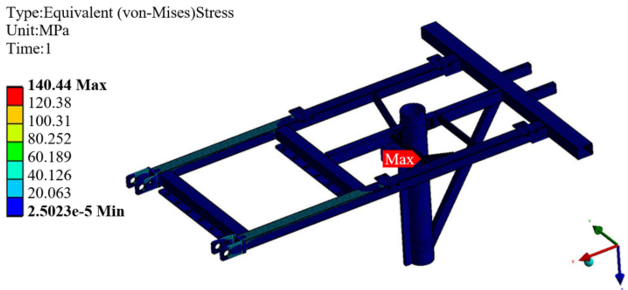


Fig. 11. Equivalent stress of the Frame

The static simulation analysis of the Frame indicates that, under the constraints of the currently given boundary conditions, the total deformation, equivalent elastic strain, and equivalent stress of the Frame of the precision deep application machine for powder organic fertilizers are small. This structure is in line with the design requirements of agricultural machinery.

3.8 Hydrostatic simulation analysis of Deep loosening fertilizer shovel

The three-dimensional geometry of the Deep loosening fertilizer shovel is transformed into a mathematical model that can be numerically calculated, and the model needs to be gridded. With the aim of improving the accuracy of the simulation results, the mesh division setup of the Deep loosening fertilizer shovel generates a total of 798,669 nodes and 368,110 cells. The specific mesh division results are shown in Fig. 12.

Fig. 12. Mesh division of shovel

Again, the definition of boundary conditions and the application of loads are conducted. The shovel handle is fixed to the Frame and the outer wall of the fertilizer pipe during the operation of the Deep loosening fertilizer shovel. Therefore, when defining the boundary conditions, fixed constraints are applied to the upper surface of the shovel handle and the bolting holes. Force constraints are added to the main force parts of the Deep loosening fertilizer shovel to form a force diagram, as shown in Fig. 13.

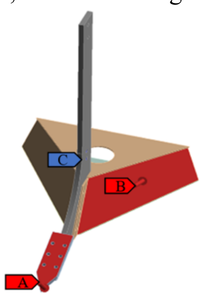


Fig. 13. Force diagram of Deep loosening fertilizer shovel

The Deep loosening fertilizer shovel designed in this study is a multifunctional shovel, which has the functions of deep pine and fertilizer application. In the operating environment of the Deep loosening fertilizer shovel, which is the tobacco planting area cultivated for many years with a thick plough subsoil layer, the shovel is mainly subjected to resistance from the shovel tip to break the soil. This resistance has a large value, which requires the analysis and verification of deformation variables and stresses to ensure alignment with the design requirements of agricultural machinery. ANSYS Workbench finite element analysis software is used to conduct simulation analysis and calculation of the Deep loosening fertilizer shovel. Based on the results of the simulation calculation, optimization and design improvements are applied to the Deep loosening fertilizer shovel.

3.9 Analysis of hydrostatic simulation results of Deep loosening fertilizer shovel

After the boundary conditions of the Deep loosening fertilizer shovel are defined, the total deformation, equivalent elastic strain, and equivalent stress are inserted into the solution module of ANSYS static analysis. The solution is clicked to solve the statics of the Deep loosening fertilizer shovel. The deformation cloud diagram of the Deep loosening fertilizer shovel obtained by analysis and calculation is shown in Fig. 14 The maximum deformation of the Deep loosening fertilizer shovel is mainly concentrated at the tip, with a maximum deformation of 0.19 mm. The equivalent elastic strain cloud diagram of the Deep loosening fertilizer shovel is shown in Fig. 15 The part with the highest equivalent elastic strain is around the bolt holes at the lower end of the handle, with a maximum equivalent elastic strain of 3.12×10^{-4} mm. The equivalent stress distribution in the Deep loosening fertilizer shovel is shown in Fig. 16. The maximum equivalent stress of the Deep loosening fertilizer shovel is 61.83 MPa, and the location of the maximum equivalent stress is around the bolt holes at the lower end of the handle of the Deep loosening fertilizer shovel.

