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Analysis and Test of the Tillage Layer Roll-Type Residual Film Recovery Mechanism

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Abstract: With the extensive use of plastic film mulching in planting, the amount of residual plastic film in soil has been increasing, causing soil and water pollution, harming crop growth, and reducing agricultural product quality and yield. In response to this issue, this study proposes a roll-type residual film recovery mechanism using the tillage layer method. The structure and operation principles of this system are discussed, and a detailed analysis of its key components and working process is provided. The lifting cutter operates at a speed of 22.37 rad/s, the pick-up drum at 4.58 rad/s, the roll forward rotation picks up the film at 13.74 rad/s, and the roll reverse film rotation unloads the film at 17.57 rad/s, with the unloading wheel rotating at a speed of 4.5 rad/s. ADAMS (software of automatic dynamic analysis of mechanical systems) Version No.2019 is used for modeling and analysis, and the displacement and velocity change patterns of MARKER_499, MARKER_500, and MARKER_505, which are marked points of the spring-tooth tips and are found to be the same. The maximum resultant displacement of MARKER_499 and MARKER_500 is 22.146 mm when picking up plastic film and 17.047 mm when unloading plastic film. Meanwhile, the maximum resultant displacement of MARKER_500 and MARKER_505 is 231.715 mm in the film-picking area and 234.028 mm in the film-unloading area. After analyzing the velocity of MARKER_499 during picking and unloading of the film, it was determined that the absolute velocity for the picking direction was 79,809.407 mm/s, and for the unloading direction it was 10,2266.168 mm/s. Bench tests show a tillage gathering rate of 71.6% and a surface gathering rate of 83.4%, meeting the performance requirements of the roller-type residual film recovery mechanism. These findings provide a theoretical basis for the design of the structure and operational parameters for the roll-type residual film recovery mechanism using the tillage layer method.

Keywords: residual film recovery; winding up roller; plow layer residual film; operational parameters; simulation

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1. Introduction

The use of plastic film mulching is prevalent in the cultivation of various crops like vegetables, melons, fruits, cotton, peanuts, and corn. Such a practice has proven to be highly effective in maintaining soil temperature, preserving moisture, sustaining soil structure, and preventing pest invasion [1,2]. In China, the plastic film utilized consists of polyethylene hydrocarbon organic polymer compounds, which undergo natural degradation very slowly and could remain in the soil for two to four centuries. Because the recycling of mulch film is incomplete, a large amount of residual film, crop stubble, and soil are mixed together and buried deeply in the plow layer after tillage and soil preparation, which increases the difficulty of residual film recovery. After years of cultivation, the residual plastic film accumulated in the plow layer is increasing, which can cause a decline in the soil quality and crop yield [3–6] and can cause significant "white pollution" to the agricultural ecological environment. Addressing residual film pollution in farmland has become a pressing issue,

with an even greater sense of urgency placed on tackling residual film pollution present in the plow layer.

Plastic film mulching technology has gained widespread adoption in various countries, including the United States, Japan, and others. These nations began developing recycling machinery for plastic film in the early 1960s, primarily owing to the high tensile strength of thicker plastic film used (more than 0.02 mm), which conferred convenience and a high recovery rate for mechanical recovery [7–9]. Moreover, significant advancements have been made in researching degradable plastic film in these countries, resulting in a minimal deep burial of plastic film in the soil's plow layer, thereby curbing pollution effectively. In contrast, China's earlier usage of plastic film involved a significantly thinner film, measuring 0.008 mm in thickness, and with lower tensile strength. Thus, recovering plastic film through mechanization is difficult. And a large number of plastic films were buried in the plow layer after plowing and land preparation is performed. This results in significant pollution of the farmland ecological environment. The problem of residual film pollution is particularly serious in Xinjiang, China. The average residue of plastic film in farmland is approximately 207 kg/hm^2, and the average residue of plastic film in some significantly polluted areas exceeded 276 kg/hm^2. It has far exceeded the standard [10] of 75 kg/hm^2 for the residue limit of plastic film in farmland. Therefore, the demand for the treatment of plastic film residue pollution in farmland and research on plastic film residue recycling machinery are mainly concentrated in China.

In the effort to address farmland residual film pollution, researchers have developed several hundred residual film recycling machines categorized according to working principles as the spring-tooth, nail tooth, clamp, chain tooth, and telescopic rod types [11–13]. However, very few machines or tools exist that can recover the residual film in the plow layer. The most significant current research on the topic is Zhang Xuejun's team's development of the chain-tooth residual film recovery machine that can recover up to 150 mm depth of residual film in the plow layer [14–16]. This machine uses a film shovel to move the residual film–soil mixture during picking operations, but its soil-breaking and transportation ability remain weak, causing difficulties in separating the film and soil and leading to high impurity rates. Another type of machine was researched by Zhang et al. [17,18], which was the rotary tillage spike-tooth type able to recycle residual film at a plow layer depth of 150 mm, but it was prone to residual film accumulation on the spike-tooth, impeding ideal unloading outcomes. Jin et al. [19] developed an automatic film-unloading-type residual film recycling machine equipped with a nail-tooth and able to work at a depth of 80 mm. Unfortunately, the mechanical properties of the plow-layer residual film are weak, meaning that the residual film cleaning rate remains low due to the reverse resistances exerted by soil and other obstacles. Consequently, more residual films fall onto the ground surface, considerably limiting the operation performance of plow-layer residue film recovery machines.

Therefore, a technical scheme of roll-type residual film recovery mechanism for the tillage layer is proposed. The residual film and soil are thrown by a film-lifting device, and the roller-type plow layer residual film is hooked and rolled along the falling direction of the film–soil mixture by using spring-teeth on the roller-type residual film, while the roller-type residual film and soil rotate along with the rotation of a pickup roller. The film-unloading function is achieved under the combined action of the film-unloading wheel. The design of the roll-type tillage residual film recycling machine effectively solves the problems of a low pick-up rate and high impurity content of the tillage residual film recycling machine. The winding roll-type recycling mechanism is the core component of the roll-type residual film recovery mechanism for the tillage layer, and its operating parameters directly affect the operating performance of the plastic film residue recycling machine. It is an effective method to study the operation parameters of the roller-type recovery mechanism by using the theoretical research method. However, the winding roller and spring-tooth have to rotate with the pickup drum and the rotation of the winding roller while moving forward. Thus, it is difficult to calculate the displacement and velocity of

the movement and the operability of the actual measurement is poor; thus, the effective analysis of the performance of the roller-type recovery mechanism is limited [20–24]. Virtual simulation technology is used to simulate the real motion process of the roller-type plow layer plastic film residue recovery mechanism, and motion analysis of the roller-type plow layer plastic film residue recovery mechanism is carried out. Thus, an effective method that improves the working performance of the roll-type residual film recovery mechanism for the tillage layer is developed. No relevant theoretical analysis and data have been seen for the roll-type tillage layer residual film collector. The operating parameters obtained in this study are not only applicable to this machine, but also can provide guidance and reference for the design of operating parameters of picking components of other residual film recovery machines.

2. Materials and Methods

2.1. Structures and Working Principle

The roll-type residual film recovery mechanism for the tillage layer is mainly composed of a suspension mechanism, a gearbox, a film-lifting device, a pickup roller, a roller, a film-unloading wheel, and a frame. Its structure is shown in Figure 1. The winding roller is installed on the pickup roller. According to the operation area, the circumferential direction of the pickup roller can be divided into a film-picking area, in which the winding roller rotates forward, and a film-unloading area, in which the winding roller rotates reversely.

