Design and Analysis of Strip-Tiller for Conservation Tillage

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Abstract: A strip-tiller was designed for the implementation of conservation tillage less-tillage planting technology for maize and the key components were analyzed statically. The structure and parameters of the strip-tiller were determined through design calculations, and the three-dimensional modeling software was used to carry out static analysis and modal analysis of the tillage components. The results show that the design of the tillage components meets the requirements of strength and stability.

Keywords: Conservation Tillage; Minimum Tillage; Design; Static Analysis

1. Introduction

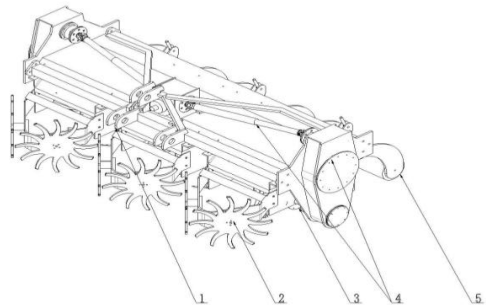
Agricultural production practices have proven that conservation tillage plays a significant role in fertilizing soil, reducing black storms, and preventing soil erosion and water erosion. Strip tillage, as a mode of conservation tillage and minimum tillage, reduces issues such as low soil temperature and uneven emergence caused by extensive straw cover. The strip tiller, a conservation tillage implement, can perform operations such as straw collection, strip tillage, and soil improvement in one go. It meets the technical requirements of conservation tillage and minimum tillage, as well as wide and narrow row planting, contributing significantly to the promotion of conservation tillage.

The tiller blade is a key component of the strip tiller equipment, and during soil cultivation, its arrangement and design characteristics can lead to vibration and energy consumption issues, negatively impacting the effectiveness of tillage. In traditional designs, increasing the size of the tiller blade roller has been employed to reduce vibration effects. However, this approach results in bulky and larger agricultural machinery, further causing soil compaction and requiring more power, making the development of lightweight and intelligent conservation tillage machinery more challenging.

To address these issues, this study conducted in-depth research on the tiller blade and its roller, utilizing finite element analysis to assess the structural strength and stiffness of the tiller blade, ensuring its safety and reliability during use [1,2]. Simultaneously, structural optimization and modal analysis of the tiller blade were employed to reduce vibrations, enhancing the performance and efficiency of conservation tillage machinery. This study provides theoretical support for the practical application and design of tiller blades in conservation tillage equipment.

2. Overall Structure and Working Principle

The conservation tillage strip tiller is primarily composed of a straw collection unit, soil tillage unit, and compaction unit (Figure 1).



1. Suspension Device; 2. Row Collection Device; 3. Tillage Device; 4. Transmission Structure; 5. Compaction Device
Figure 1. Overall Structure of the Strip Tiller

The tiller is connected to the tractor through a three-point suspension system. Three sets of row-collecting disc blades are symmetrically mounted at the front of each tillage strip, slightly lower than the rotation axis of the tillage unit. The soil tillage unit is installed behind the row-collecting disc blades and consists of tiller blades and three sets of tillage knives.

A compaction unit is installed behind the soil tillage unit. The transmission mechanism mainly consists of a gearbox, universal joint, and transmission box. The tractor's power is connected to the input shaft of the gearbox through the universal joint, and after redirection through the gearbox, it is transmitted to the tiller shaft. This drives the rotary tiller roller and tiller blades to rotate at high speed, cutting through the soil and crop residues to achieve the purpose of soil fragmentation [3].

2. Structure Analysis of Tiller Blade

The strip tiller is primarily used for strip tillage on uncultivated land with crop residues, especially after maize harvesting, requiring residue chopping and soil cultivation. Therefore, a chopping-type curved blade is chosen as the tiller blade, composed mainly of a side-cutting edge, a positive-cutting edge, and a blade handle. During operation, the side-cutting edge vertically cuts the soil, followed by the gradual cutting action of the positive-cutting edge to achieve soil cultivation, leveling, and residue shredding [4]. This operational approach places the side-cutting edge near the blade handle under the highest stress, effectively pulverizing the soil with higher strength, and utilizing the intersecting blade edges to cut through straw and grass stems, thereby improving tillage quality. Additionally, due to the non-vertical angle between the positive-cutting edge and the side-cutting edge, challenging-to-cut residues can smoothly slide towards the blade tip, preventing entanglement with the tiller blade and roller and avoiding potential jams [5].