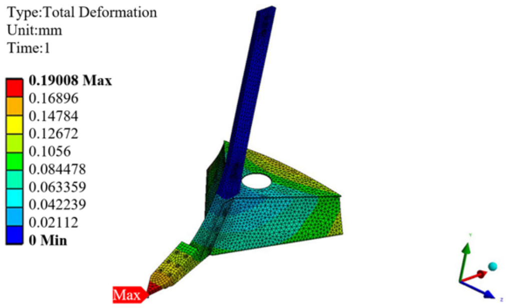


Fig. 14. Total deformation of Deep loosening fertilizer shovel

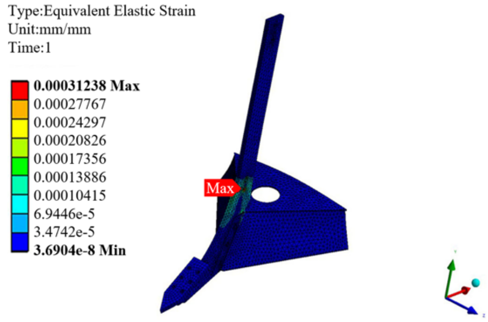


Fig. 15. Equivalent elastic strain of Deep loosening fertilizer shovel

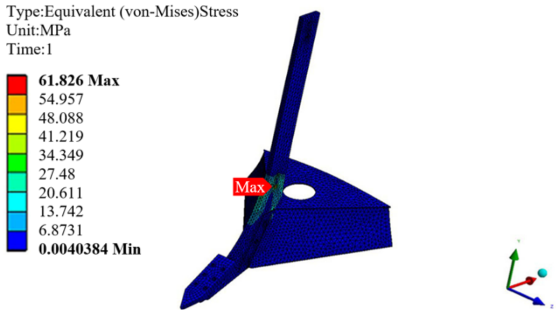


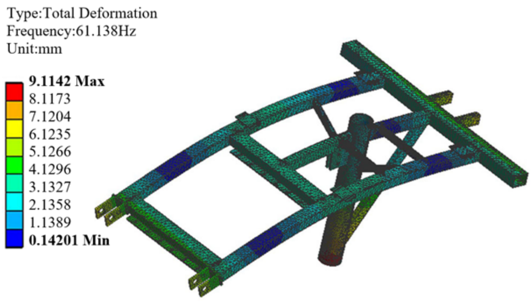
Fig. 16. Equivalent stress of Deep pine fertilization shovel

The results of the static force analysis of the Deep loosening fertilizer shovel show that the values of its shape variable, equivalent elastic strain, and equivalent stress are small. This structure is in line with the design requirements of agricultural machinery. It also provides references for subsequent related design research.

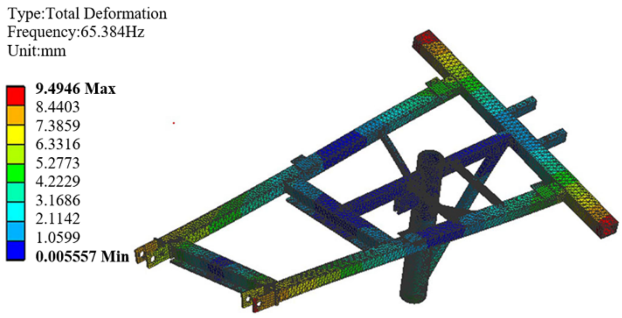
3.10 Modal simulation calculation and analysis of the Frame

The Frame of the precision deep application machine for powder organic fertilizers is superimposed with multiple excitation sources during operation. Moreover, the motion of the Frame during operation is complex and irregular, which causes difficulties in accurately simulating its motion state. Accordingly, a free modal analysis of the Frame is conducted to calculate its intrinsic frequency and vibration pattern.