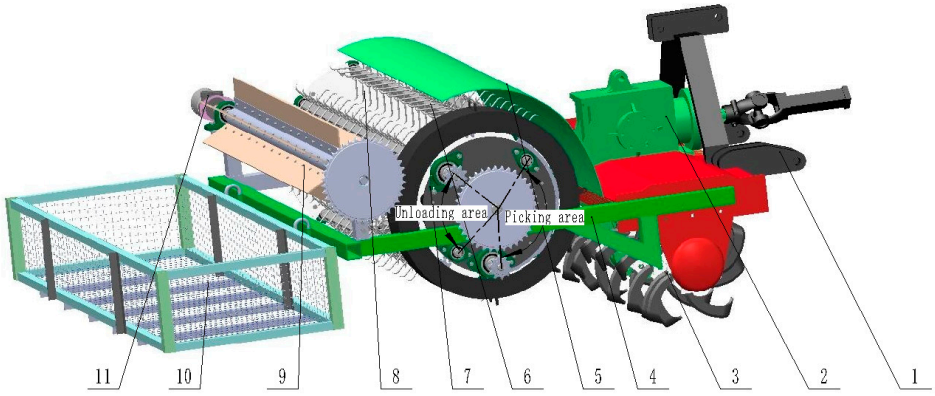


Figure 1. Schematic diagram of the whole machine structure (1, suspension mechanism; 2, gearbox; 3, film-lifting device; 4, frame; 5, retaining plate; 6, roller; 7, double chain drive; 8, pickup roller; 9, film-unloading wheel; 10, diaphragm tank; 11, hydraulic motors).

During the operation of the roll-type residual film recovery mechanism for the tillage layer, the machine is towed forward by the tractor through the suspension mechanism, the power output shaft of the tractor drives the gearbox to rotate, and the power is transmitted to the film-lifting device to drive the film-lifting device to rotate counterclockwise so that the film–soil mixture with a depth of 150 mm in the plow layer is thrown. Moreover, the film-lifting operation of the plow layer residual film is achieved. The power from the gearbox is directed to the pickup roller and unloading wheel of the film through the transmission device, facilitating the counter-rotational movement of the former. The film-unloading wheel rotates clockwise, and the winding roller is driven by the double-row chain through the transmission chain to perform the forward rotation film-picking operation in a forward rotation film-picking area and performs reverse rotation in a reverse film-unloading area to coordinate with the film-unloading operation of the film-discharging wheel.

The essential component of the plow layer residual film recovery machine is the winding roller, with its structure outlined in Figure 2. During operation, the film lift device ejects a mixture of soil and film, which is then propelled toward the forward rotation film-picking area thanks to the soil retaining plate. Moreover, the movement direction of the drive spring -tooth is the same as the falling direction of the film–soil mixture by self-weight

under the action of rotation of a winding roller. Finally, the effective film-picking operation is achieved by using a tooth tip hook of the spring-tooth to roll the residual film. The movement direction of the spring-tooth is the same as the falling direction of the film–soil mixture, and the speed of the spring-tooth is greater than the falling speed, which can effectively reduce the reaction force of the soil on the residual film in the process of picking up the film by the spring-tooth and is beneficial to improving the cleaning rate. The winding roller continues to rotate along with the pickup roller. When the winding roller moves to the film-unloading area, the winding roller rotates reversely. The movement direction of the spring-tooth is the same as that of the film-unloading wheel, and the residual film is easy to strip when the spring-tooth moves reversely. Thus, the film-unloading capacity is further improved under the mechanical force of the film-unloading wheel.

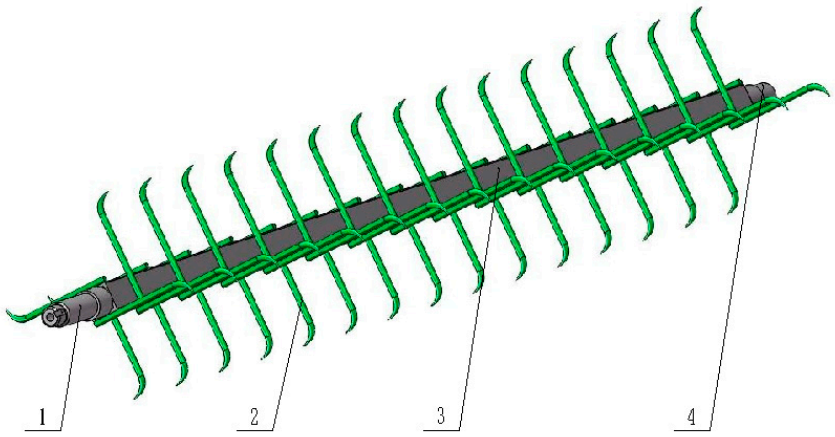


Figure 2. Winding roll structure function. (1, drive shaft head; 2, spring-tooth; 3, square tube; 4, support the shaft head).

2.2. Analysis of the Operation Parameters

2.2.1. Analysis of Residual Film-Lifting Process

A film-lifting device is a necessary mechanism for the mechanized recovery of residual film in the plow layer. Its function is to loosen and throw the mixture of film and soil in the plow layer, reduce the soil resistance in the process of picking up residual film, and improve the operational performance of the picking component. During the film-lifting work, the film-lifting knife rotates around the knife shaft and moves in a straight line along with the machine at the same time to achieve the continuous throwing of the plow layer film–soil mixture. To facilitate the recovery operation of the picking device, it is necessary to study the movement of the film-lifting knife and the operation conditions of throwing the film–soil mixture. Point O is selected as the rotation center of the cutter shaft, a circle with a radius of R as the rotation radius is drawn, the forward direction of the unit is taken as the x-axis, the plowing depth direction is taken as the y-axis, and the xOy coordinate system is established, as shown in Figure 3. In this figure, the film-lifting knife coincides with the x-axis as the starting position, moves Point O at the forward speed of V_m, rotates at the angular speed of ω, and connects the moving endpoints to form the absolute trajectory of the film-lifting knife.

The velocity equation of motion at Point M is:

$$\begin{cases} v_x = V_m - R\omega sin\omega t \\ v_y = R\omega cos\omega t \end{cases} \quad (1)$$

In this formula, R is the radius of the largest slalom of the film-lifting knife, m; V_m is the machine's forward speed, m/s; ω is the rotating angular velocity of lifting blade, rad/s; and t is the time, s.

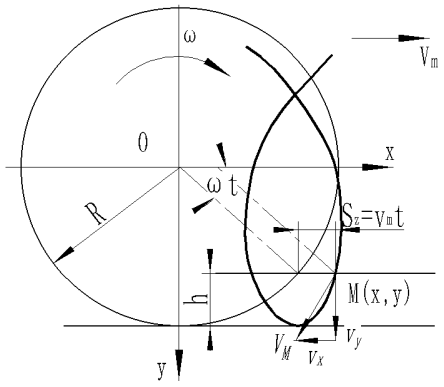


Figure 3. Motion analysis of the membrane cutter.