This design of the chopping-type tiller blade effectively meets the requirements of strip tillage and residue chopping, enhancing tillage results and preventing interference from straw and grass residues, ensuring a smoother and more efficient operation of the implement.

2.1 Three-dimensional Model of Tiller Blade

Designed according to agronomic requirements, the tiller blade has a rotational radius of 270 mm. The blade handle is designed with a width of 50 mm, thickness of 10mm, hole diameter of ϕ10 mm, a bending angle of 120° for the positive-cutting surface, and a blade thickness of 1-2mm (Figure 2).

This design meets the structural requirements of the tiller blade, ensuring stability and durability. The appropriate width and thickness of the blade handle provide sufficient strength and rigidity, and the hole diameter is chosen to meet the installation requirements of the tillage machinery. Simultaneously, the bending angle of the positive-cutting surface and the blade thickness fall within the agronomic requirements, effectively accomplishing the tillage task. This contributes to improving the effectiveness of the tiller blade, making it better suited for strip tillage and residue chopping. Additionally, a well-designed blade handle can reduce the weight of the implement, enhancing its flexibility and operability.

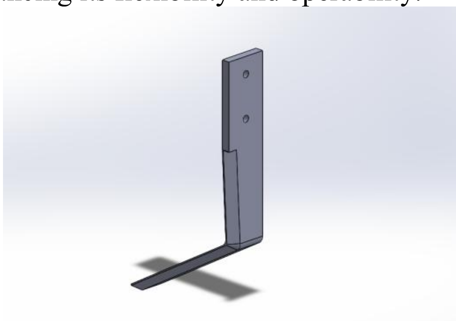


Figure 2. 3D Model of Tiller Blade

2.2 Load Determination

In actual field operations, the resistance experienced by the tiller blade is closely related to parameters such as cultivated soil, tillage depth, blade rotation speed, and implement forward speed. During the operation of a strip tiller, the tiller blade bears the load for both the cultivation task and forward movement, making it responsible for a significant portion of the engine's power. To simplify the calculation of the resistance on the tiller blade, the following formula can be used to describe the relationship between the resultant force on the tiller blade, engine power, blade shaft rotation speed, and the rotational radius of the tiller blade:

$$P = \frac{2Fv}{1000} = \frac{2Fwr}{1000} \quad (1)$$

Where, P—engine power in kW; F—the load acting on the tiller blade tip in N; v—the rotation speed of the tiller blade tip in m/s; w—the angular speed (calculated as w=2πn) in rad/s; n—the rotation speed in 250 r/min; r—the rotational radius of the tiller blade in 270 mm.

The typical driving power for a strip tiller is usually between 40-60 kW, and for calculation purposes, let's assume P=50 kW, Based on the calculation, the load (F) on the tiller blade tip is 635.85 N. When considering the instantaneous impact during the initial soil penetration, an initial cultivation resistance coefficient of 1.5 is applied [6]. Therefore, the calculated load on the tiller blade is:

$$F = 1.5 \times 635.85 \text{ N} = 953.78 \text{ N} \quad (2)$$

In practical operations, the tiller blade cyclically rotates along the rotation axis, reciprocating to cut through the cultivated soil. This working method results in a periodic oscillating force acting on the tiller blade. To facilitate the study of the force performance on the tiller blade, the cutting force is effectively decomposed into vertical force components acting on the side-cutting edge, transition edge, and positive-cutting edge. According to calculations, the magnitude of the resultant force is 953.78 N.

In real-world operations, additional factors need consideration, such as soil moisture, soil types, and blade design. Therefore, adjustments and optimizations based on actual conditions are necessary. This simplified model aids in estimating the resistance on the tiller blade, helping determine the implement's working capacity and operational efficiency.

2.3 Finite Element Analysis of Tillage Blade

2.3.1 Material of the tiller blade

In harsh agricultural working environments, the tiller blade must endure continuous operation without irreversible failures such as deformation, fracture, or fatigue damage when encountering hard objects like bricks or rocks. Therefore, in selecting the material for the tiller blade, it is essential to choose a material with high hardness, strong elasticity, and good toughness. According to requirements, the material properties for the tiller blade are defined as $60Si_2Mn$. This material has a density of 7.85×10^3 kg·m^{-3}, an elastic modulus of 2.06 GPa, a Poisson's ratio of 0.26~0.32, and a yield strength of 1,176 MPa. Choosing such a material ensures that the tiller blade meets the demands of adverse working conditions, providing high strength, fatigue resistance, and toughness. This design effectively enhances the service life, durability, stability, and reliability of the tiller blade in agricultural operations.