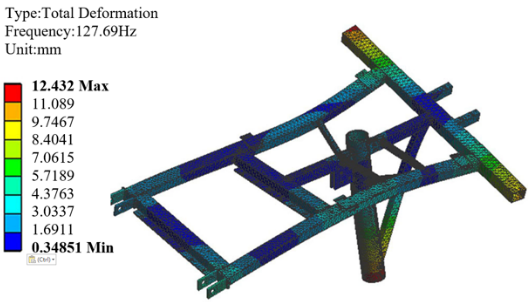
The preprocessing of modal simulation calculation is conducted. The calculation grid size is set to 10 mm, and the maximum modal order is set to 12. Considering that this test analyzes the intrinsic frequency and vibration shapes of the Frame in free mode, only the first six orders of vibration shapes are extracted. The first six orders of vibration shapes are shown in Fig. 17. The results of modal analysis in ANSYS Workbench are shown in Table 1.



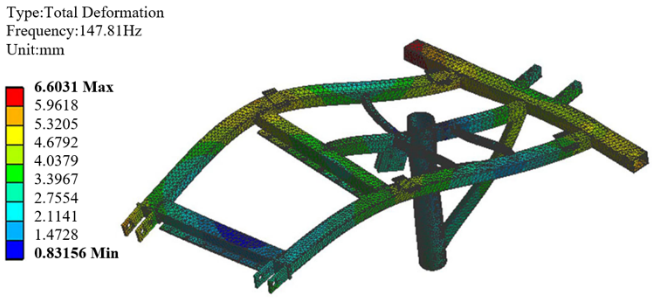
(a) Cloud diagram of first-order mode shapes



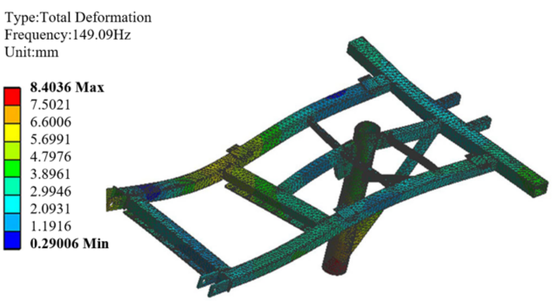
(b) Cloud diagram of second-order mode shapes



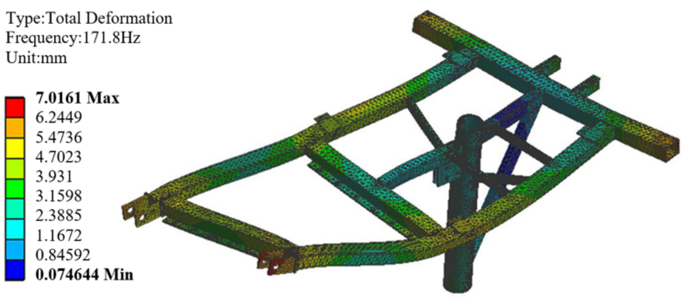
(c) Cloud diagram of third-order mode shapes



(d) Cloud diagram of the fourth-order mode shapes



(e) Cloud diagram of fifth-order mode shapes



(f) Cloud diagram of sixth-order mode shapes

Fig.17. Simulation cloud diagram of the first six-order modal simulation of the Frame

Table 1. Frame modal analysis results

Ordinal number	Frequency (Hz)	Vibration pattern
1	61.138	Vertical bending back and forth in the X direction
2	65.384	Twisting in the Z direction
3	127.69	Torsion in the Z direction and vibration in the Y direction
4	147.81	Torsion in the X direction and vibration in the Y direction
5	149.09	Variation of both sides in the Y direction
6	171.8	Twisting in the Z direction and oscillation along the front and rear rods