To meet the condition that the film-lifting cutter throws the film–soil mixture backward, the horizontal component velocity V_x of the absolute velocity at any point on the absolute motion trajectory of the film-lifting cutter is less than 0. According to Equation (1), the following can be obtained:

$$v_x = V_m - R\omega sin\omega t = V_m(1 - \lambda sin\omega t) < 0 \tag{2}$$

Equation (2) can be varied as follows:

$$V_m - R\omega(R - h)/R < 0 \tag{3}$$

Moreover, the following is obtained:

$$V_m < (R - h)\omega \tag{4}$$

After a change is made, we can obtain:

$$h < R - V_m/\omega = R(1 - 1/\lambda) \tag{5}$$

Equations (4) and (5) reflect the influence of the change in R, ω, and V_m on the working depth H. When R is determined, ω and V_m determine the value of λ and the shape of the motion trajectory of the membrane knife. The larger λ is, the larger the maximum chord length value is, which can meet the height requirement of the plowing depth trajectory. According to the index requirements of GB/T 25412-2021 [25] on the operation performance of residual film recycling machine, the film-lifting depth h is taken as 150 mm, the blade of I T225 type is selected, its operation radius is 225 mm, and the forward speed of the tractor is taken as 2.5 km/h. After a calculation is performed, the critical speed of the film-lifting blade that causes the backward throwing of the mixture of film and soil in the plow layer is $\omega > 9.2$ rad/s. At this time, $\lambda > 3$ is obtained. According to the analysis of the influencing factors, such as film lifting, soil breaking, and power consumption, combined with the design and calculation of the transmission system, the rotating speed ω of the film-lifting knife is 22.37 rad/s.

2.2.2. Analysis of Film Collecting Process

The function of the pickup roller is to drive the winding roller to revolve around the pickup roller and continuously pick up the film–soil mixture thrown by the film-lifting device. Therefore, the movement of the pickup cylinder depends on the advance speed V_m of the implement and the film-lifting depth h. The larger the forward speed V_m is, the higher the rotational speed of the pickup drum, and vice versa. The larger the film-lifting depth h is, the greater the mixed amount of film and soil entering the pickup roller per unit time is, and the speed of the pickup roller is correspondingly increased to improve the clean rate of the residual film. However, the minimum critical value of the pickup cylinder

rotation speed n_1 is that the linear speed of the outer circle of the pickup cylinder is equal to the forward speed, that is:

$$n_1 = \frac{V_m}{\pi D_1} \tag{6}$$

where D_1 is the diameter of the pickup drum, m; V_m is the forward speed of the unit, m/s; and n_1 is the rotational speed of the pickup drum, r/min.

When the forward speed V_m is calculated to be 2.5~5 km/h, the angular velocity of the pickup cylinder speed ω_1 is 2.29~4.58 rad/s. During operation, the advancing speed V_m determines the amount of the soil mixture entering the film collecting area. The greater the speed is, the greater the amount of the soil mixture entering the film collecting area, and vice versa. Therefore, to improve the picking rate of the residual plastic film, the rotation speed of the picking roller is calculated according to the maximum amount of the film–soil mixture entering the film-picking area, and the angular velocity of the rotation speed ω_1 of the picking roller is 4.58 rad/s.

To increase the effective film collecting area of the roller and reduce the reverse resistance of the soil to the residual film, we determine that the effective film-picking area of the roller is 120° in the forward rotation film collecting area, as shown in Figure 4.

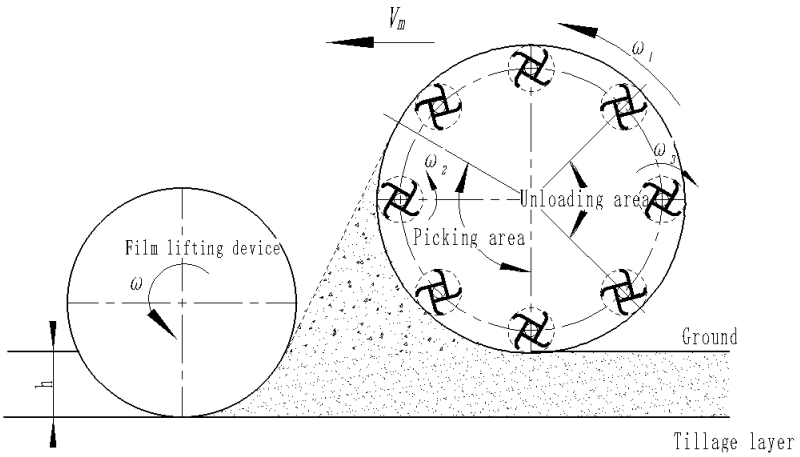


Figure 4. Analysis of the film collecting process.

When the pickup cylinder rotates at ω_1, the time for the pickup cylinder to rotate one circle is t_1, and the time for the winding roller to enter the positive rotation film pickup area is $t_1/3$. According to the design of the winding roller structure, a single spring-tooth on the winding roller just rotates one circle in $t_1/3$. The rotation speed ω_2 of the winding roller is 13.74 rad/s.

The picking mechanism is the core of the plastic film recycling machine, and its performance directly affects the pick-up rate of the plastic film recycling machine. During operation, the film-lifting device throws the plow layer film–soil mixture into a positive rotation film-picking area, and under the action of the mechanical force of the spring-teeth, the residual film in the mixture bears the hooking and picking action of the spring-teeth to separate the residual film from the soil. There are two kinds of mechanical forces of the spring-tooth on the residual plastic film. One is the film-picking effect of the spring-tooth on the residual plastic film, and the other is the film-hooking effect of the tooth tip of the spring-teeth on the residual film. During the picking of the plastic film residue, the acting force of the soil and stubble on the residual film and the wind resistance affects the process in addition to the gravity of the plastic film residue, the friction force of the spring-tooth on the plastic film, and the centrifugal force during movement. Because the force of the soil and stubble on the residual film and the resistance of wind are random forces, the magnitude and direction of the force cannot be determined. Therefore, the acting force of the soil and stubble on the residual plastic film and the wind resistance are not considered in the force analysis of the process of picking up plastic film by spring-teeth.

The spring-tooth picking up the plastic film is the key action of the winding roller to collect plastic film residue, and its motion parameters determine the performance of picking up plastic film. To further clarify the process of the spring-tooth picking membrane, a force analysis of the spring-tooth picking membrane is carried out, as shown in Figure 5.

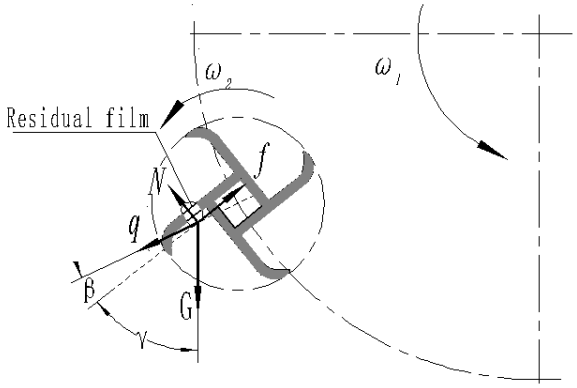


Figure 5. Force diagram of the residual film under the action of the spring-tooth picking film. (β is the included angle between the centrifugal force and the spring-tooth axis, rad; γ is the included angle between the centrifugal force and the gravity direction, rad; q is the centrifugal force, N; N is the normal force of the residual film, N; G is the gravity of the residual film, N; f is the friction force, N).

As shown in Figure 5, the following is observed:

$$f = qcos\beta + Gcos\gamma \tag{7}$$

$$N + qsin\beta = Gsin\gamma \tag{8}$$

$$q = m{\omega_2}^2 R_1 \tag{9}$$

$$f = \mu N \tag{10}$$

In Equation (9), R_1 is the radius from the rotation axis of the roller to the residual film, and in Equation (10), μ is the friction coefficient between the residual film and the spring-teeth.

According to Equations (7) and (8), the conditions for the spring-teeth to pick up the residual film without slipping are as follows:

$$f \geq qcos\beta + Gcos\gamma \tag{11}$$

Moreover, the following is obtained:

$$\omega_2 \leq \sqrt{\frac{g(\mu sin\gamma - cos\gamma)}{R_1(cos\beta + \mu sin\beta)}} \tag{12}$$

According to Equation (12), when γ is 90°, the spring-teeth are in the horizontal position, which is the critical state of the spring-tooth picking film. Because β is determined by the structure of the winding roller, β is 9.59° when the value of μ is 0.6, ω_2 is calculated to be 8.89 rad/s, and the design speed of the roller is 13.74 rad/s, which is not less than the critical speed for picking up plastic film and can meet the requirements for picking up plastic film.