2.3.2 Constraints and applied loads

In practical usage scenarios, the tiller blade is fixed onto the rotary tiller roller shaft using bolts and undergoes cyclic rotational motion along with the roller. To ensure the stability of the tiller blade, fixed constraints are applied at the mounting hole. Additionally, to conduct finite element analysis on the model, a "standard mesh" was used for meshing the model. In this process, a Jacobian point of 16 points was chosen, and the mesh was automatically partitioned to an appropriately sparse level. With this partitioning, the model obtained 4,352 nodes and 2,218 mesh divisions. For the finite element preprocessing model setup, vertical forces perpendicular to the blade edge were applied at the side-cutting edge, transition edge, and positive-cutting edge, with a force magnitude of 953.78 N. With these settings, the finite element preprocessing model setup for the tiller blade was completed (Figure 3).

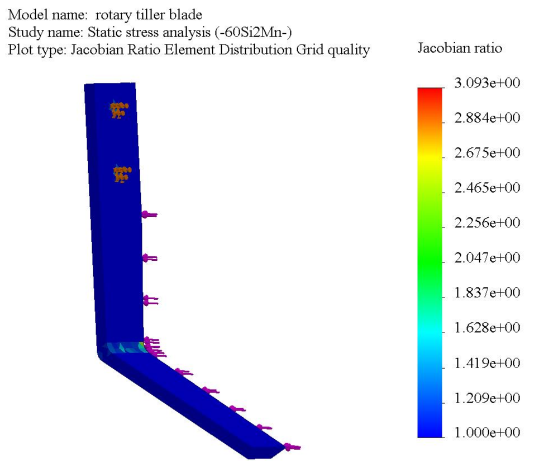


Figure 3. Mesh Division and Constraints/Load Application for the Tiller Blade Model

2.4 Finite Element Solution and Results Analysis for the Tiller Blade

When the load on the tiller blade reaches or exceeds the material's yield limit, irreversible failure behaviors like bending deformation or fracture may occur [7]. To address this, the solution and optimization can be achieved by incorporating total deformation, stress, and strain analysis components.

Based on the stress distribution contour plot (Figure 4), it is observed that the maximum stress value of 197.4 MPa occurs at the smooth transition between the tiller blade handle and the back curve, as well as at the hole in the blade handle. However, this stress value does not surpass the permissible stress value for the material, which is 1,176 MPa. The stress contour plot visually indicates a gradual reduction and dispersion of stress in the horizontal direction towards the positive-cutting edge. This phenomenon is attributed to the centrifugal force exerted by the rotation of the tiller roller shaft during tillage operations. Additionally, the $60Si_2Mn$ material exhibits excellent mechanical properties, contributing to a relatively stable expansion of stress in all directions.

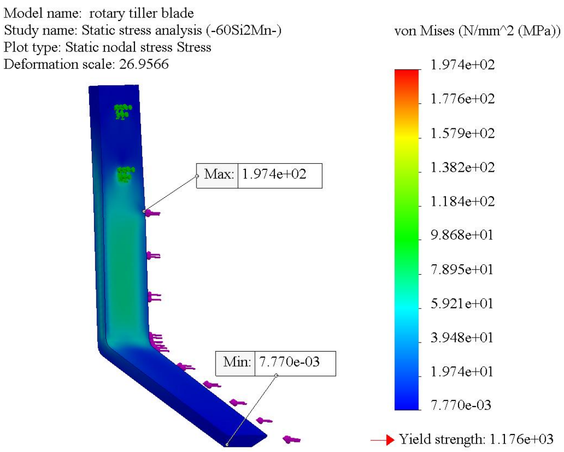


Figure 4. Stress Distribution Contour Plot

The displacement distribution contour plot (Figure 5) reveals that the maximum displacement occurs at the tiller blade tip, with a value of 1.145 mm. The region with the least stiffness in the tiller blade during operation is at the blade tip, where the minimum displacement is extremely small, approximately 1.000×10^{-30} mm, and the deformation ratio is 26.95. The strain distribution cloud map (Figure 6) reveals that the maximum strain of rotary tillage at the through-hole of the blade handle, with a value of 5.16×10^{-4}, which is consistent with the failure of tiller blade such as bending and fracture during actual production.