Table 1 shows that the resonance frequency of the Frame is higher than 61.138 Hz, and the excitation source of the precision deep application machine for powder organic fertilizers is the supporting rotary tiller. The rotational speed of the rotary tiller is about 190–280 r/min, according to the frequency calculation formula:

$$f_1 = \frac{n_1}{60} \tag{7}$$

In the formula,

f_1 excitation frequency, Hz;

n_1 excitation source rotational speed, r/min;

As obtained by Equation 6, the excitation frequency of the rotary tiller ranges from 3.16 Hz to 4.67 Hz. Therefore, the excitation frequency of the rotary tiller as the excitation source is low, and the resonance frequency of the precision deep application machine for powder organic fertilizers is more than 61.138 Hz, which will not produce resonance phenomenon.

4. Result Analysis and Discussion

4.1 Frame modal test based on Donghua test system

The modal test of the precision deep application machine for powder organic fertilizers was conducted in the Experimental Center of Sichuan Agricultural University. The DHDAS dynamic signal acquisition instrument produced by Jiangsu Donghua Testing Technology Co., Ltd. was used. The instruments required for the test are shown in Table 2.

Table 2. Equipment required for signal acquisition in modal test

Name of test equipment	Remarks
Single electric excitation force hammer	Nominal sensitivity of 2.27 MV/N
IMC three-way acceleration sensor	4 pcs
Data acquisition instrument	1 unit
Notebook computer	1 unit
Modal data analysis software	

The modal test of the Frame of the precision deep application machine for power organic fertilizers adopts the test method of single-point excitation and multi-point vibration pickup. The Frame is suspended using an elastic rope, and sensors arranged on the Frame. Fixed points are tapped with a force hammer, and the frequency information is collected using the Data Acquisition Instrument. Finally, the collected frequency information is analyzed. The field test diagram is shown in Fig. 18.

Fig. 18. Field diagram of the modal test

The modal test correlation of the frame of the precision deep application machine for powder organic fertilizers was analyzed and determined, and the MAC matrix image of the Frame was obtained, as shown in Fig. 19 According to the judgment basis of the MAC matrix image, the values of the vibration modes on the diagonal of this matrix image are 1, and the values on the non-diagonal are much less than 1. Therefore, a correlation exists between the modal vibration modes of the Frame.

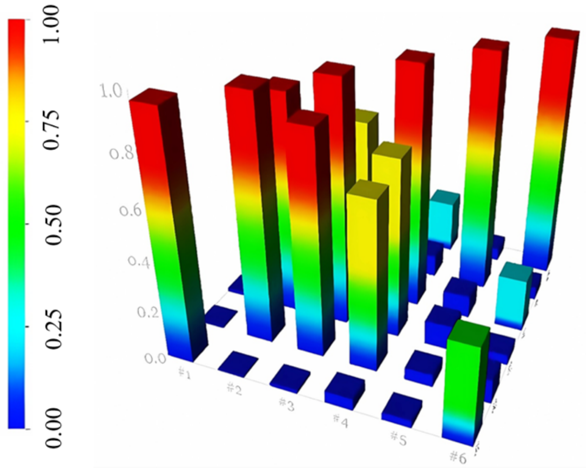


Fig.19. Graph of MAC matrix of the Frame

Comparative analysis of modal test and modal simulation results, as shown in Table 3, indicates that the largest error between the two is the third order, with an error rate of 9.72%, and the smallest is the sixth order, with a minimum error of 0.33%. Notably, the error rate between modal simulation and modal test is less than 10%.

Table 3. Comparison and analysis table between modal simulation and modal test

Ordinal number	Modal Simulation Frequency (Hz)	Modal test frequency (Hz)	Inaccuracy
1	61.138	56.31	8.57%
2	65.384	62.18	5.15%
3	127.69	116.38	9.72%
4	147.81	135.23	9.30%
5	149.09	146.40	1.84%
6	171.8	171.23	0.33%

In summary, the modal simulation results are consistent with the results of the experimental modal. The structure of the Frame is in line with the design requirements of the precision deep application machine for powder organic fertilizers, which will not lead to resonance phenomenon of the machine when working.