To analyze the mechanical force exerted by the spring-tooth tip on the residual film, as well as the film hooking effect of the tooth tip, Figure 6 shows the analysis of the film hooking process of the spring-tooth tip. The effectiveness of the spring-tooth in hooking

and rolling the residual plastic film depends mainly on whether the hook and roll force of the spring-tooth tip can overcome the gravity of the residual plastic film, as well as the centrifugal force and frictional resistance of the spring-tooth on the residual film.

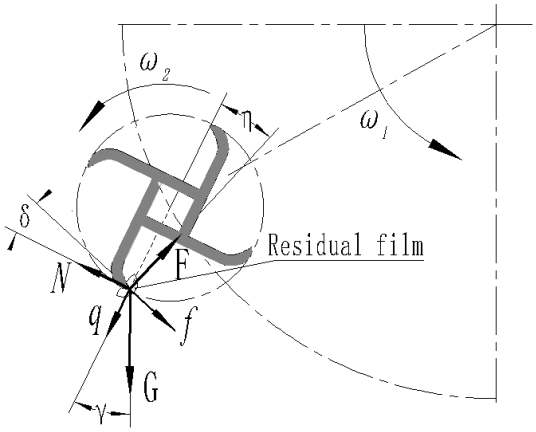


Figure 6. Stress diagram of the residual film when hooked by the tooth tip of the spring-tooth. (η is the included angle between the centrifugal force and the axial normal line of the spring-tooth tip, rad; γ is the included angle between the centrifugal force and the gravity direction, rad; δ is the angle between the normal force of the remnant film and the axis of the tooth, rad; q is the centrifugal force on the remnant film when the tooth is rotating, N; N is the normal force on the remnant film by the tooth, N; G is the gravitational force of the remnant film itself, N; f is the frictional force between the remnant film and the tooth, N; F is the hooking and coiling force of the tooth tip, N).

As shown in Figure 6, the following is observed:

$$N = Gsin\gamma + fcos\delta + Fsin\eta \tag{13}$$

$$q + Gcos\gamma + fsin\delta = Fcos\eta \tag{14}$$

According to Equations (13) and (14), the condition that the hook film of the tooth tip of the spring-tooth does not fall off is as follows:

$$F \geq q/cos\eta + Gcos\gamma/cos\eta + ftan\eta \tag{15}$$

When γ is 0°, the centrifugal force q coincides with the gravitational force G of the remaining film, the vertical downward direction, and the force of the spring-tooth hook to lift the residual film is the largest, which is the critical state of the spring-tooth tip hook film.

$$F \geq G(\frac{1}{cos\eta} + \frac{\mu\, tan^2\eta}{1-\mu(cos\eta + tan\eta sin\eta)}) + q(\frac{1}{cos\eta} + \frac{tan^3\eta}{1-\mu(cos\eta + tan\eta sin\eta)}) \tag{16}$$

Since the centrifugal force q and the gravity G of the residual film are the relationships between the quality of the residual film and the rotating speed of the roller and are not affected by the angle η, the maximum value of Equation (16) can be obtained and transformed into:

$$f(\eta)\ cos\eta tan\eta sin\eta_{min} \tag{17}$$

where η ranges from $0 \leq \eta \leq \frac{\pi}{2}$. After simplification is performed, we can obtain:

$$f(\eta)\frac{\mu}{cos\eta}_{min} \tag{18}$$

It can be concluded that when η is 90°, the hooking force F of the spring-tooth tip reaches the maximum value.

2.2.3. Analysis of the Film-Unloading Process

The film-unloading mechanism is a key mechanism of the plastic film recycling machine, and its working effect affects the working performance of the whole machine. To continuously pick up the residual plastic film in the plow layer film–soil mixture, the hook and the residual plastic film picked on the spring-tooth need to be eventually removed. Therefore, a film-unloading method with the coaction of the reverse rotation of the winding roller and the film-unloading wheel is designed, and the residual film hooked on the spring-teeth in the unloading area is separated from the spring-teeth and thrown into the collection box by the reverse action of the unloading wheel to achieve film removal. The stress analysis of the residual film and film-unloading process is shown in Figure 7.

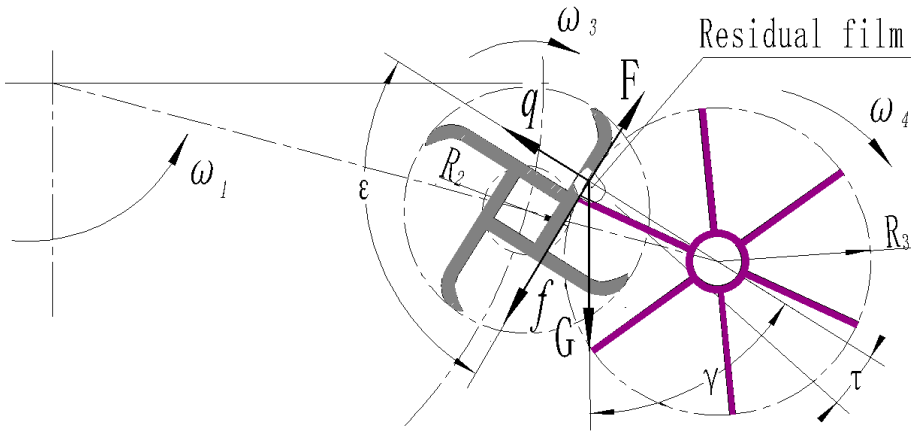


Figure 7. Stress analysis of the film-unloading process. (γ is the included angle between the centrifugal force and the direction of gravity, rad; ε is the included angle between the centrifugal force and the axis of the spring-tooth, rad; τ is the inclined angle between the centrifugal force and normal direction of the axis of the spring-tooth, rad; q is the centrifugal force of the film-unloading roller on the film residue, N; G is the gravity of the residual film, n; f is the friction force, n; F is the tangential force of the film-unloading wheel on the residual film, N).

The critical condition for the residual film to be taken off from the spring-tooth is that the sum of the tangential acting force of the film-unloading wheel and the centrifugal force of the residual film is equal to the sum of the component forces in the stress direction of the gravity of the residual film and the friction force between the residue film and the spring-tooth, namely:

$$F = Gsin\gamma + fsin\varepsilon \tag{19}$$

$$q + fcos\varepsilon = Gcos\gamma \tag{20}$$

$$\varepsilon + \tau = 90^{\circ} \tag{21}$$

As shown in Figure 7, during film unloading, the winding roller rotates reversely. When the spring-teeth contact the film-unloading wheel, the residual film is thrown along the tangential direction by the tangential force of the film-unloading wheel. The normal centrifugal force of the film-discharging wheel is the key to separating the residual film from the film-discharging wheel. Therefore, the conditions for unloading the plastic film residue from the spring-tooth and throwing it backward are as follows:

$$q \geq Gcos\gamma - fcos\varepsilon \tag{22}$$

According to Equations (19) and (20), when ε is 90°, the centrifugal force on the residual film is perpendicular to the friction force of the spring-tooth on it. At this time, the

centrifugal force q required for the film-unloading wheel to throw out the residual film is the minimum, namely,

$$q \geq Gcos\gamma \tag{23}$$

After transformation is performed, we can obtain:

$$\omega_4 \geq \sqrt{\frac{gcos\gamma}{R_3}} \tag{24}$$

Through a calculation, the minimum rotating speed ω_4 of the film-unloading wheel is found to be 4.5 rad/s. To ensure the reliability of film unloading in reversing the roller, it is required that the speed of the film-unloading reversing rotating speed ω_3 of the roller is equal to the speed of the film-unloading wheel ω_4 at the tangent point of R_2 and R_3, as shown in Figure 7. Then, the reverse rotation speed ω_3 of the winding roller is 17.57 rad/s.