Behind the soil tillage unit, a compaction device is installed. The transmission mechanism is mainly composed of a reducer, universal joint, transmission box, etc. The tractor power is connected to the tiller blade shaft through the universal joint and the input shaft of the reducer. After changing direction through the reducer, it is transmitted to drive the rotary tiller roller and tiller blade to rotate at high speed, cutting through the soil and crop residues to achieve the purpose of soil fragmentation in conservation tillage.

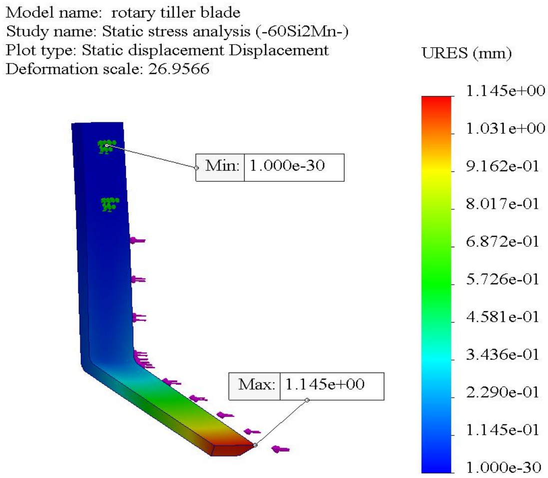


Figure 5. Displacement Distribution Contour Plot

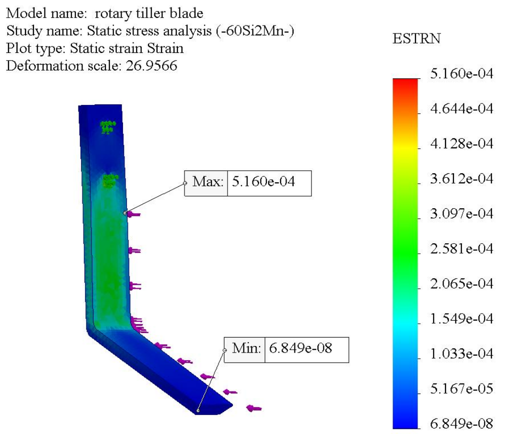


Figure 6. Strain Distribution Contour Plot

3 Structure Analysis of Tillage Blade Roller

3.1 Distribution of Tillage Blade

To ensure the normal operation of the strip tiller, particular attention is given to the rotational balance between the roller and tiller blades in the design process. Proper arrangement and installation are crucial for improving operational efficiency; otherwise, it may lead to the displacement of tiller blades, exacerbating machine oscillation. Since the strip tiller is primarily composed of three non-overlapping soil strips, a staggered arrangement is used to balance the blades in the left and right soil strips. In the central soil strip, a helical arrangement is adopted for the tiller blades. This sorting method balances the forces and helps transfer the residue left in the straw collecting unit to one side of the soil strip through the helical arrangement [8,9]. Figure 7 illustrates the installation of the tiller blades, effectively balancing force distribution and facilitating the transfer of straw to one side, thereby enhancing operational efficiency and accuracy.

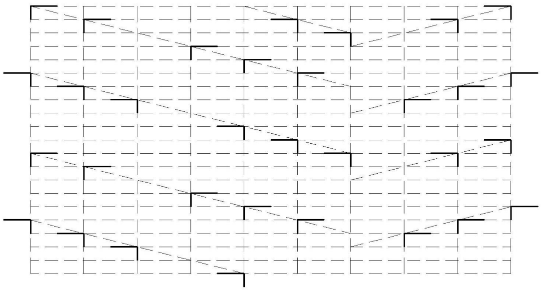


Figure 7. Schematic Diagram of Rotary Tiller Blade

3.2 Modal Analysis of Tillage Blade Roller

3.2.1 Material of tillage blade roller

To reduce computation time and costs, a simplified treatment can be applied to the tiller blade roller. This involves removing features such as chamfers and fillets that do not significantly impact modal analysis, thereby reducing the modeling complexity. It is assumed that the material is uniform throughout, and alloy steel is used for the analysis.