4.2 Field trials of machines

Fig.20. On-site operation diagram

The machine was tested in a large field in Huidong County, Liangshan Yi Autonomous Prefecture, Sichuan Province, in early April 2022, as shown in Fig. 20. A 75-hp agricultural tractor was selected for the test to pull the machine and verify the operation of the main functions of the machine, such as deep-polishing and fertilizer application. Considering the operating area and topography of the test area, the test field was divided into two major areas, A and B (area B has a lower terrain), and the plots were divided, as shown in Fig. 21.

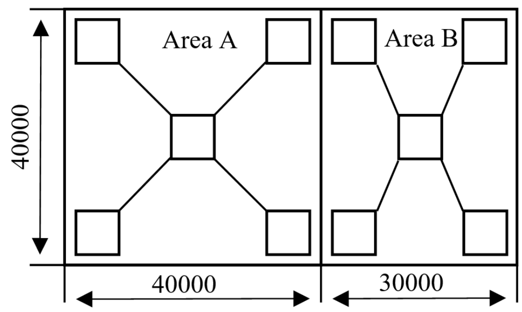


Fig.21. Map of the experimental field delineation

4.3 Experiments on deep loosening of the deep application machine for powder organic fertilizers

Deep pine operation can break the hard plow subsoil layer formed by years of tobacco planting and provide a good soil environment for tobacco planting. Based on the agronomic requirements of tobacco planting, the depth of deep pine of the deep application machine for powder organic fertilizers should be more than 300 mm. According to the sampling method stipulated in GB/T 5262-2008 General Provisions on Measurement Methods for Testing Conditions of Agricultural Machinery, a five-point sampling method was used in the operation area to sample and measure the depth of deep-polishing operation of the machine. According to the division of the operation area, a total of 10 points were considered. The results of the measurements are shown in Table 4.

Table 4. Measurement results of deep pine depth

Group	Measuring point	Deep pine depth measurement results D_1 (mm)	Satisfactory rate P_1(%)
Region A	1	350	100
	2	390	100
	3	410	100
	4	380	100
	5	380	100
Region B	1	370	100
	2	380	100
	3	380	100
	4	350	100
	5	390	100

The formula for the pass rate of deep pine depth is

$$P_1 = \frac{D_1}{300} \quad (8)$$

In the formula, the pass rate is 100% when the deep pine depth equals or exceeds the design requirement value.

The results of deep pine depth measurement shown in Table 4 indicate that, according to the operational requirement of deep pine depth of above 300 mm, the deep pine depth in area A is 350–410 mm, and the deep pine depth in area B is 350–390 mm. The deep pine depth meets the operational technical requirements, and the qualification rate of deep pine operation reaches 100%.

4.4 Fertilizer application test of the deep application machine for powder organic fertilizers

Fertilizer width and depth are important indexes to measure the effect of fertilizer application by the deep application machine for powder organic fertilizers. According to the technical design requirements of the deep application machine for powder organic fertilizers and the agronomic requirements of tobacco planting, when the width of fertilizer application is ⩾300 mm and the depth of fertilizer application is ⩾300 mm, the needs of the tobacco root growth can be met. The requirement on the width and depth of the fertilizer application can maximize the effectiveness of powder organic fertilizers and improve the organic composition in the deep soil. The measurement site map for deep fertilization operations with powder organic fertilizers is shown in Fig. 22.

(a) Fertilizer width measurement (b) Fertilizer depth measurement

Fig.22. Measurement of the effect of fertilizing operations

According to the provisions of GB/T 5262-2008 General Provisions on Measurement Methods for Testing Conditions of Agricultural Machinery, the effect of fertilizer application operations of the deep application machine for powder organic fertilizers was measured using a five-point sampling method in the operation area. A total of 10 data measurement points were sampled and counted according to the division of the operation areas of A and B. The results of fertilizer width measurement are shown in Table 5, and the results of fertilizer depth measurement are shown in Table 6.