2.3. Simulation Analysis of Spring-Tooth Motion

The application of virtual prototype technology to the kinematic analysis of mechanical systems can predict the performance of picking up gear and accurately output the curve of displacement and velocity, which is the critical link to carry out the kinematics and dynamics of the mechanism. In order to study the motion velocity popping up during the operation of the roll-type plow residual film recovery machine, ADAMS was used to carry out the kinematics and dynamics analyses of the recovery machine [26,27], and a model was established, as shown in Figure 8.

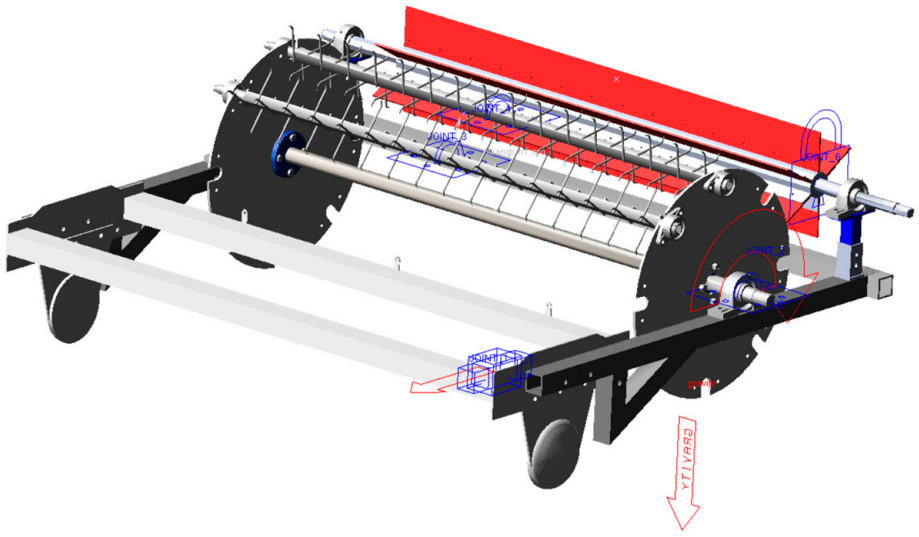


Figure 8. Simulation model of the roller-type plow layer plastic film residue recovery mechanism.

Based on analysis and calculations of operational parameters, the translational driving speed of the roll-type residual film recovery mechanism for the tillage layer has been determined to be 1388.89 mm/s, and the rotating speed of the roller is 4.58 rad/s. According to the forward rotation of the roller on the roller, the rotating speed of picking up plastic film is 13.74 rad/s, and the reverse rotation of unloading plastic film is 17.57 rad/s. To simulate the real motion state of the roller, an IF function is added to the roller to construct a motion model in which the roller rotates forward in the forward rotation area and reversely in the reverse rotation area. For this reason, the starting time of the roller at the highest point of the drum is set to divide the time of each stage, as shown in Figure 9.

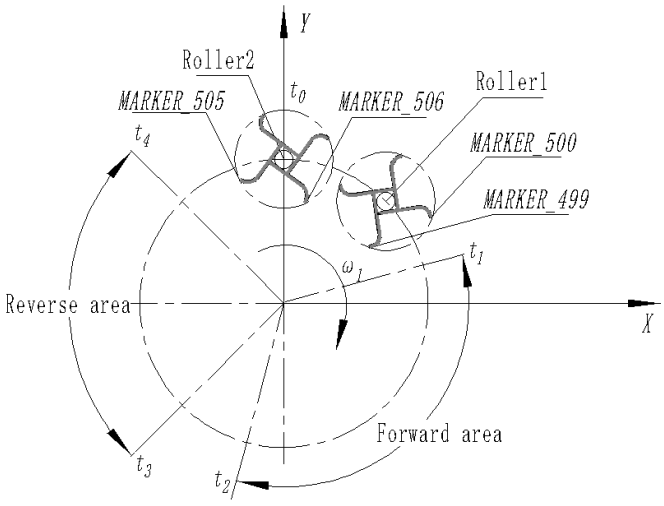


Figure 9. Time division of the operation process.

According to the rotation speed of the pickup cylinder, the time for one rotation of the pickup cylinder is calculated to be 1.371 s. Combined with the forward and reverse rotation areas and the position of the winding roller, the IF functions applied on Winding Roller 1 is calculated to be IF (time-0.1142: 0, 0, IF (time-0.5712: −787.64, −787.64, IF (time-0.6855: 0, 0, IF (time-1.0283: 1007.19, 1007.19, and IF (time-1.371: 0, 0, 0))))). The IF functions applied on Roller 2 are IF (time-0.2856: 0, 0, IF (time-0.7426: −787.64, −787.64, and IF (time-0.8569: 0, 0, IF (time-1.199: 1007.19, 1007.19, IF (time-1.371: 0, 0, 0)))). Specific IF functions are shown in Figure 10.

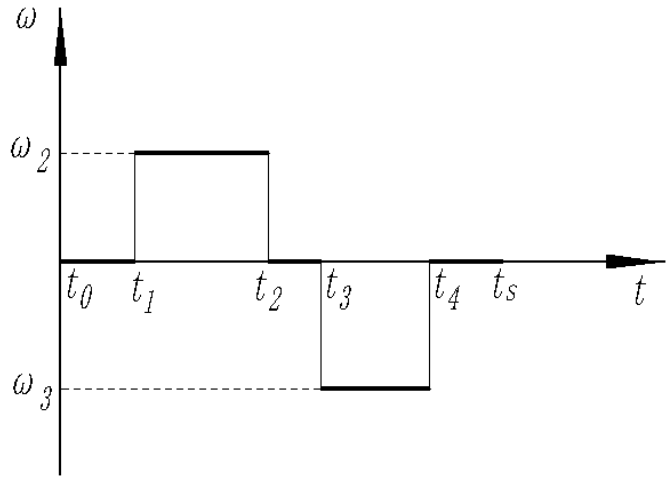
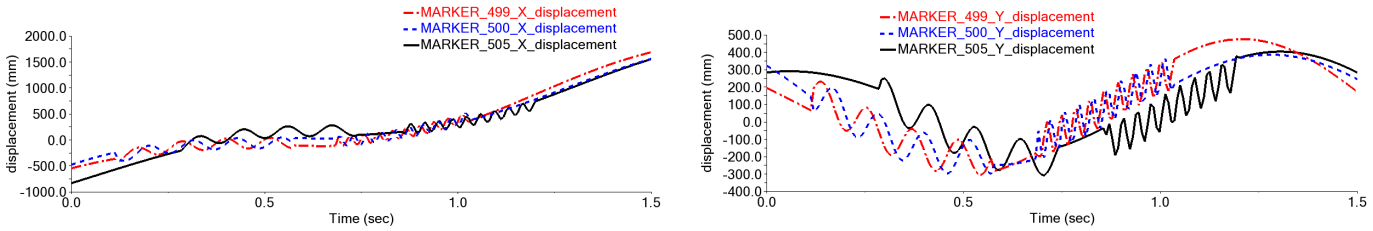


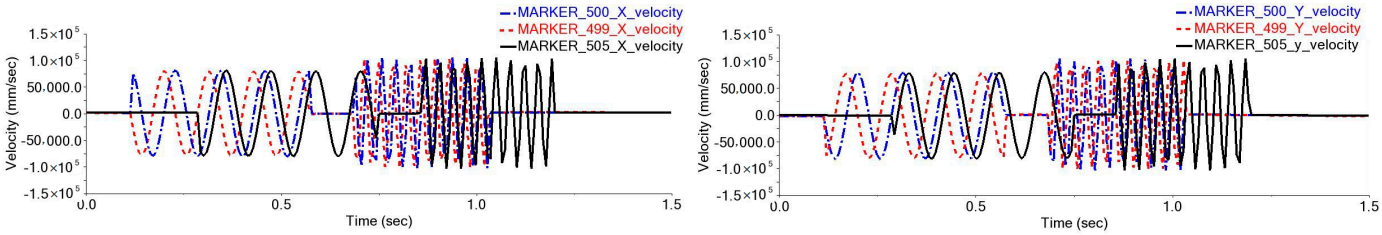
Figure 10. Motion control of the winding roller.