3.2.2 Constraints and applied loads

In practical usage scenarios, the tiller blade roller is fixed to the transmission shaft through a flange structure, undergoing cyclic rotational motion [10]. To ensure the stability of the tiller blade roller, fixed constraints are applied at the flange hole mounting points. Simultaneously, for modal analysis, a standard mesh is used to partition the model. In this process, a Jacobian point of 16 points is chosen, and the mesh is automatically partitioned to an appropriately sparse level. With this partitioning, the model has 193,054 nodes and 96,276 mesh divisions. In the modal preprocessing model setup, the configuration for the tiller blade roller is completed (Figure 8).

3.2.3 Modal analysis results of tillage blade roller

The natural frequencies and vibration modes are shown in Table 1 and figure 9 to 13.

3.2.4 Analysis of tiller blade roller modal results

The analysis leads to the following conclusions: with the increase in natural frequencies, the variation in the maximum deformation of the tiller blade roller is not significant, but there is a substantial change in the overall deformation pattern. The first mode frequency is 34.36 Hz, and from the mode shape diagram, it is observed that the primary deformation occurs in the middle section of the tiller blade roller, exhibiting radial deformation. The second mode frequency is 34.44 Hz, and the main deformation still occurs in the middle section of the tiller blade roller, also displaying radial deformation. The third mode frequency is 91.39 Hz, and the main deformation occurs at both ends of the tiller blade roller, exhibiting axial deformation. The fourth mode frequency is 92.9 Hz, with significant deformation in the middle section's radial deformation and the tiller blade. The fifth mode frequency is 98.6 Hz, with the primary deformation being radial deformation of the tiller blade.

The rotational speed of the tiller blade roller is 250 r/min, corresponding to a frequency of 4.16 Hz in the design. According to the modal analysis results mentioned earlier, the first mode frequency is 34.36 Hz, significantly higher than the current rotational speed frequency. Therefore, the conclusion can be drawn that the rotational speed frequency of the tiller blade roller is much lower than the first mode frequency, thus avoiding resonance [11].

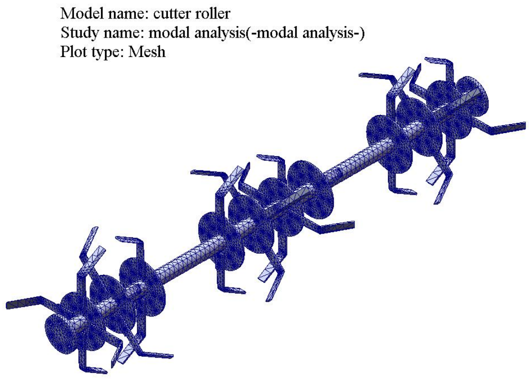


Figure 8. Modal Preprocessing Model of Tiller Blade Roller

Table 1. Natural Frequencies and Vibration Modes

Order	Natural frequency/ Hz	Position of maximum deformation	Deformation style
1	34.36	In the middle section of the tiller blade roller Tiller blade tips	Extend radially towards the roller Extend towards the outer side
2	34.44	In the middle section of the tiller blade roller Tiller blade tips	Extend radially towards the roller Extend towards the outer side

3	91.39	In the middle section of the tiller blade roller Tiller blade tips	Extend towards the roller Extend towards the outer side
4	92.9	In the middle section of the tiller blade roller Tip of outside tillage blade	Extend towards the roller Extend towards the outer side
5	98.6	In the middle section of the tiller blade roller Tip of outside tillage blade	Simultaneously extend radially and axially towards the outer side