Table 5. Fertilizer width measurements

Group	Measuring point	Fertilizer width measurements L_1 (mm)	Satisfactory rate P_2(%)
Region A	1	250	83
	2	230	77
	3	260	87
	4	240	80
	5	240	80
Region B	1	230	77
	2	240	80
	3	250	83
	4	260	87
	5	260	87

Table 6. Fertilizer depth measurements

Group	Measuring point	Fertilizer depth measurement results D_2 (mm)	Satisfactory rate P_3(%)
Region A	1	380	100
	2	410	100
	3	400	100
	4	400	100
	5	390	100
Region B	1	400	100
	2	410	100
	3	380	100
	4	370	100
	5	370	100

The formula for the fertilizer width pass rate is

$$P_2 = \frac{L_1}{300} \quad (9)$$

The formula for the fertilizer depth pass rate is

$$P_3 = \frac{D_2}{300} \quad (10)$$

In the formula, the pass rate is 100% when the width and depth of fertilizer application are equal to or more than the design requirements.

The statistical results of fertilizer width shown in Table 5 indicate that the maximum width of fertilizer application in areas A and B is 260 mm, and the minimum is 230 mm. Approximately 80% of the predetermined width is reached due to the deep soil slumping and extrusion. These phenomena decrease the width of organic fertilizer broadcasting. The statistical results of fertilizer depth shown in Table 6 reveal that the deepest fertilizer depth in area A is 410 mm, and the shallowest is 380 mm. Meanwhile, the deepest fertilizer depth in area B is 410 mm, and the shallowest is 370 mm. The fertilizer depths are all more than the original technical requirements of 300 mm.

5. Conclusion

This study designed an implement that could conduct deep pine, fertilization, and ridging operations in one to consider the mechanical properties of the implement and the operating effect. The finite element analysis method was adopted to analyze the deformation, equivalent stress, and equivalent elastic strain of the Frame and Deep loosening fertilizer shovel. The modal analysis method was used to calculate the intrinsic frequency and vibration mode of the Frame. Modal and field tests were completed to verify the structural design and assess the reasonableness of the design. The structural design and rationality were verified. The following conclusions were obtained through the study:

(1) The cloud diagram of the finite element analysis of the Frame shows that the maximum deformation of the Frame is 6.20 mm, and the maximum deformation of the Deep loosening fertilizer shovel is 0.19 mm. This structure is in line with the requirements for the use of deep pine operation equipment in agricultural machinery.

(2) The maximum equivalent stress of the Frame is 140.44 MPa, and the maximum equivalent stress of the Deep loosening fertilizer shovel is 61.83 MPa.

(3) The maximum equivalent elastic strain of the Frame is 6.70×10^{-4} mm/mm, and the maximum equivalent elastic strain of the Deep loosening fertilizer shovel is 3.12×10^{-4} mm/mm.

(4) The first-order modal test frequency of the Frame is 56.31 Hz, which is much higher than the frequency range of the excitation source of the precision deep application machine for powder organic fertilizers from 3.16 Hz to 4.67 Hz. This frequency will not cause the resonance phenomenon of the Frame.

(5) In the field test, the operating effects of the Deep loosening fertilizer shovel meet the design requirements.

This study combines theoretical calculations and finite element analysis calculations with modal tests and field tests to calculate and design a deep application machine for powder organic fertilizers. The results are compared with the data verification of modal tests and field tests, which have similar data results. The test results verify the reliability of the design and simulation results, which provides an important basis for the use of the deep application machine for powder organic fertilizers. In this study, the model establishment of the Deep loosening fertilizer shovel in the simulation and calculation process is relatively simple. The next step will involve using a higher-performance computer to create a more detailed simulation model. This way ensures that the finite element analysis results are more accurate.

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