To facilitate the analysis of the motion of the roll and the spring-tooth, the mark coordinates of MARKER_499 and MARKER_500 are created on the adjacent spring-tooth tips of Roll 1, and the mark coordinates of MARKER_505 and MARKER_506 are created on the adjacent spring-tooth tips of Roll 2, as shown in Figure 9. After the simulation is performed, the simulation result is output from the postprocessor. Figure 11a,b are the displacement variation curves of the MARKER_499, MARKER_500, and MARKER_505 marked points of the spring-tooth tips in the X and Y directions, respectively; Figure 12a,b shows the velocity variation curves of the MARKER_499, MARKER_500, and MARKER_505 marked points on the spring-teeth in the X and Y directions, respectively.



(**a**) (**b**)

Figure 11. Displacement curve of the spring-tooth tip. (**a**) Motion displacement curve in the X direction; (**b**) motion displacement curve in the Y direction.



(**a**) (**b**)

Figure 12. Speed change curve of the spring-tooth tip. (**a**) Motion speed curve in the X direction; (**b**) motion speed curve in the Y direction.

As shown in Figure 11, the movement displacement of the MARKER mark point on the spring-tooth tip in the X and Y directions is consistent with the movement displacement trend of the roll centroid in the X and Y directions. MARKER_499 and MARKER_500 of the spring-teeth represent the displacement of the tooth tip of the adjacent spring-tooth on the same roller in the X and Y directions. MARKER_500 and MARKER_505 of the spring-teeth indicate the displacement of the adjacent spring-tooth tip in the X and Y directions.

As shown in Figure 12, the movement velocity change curves of the spring-tooth tips MARKER_499, MARKER_500, and MARKER_505 in the X and Y directions are basically the same. Therefore, only MARKER_499 is taken as the research object to analyze the speed change of the spring-tooth tip. Combined with the movement of the roller-type recovery mechanism, the key movement points of the extreme values in the film-picking area and the film-unloading area were analyzed to improve the efficiency of analysis and calculation.

2.4. Soil Trough Test

A prototype of the complete machine was tested to verify the operational performance of the roll-type residual film recovery mechanism for the tillage layer. In March 2023, The residual film recovery performance tests were carried out in the soil tank test bench of Xinjiang Key Laboratory of Intelligent Agricultural Equipment, Xinjiang Agri-cultural University [28]. This is shown in Figure 13. Tillage and watering were carried out on the soil tank before the experiment so that the experimental land in the soil tank was relatively flat, and the soil state was consistent with that of the actual field after tillage before spring sowing. The supporting engine of the test is a TCC electric four-drive soil trough test rig, operating at a speed of 4.5 km/h–5.0 km/h. The rotation speed of the film cutter shaft of the roll-type plow residual film recovery machine is 22.37 rad/s, the rotation speed of the pickup roller is 4.58 rad/s, the rotation speed of the unloading wheel is 4.5 rad/s, the pickup roller, and the unloading wheel are, respectively, driven by the hydraulic system of the soil tank test bench to rotate the hydraulic motor, and the speed control valve is used. The rotation of the roll to pick up the film is driven by the film-unloading wheel through the chain drive to ensure that the speed is 13.74 rad/s; The rotation of the reversing film-unloading roll is driven by the pickup drum through the chain drive. Its speed is 17.57 rad/s.



Figure 13. Soil trough test of the roll-type residual film recovery mechanism for the tillage layer.

During the operation performance test of the roller plow residual film recovery machine, first, a square with an area of 1 × 1 m was selected from cotton fields planted for more than 10 years in Shaya County, Xinjiang. The residual film was excavated at the soil depth of 0~50 mm, 50~100 mm, and 100~150 mm, with dust and moisture removal after—called its quality; Then, we selected a 1 × 1 m area in the field and buried the residual film obtained from the field according to the depth of soil layer. Then, the operation test of the roller-type topsoil residual film recovery machine is carried out. Finally, the residual film of the soil taken through the test site is dug, and its quality is measured after removing dust and water. Equation (25) is utilized to compute the collection rate of the tilled layer, and the results of the field tests are shown in Table 1.

$$J = \left(1 - \frac{W}{W_0}\right) \times 100 \tag{25}$$

Table 1. Performance of the roll-type residual film recovery mechanism for the tillage layer.

Parameters	Test Value	Technical Requirements
Tillage gathering rate/%	71.6	≥70
Surface gathering rates/%	83.4	≥80
Gathering depth/mm	150	100–150

3. Results and Discussion

3.1. Analysis of Simulation Result

As shown in Figure 13, in the film-picking area and film-unloading area, the middle peak of the curve is selected as the research object according to the movement of the tooth tips MARKER_499, MARKER_500, and MARKER_505, and the movement displacement parameters of the tooth tips are obtained, as shown in Table 2.

Table 2. Movement and displacement of the spring-tooth tip.

Region	MARKER Point	X Direction (mm)	Y Direction (mm)	Displacement Difference in X Direction (mm)	Displacement Difference in Y Direction (mm)	Resultant Displacement (mm)
Film picking area	MARKER_499	28.077	−39.784	/	/	/
	MARKER_500	36.830	−60.124	8.754	−20.340	22.146
	MARKER_505	204.406	99.908	167.576	160.032	231.715
Film unloading area	MARKER_499	354.786	274.470	/	/	/
	MARKER_500	365.384	287.822	10.599	13.352	17.047
	MARKER_505	370.808	53.856	5.423	−233.965	234.028

As shown in Figure 14, to analyze the speed change law of the spring-tooth tip, MARKER_499 was taken as the analysis object, the speeds in the middle of the film-picking

area and the film-unloading area were selected to obtain the speed of MARKER_499 in the X and Y directions, and its absolute speed was calculated, as shown in Table 3.

Table 3. Movement speed of MARKER_499.