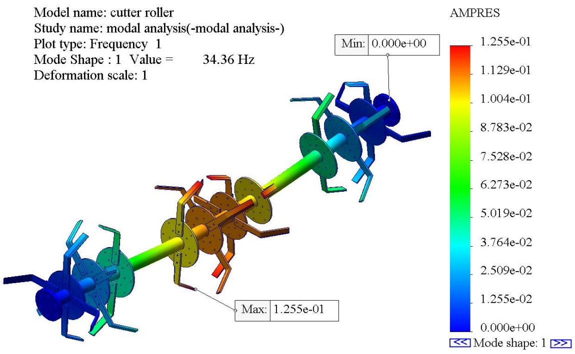


Figure 9. First Order Modal Vibration Direction Diagram

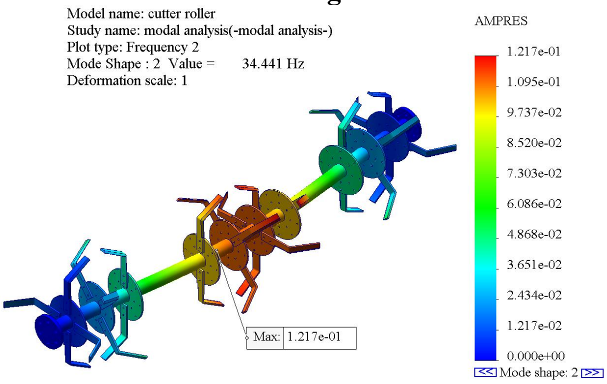


Figure 10. Second Order Modal Vibration Direction Diagram

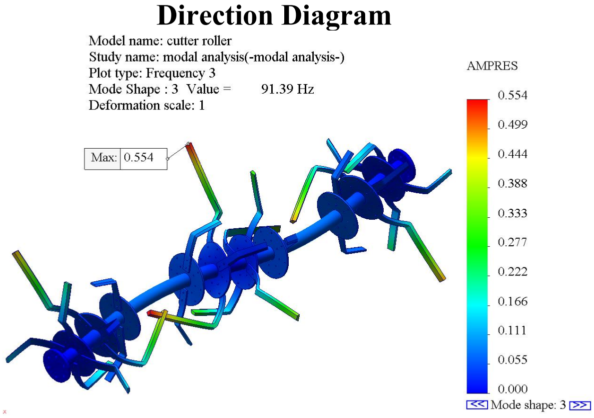


Figure 11. Third Order Modal Vibration Direction Diagram

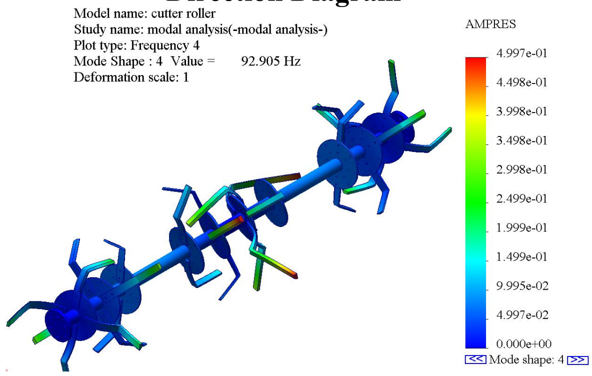


Figure 12. Fourth Order Modal Vibration Direction Diagram

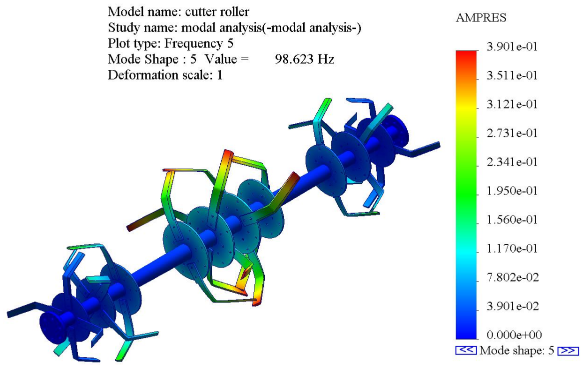


Figure 13. Fifth Order Modal Vibration Direction Diagram

4. Conclusion

Finite element static analysis indicates that the stress and strain experienced by the tiller blade during operation are primarily concentrated in the handle area. The maximum total deformation of the tool reaches 1.145 mm, occurring at the tip of the positive cutting edge. The maximum stress value of the tiller blade is 197.4 MPa, mainly distributed in the smooth transition area between the handle and the back of the blade, as well as at the hole position in the handle, consistent with actual working conditions.

Modal analysis results indicate that, under fixed constraints and stable loads, the first five natural frequencies of the tiller blade range from 34.36 to 98.6 Hz, with the lowest frequency higher than the working frequency of the tiller blade. This study provides a detailed analysis of the tiller blade and roller for strip tiller machinery, aiming to reduce the weight of the tiller blade, ensuring efficient completion of tillage tasks. An analysis of the frequency of the tiller blade roller is also conducted to avoid resonance.

Acknowledgments

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