Region	Time (s)	Speed	Speed Value (mm/s)
Film picking area	0.1725	V_X	10,853.304
		V_{Y_max}	79,067.991
		V_1	79,809.407
	0.2025	V_{X_max}	79,547.043
		V_Y	−16,299.129
		V_2	81,199.715
	0.225	V_X	13,087.599
		V_{Y_min}	−80,130.655
		V_3	81,192.408
	0.255	V_{X_min}	−78,571.015
		V_Y	−7680.219
		V_2	78,945.489
Film unloading area	0.8925	V_{X_max}	104,590.000
		V_Y	3777.761
		V_1	104,658.204
	0.9	V_X	−97,438.332
		V_{Y_min}	31,050.612
		V_2	102,266.168
	0.9075	V_{X_min}	−85,883.109
		V_Y	−53,020.734
		V_3	100,931.198
	0.9225	V_X	−54,415.665
		V_{Y_max}	87,476.569
		V_4	103,020.458

The maximum displacement of the adjacent spring-tooth tips MARKER_499 and MARKER_500 of the same roller was 22.146 mm in the film-picking area and 17.047 mm in the film-unloading area. Regarding MARKER_500 and MARKER_505 on the adjacent roller, the maximum displacement between the spring-teeth in the film-picking area was 231.715 mm, and the maximum displacement between the spring-teeth in the film-unloading area was 234.028 mm. These results indicated that the gap between the spring-teeth of the picking mechanism was smaller during the film-picking operation, which is conducive to picking up smaller plastic film. The working width between the spring-teeth was larger when the film was unloaded to guide the design of the position and structural parameters of the film-unloading wheel.

According to the graphical analysis of the absolute speed of MARKER_499 at different time points, the speed distribution of MARKER_499 in the film-picking area and film-unloading area when the winding roller rotates one circle is shown in Figure 14. When MARKER_499 rotates with the pickup drum and the winding roller rotates, the speed direction of the spring-tooth tip was consistent with the direction of the spring-tooth picking up plastic film when it was in the positive direction of X, and the absolute speed of picking up plastic film was 79,809.407 mm/s, which was much faster than the speed of soil falling. This is conducive to the spring-tooth pick-up operation. When MARKER_499 was in other positions, the speed direction of the tooth tip would not convolve the residual film continuously, which was conducive to the later film-unloading operation. To ensure that the spring-tooth did not fall off when picking up the film, it was necessary to design the spring-tooth with a radian. In the unloading area, the speed direction of MARKER_499 in the X negative direction was consistent with the stripping direction of the tooth tip, and the absolute unloading speed was 102,266.168 mm/s, which was beneficial to the

stripping operation of the spring-tooth. Efficient stripping of residual plastic film from the spring-tooth had been achieved through the use of the unloading wheel, providing valuable guidance for the design of roller mechanisms. The success of this approach highlights its potential applicability in related areas.

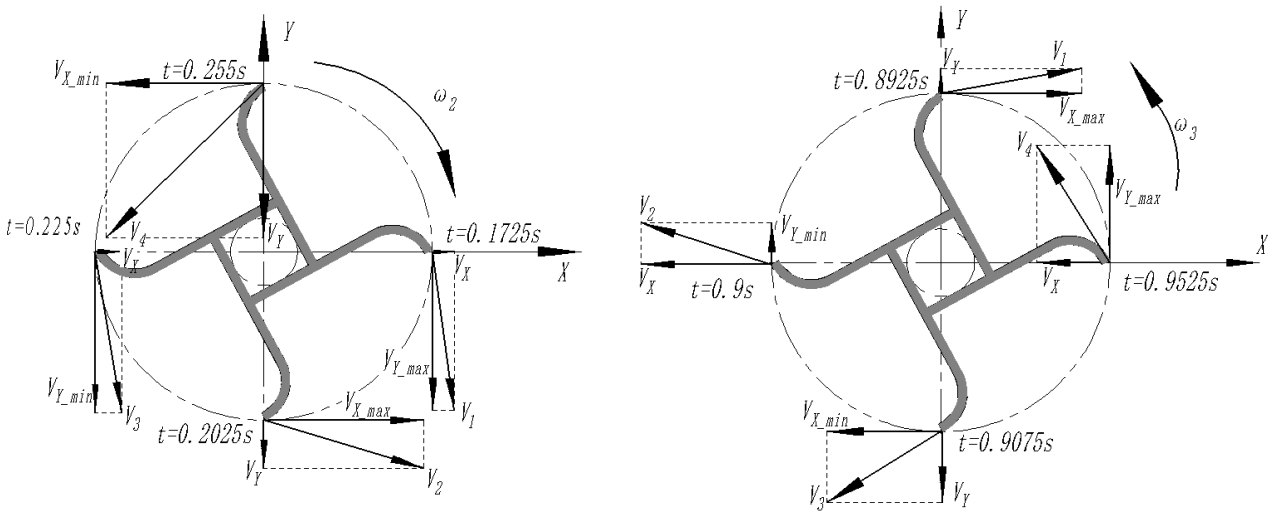


Figure 14. Velocity analysis of MARKER_499. (**a**) Speed change in the film-picking area; (**b**) speed change in film-unloading area.

3.2. Analysis of Results

The simulation results showed that the maximum displacement of the adjacent spring-tooth tips MARKER_499 and MARKER_500 in the picking up film area was 22.146 mm, and the maximum displacement of adjacent spring-tooth tips in the unloading film area was 17.047 mm. Regarding the spring-tooth tips MARKER_500 and MARKER_505 on the adjacent winding rollers, the maximum displacement of the spring-tooth tip in the film-picking area was 231.715 mm, and the maximum displacement of the spring-tooth tip in the film-unloading area was 234.028 mm. By simulation and graphic analysis, when the spring-tine MARKER_499 was in the X positive direction, the velocity direction of the spring-tine MARKER_499 was determined to be the same as the direction of the spring-tine picking up plastic film, and the absolute velocity of the picking of plastic film was 79,809.407 mm/s, which was good for the spring-tine picking up. When MARKER_499 was at other positions, the speed direction of the tooth tip would not wind the residual film continuously, which was beneficial to the later film-unloading operation. In the area of the stripping film, the speed direction of MARKER_499 was the same as the direction of the stripping film when it was in the negative direction of X, and the absolute speed of the stripping film was 102,266.168 mm/s, which was beneficial to the stripping work of the spring-tooth.

The roller-plow residual film recovery machine demonstrated an operating depth of 150 mm during bench testing, with a tillage gathering rate of 71.6% and a surface gathering rate of 83.4%. These results aligned with national and industry standards, confirming the machine's design requirements and validating simulation analysis results. Overall, the experimental findings were consistent with expectations.

3.3. Discussions

At present, there are more studies on tillage residue film recovery, but there are still problems, such as a low pick-up rate of tillage residue film recovery and large amount of soil in the recovered residue film. Because of the above problems, this paper proposed an active roll-type method of picking up residual film, designed a roll-type tillage residual film recovery machine, and analyzed the operating parameters of key components of

the roll-type recovery mechanism. While ensuring that the effective working depth was maintained at 150 mm, the residual film pick-up rates were improved from 68% and 73.83% in the past to 71.6% and 83.4%. In addition, the operational parameters of the roll-type tillage residue collector were analyzed using the ADAMS software (Version No. 2019), and the analysis process in this study was more efficient and the analysis and simulation results were more reliable compared to the traditional research methods. Compared with the existing related studies, the active hook-and-roll method of picking up residual film proposed in this paper is more innovative, which can effectively overcome the problem of difficult recovery of tillage layer residual film and can provide an effective solution for the management of tillage layer residual film pollution in agricultural fields.

4. Conclusions

(1). Through the analysis of the working principle of the roller-type plow layer plastic film collector, it could collect the plastic film residue within the plow layer depth of 150 mm [25,28]. The roller-type plastic film collector could effectively separate the plastic film residue from the soil and stubble mixture by using the spring-tooth and the film–soil mixture falling in the same direction. Moreover, the spring-tooth speed was greater than the falling speed to reduce the reaction force of the soil on the residual film in the process of picking up the film by the spring-tooth, overcome the problem of poor mechanical properties of the plow layer residual film, and improve the operation performance of the plow layer residual film recovery mechanism.

(2). According to the kinematics and dynamics analyses of the roller-type mulch film collector in the process of picking up and unloading the film, the rotating speed of the film-picking knife was 22.37 rad/s, the rotating speed of the picking roller was 4.58 rad/s, the forward rotation speed of the roller for picking up the film was 13.74 rad/s, and the reversing unloading speed of the roll was 17.57 rad/s. The rotation speed of the film-unloading wheel was 4.5 rad/s, which provided theoretical guidance for the design of the operation parameters of the roller-type plow layer plastic film collector.

(3). By simulation, the analysis showed that the gap between the spring-teeth of the winding roller-type recovery mechanism was smaller during the film-picking operation, which was conducive to picking up small residual films. During the unloading of the film, the working width between the spring-tooth tips was larger, which provided a guiding basis for the position and parameter design of the film-unloading wheel. The movement of the roller-type plastic film recycling mechanism met the design requirements, which could complete the operation process of the roller-type plastic film recycling mechanism in the film collection area and in the film discharge area. Moreover, the plastic film could be effectively recycled in the plow layer, which provided theoretical guidance for the design of the roller-type plastic film recovery mechanism.

(4). Through the bench test, the operating depth of the roller plow residual film recovery machine reached 150 mm, the tillage gathering rate was 71.6%, and the surface gathering rate was 83.4%. All the test indexes met the requirements of the national and industry standards, the test results met the design requirements, and the results of experiments were consistent with the simulation analysis results.

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References

1. Chen, Q.; Wu, C.; Chen, G.; Li, Z. The effect of the different overlay on growth and yield of spring peanut. *J. Guangxi Agric.* **2013**, *28*, 28–30.
2. Xie, J.; Chen, X.; Sun, C. Unloading film process analysis and high-speed photography experiment of pole-tooth residual plastic film collector. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 17–24.
3. Jin, W.; Liu, J.; Xu, C.; Zhang, X.; Bai, S. Design, Simulation and Experimentation of a Polythene Film Debris Recovery Machine in Soil. *Appl. Sci.* **2022**, *12*, 1366. [CrossRef]
4. Peng, Q.; Li, K.; Wang, X.; Zhang, G.; Kang, J. Design and Test of Stripping and Impurity Removal Device for Spring-Tooth Residual Plastic Film Collector. *Agriculture* **2023**, *13*, 42. [CrossRef]
5. Wang, H. Preparation and Performance Study of the Full-Degradable Polythene Films. Master's Thesis, Shangdong University of Science and Technology, Qingdao, China, 2011.
6. Yan, W.; Hu, Z.; Wu, N.; Xu, H.; You, Z.; Zhou, X. Parameter optimization and experiment for plastic film transport mechanism of shovel screen type plastic film residue collector. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 17–24.
7. Xie, J.; Hou, S.; Liu, Y. Research status and trends of plastic film residue collectors. *Chin. Agric. Mech.* **2012**, *5*, 41–44. [CrossRef]
8. Xue, S.; Chen, X.; Li, J.; Wang, X.; Zhang, Z. Design of and Experiment on a Film Removal Device of an Arc-Toothed Residual Film Recovery Machine before Sowing. *Appl. Sci.* **2021**, *11*, 8551. [CrossRef]
9. Tuna, E. *Producing Biodegradable Plastics Using Activated-Sludge Polyhydroxyalkanoates in Mixed Composition*; University of California: California, CA, USA, 2012.
10. Hu, C.; Hu, Y.; Wang, X. Effect of residual plastic films on survival rate of cotton seeds in South Xinjiang. *Int. Agric. Eng.* **2017**, *26*, 19–25.
11. Zhou, X.; Hu, Z.; Yan, W.; You, Z.; Wu, N. Research status of domestic residual film recovery machine to take off the film device. *J. Agric. Mech. Res.* **2016**, *38*, 263–268.
12. Xu, H.; Hu, Z.; Wu, F.; Gu, F.; Wei, H.; Yan, J. Design and experiment of network chain type residual plastic film collector for peanut field. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 1–9.
13. Duan, W.; Wang, J.; Li, Y.; Gong, H.; Niu, H.; Luo, W.; Bi, X. Design and test of clamping finger-chain type device for recycling agricultural plastic film. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 35–42.
14. Zhao, Y.; Zhang, X.; Jin, W.; Yuan, P.; Liu, J. Design of Pick-up mechanism for the chain-teeth-rake topsoil incomplete plastic film recycling machine. *J. Agric. Mech. Res.* **2019**, *41*, 119–123.
15. Li, C.; Bai, S.; Jin, W. Design and experiment on picking mechanism of chain tooth type plough residue film reclaiming machine. *J. Agric. Mech. Res.* **2019**, *41*, 107–111.
16. Shi, Z.; Tang, X.; Zhen, J.; Zhang, X.; Jin, W. Performance test and motion simulation analysis of nail tooth type mechanismfor collecting plastic residue. *Trans. Chin. Soc. Agric. Eng.* **2019**, *35*, 64–71.
17. Zhang, P.; Hu, C.; Wang, X.; Lu, B.; Liu, C. Kinetic analysis of rotary tillage nail Tooth plastic film recycling machine hook film unit. *J. Agric. Mech. Res.* **2018**, *40*, 14–19.
18. Zhang, P. Design and Test Research of Rotary Tillage Nail Tooth Plastic Film Recycling Machine. Master's Thesis, Tarim University, Alar, China, 2018.
19. Jin, W.; Zhang, X.; Zhang, C.; Shi, Z.; Yan, J.; Wang, H.; Shu, D. Optimization of pick-up teeth and roller for automatic unloading film recycling machine. *J. Agric. Sci. Technol.* **2016**, *18*, 96–103.
20. Li, B.; Wang, J.; Hu, K.; Jiang, B. Analysis and test of forward film removing mechanism for polythene film collector. *Trans. Chin. Soc. Agric. Eng.* **2012**, *28*, 23–28.
21. Shi, Z.; Zhang, X.; Yan, J.; Jiang, Y.; Yao, J. Experiment and Analysis of Film-Soil Separation Motion Characteristics of a Chain Drive Residual Film Recovery Mechanism for the Tillage Layer. *Appl. Sci.* **2022**, *12*, 5884. [CrossRef]
22. Han, C.; Yuan, P.; Zhang, X.; Jin, W.; Shi, Z. Design and test of combined operation machine for collecting nail-tooth plastic film. *Int. Agric. Eng. J.* **2017**, *26*, 87–94.
23. Wang, C.; Cheng, F.; Wang, X.; Liu, Y.; Guo, X. Analytical research on intensity of the arc spring-finger type plastic film residue pickup cylinder. *Trans. Chin. Soc. Agric. Mach.* **2007**, *38*, 76–78.
24. Na, M.; Dong, X.; Hou, S.; Zhang, H.; Li, Y.; Yang, X. Research on main components of the machine for retrieving the used plastic film after harvesting. *Trans. Chin. Soc. Agric. Eng.* **1999**, *15*, 112–115.
25. *GB/T 25412-2021*; Farm Waste Film-Pick Up Machines. China National Standardization Administration Committee, China Standards Press: Beijing, China, 2021.
26. Zhao, W.; Shi, Z.; Dai, F. *ADAMS2013 Basic and Application Case Tutorial*; Tsinghua University Press: Beijing, China, 2015.

27. Shi, Z.; Zhang, X.; Zhao, W.; Yan, J.; Wei, L. Analysis of kinetic characteristics and simulation of vibrating sieve of 4UX-550 potato harvester. *J. Gansu Agric. Univ.* **2013**, *48*, 156–160.
28. *NY/T 1227-2019*; Operation Quality of Residual Plastic Film Recycling Machine. Ministry of Agriculture of the People's Republic of China: Beijing, China, 2019.

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