DESIGN AND EXPERIMENT OF FINGER-CHAIN GRAIN LIFTER FOR RATOON RICE STUBBLE ROLLED BY MECHANICAL HARVESTING
/
再生稻机收碾压稻茬扶正机设计与试验

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ABSTRACT
For rice ratooning, the lateral bud germination of the rice stubble after the first harvesting can be used to continue the next growing season, but the first harvesting machinery will crush and damage the rice stubble, resulting in the reduction of yield in the ratooning season. Lifting the rolled stubble can reduce this loss, and thus a double-chain finger grain lifter was designed in this study. Then, a kinematic model and motion trajectory curve of the grain lifter was established. The influence law of the chain speed, chain spacing and the number of fingers of the rear lifting chain was determined. Furthermore, taking into account the success rate and the rate of secondary damage of the lifting, a full-factor bench test was performed. The best operating characteristics of the grain lifter are: chain speed of 345 r/min, adjacent chain spacing of 300 mm, and the number of gears and fingers on the rear lifting chain of 3. The success rate and the secondary damage rate of the lifting is 90.05% and 1.72%, respectively. A field verification test was conducted, with an average success rate of 55%. The results of this study can provide valuable reference for the lifting technology of rolled rice stubble and promote the whole mechanized production of ratoon rice.

摘要
再生稻可利用头季收割后稻茬的侧芽再萌发继续完成下一个生长季，但头季稻机械收获会碾压和损伤稻茬造成再生季减产。扶正被碾压的稻茬能够减小这种损失。为此本研究设计了双链排扶正装置，构建了扶正齿爪运动学模型及其运动轨迹曲线，确定了影响扶正装置工作性能的主要因素为链排转速、相邻链排间距和后扶正链排齿爪个数；进而以扶正成功率和扶正二次损伤率为评价指标，开展全因素台架试验，确定扶正装置最优工作参数组合为链排转速345r/min、相邻链排间距300mm和后扶正链排齿爪数3个，其扶正成功率为90.05%，扶正二次损伤率为1.72%；通过田间试验验证了田间平均扶正成功率为55%。本研究结果可为再生稻机收碾压稻茬扶正装置研发提供参考。

INTRODUCTION
Rice ratooning is a kind of rice production mode, which uses the lateral bud germination characteristics of rice stubble after harvesting to promote lateral bud growth, regenerated tillers and earings again through irrigation and fertilization, so as to achieve the purpose of one planting and two harvests. Agronomic experts labeled the rice varieties with strong lateral bud germination ability as ratoon rice and optimized their cultivation. *(Mamun et al., 2019; Munda et al., 2009; Faruq et al., 2014; Bahar et al., 1977; Shamiul et al., 2008; Thi et al., 2017)* However, in the mechanized production of ratoon rice, its mechanical harvesting in the first season will crush and seriously damage the stubble, resulting in the reduction of the second harvest yield, which is one of the main problems affecting the mechanized production of ratoon rice and preventing its large-scale adoption and utilization, at present.

This problem was addressed by the relevant scholars through research on the damage reduction technology and equipment for harvesting rice, both in terms of improving or redesigning the special harvester for ratooning rice and harvesting path planning. For the new type of rice combine harvester, the academic team of Luo Xiwen of South China Agricultural University *(Zeng et al., 2018a; Zeng et al., 2018b; Yang et al., 2019)* explored how to minimize the rolled rate by shifting the distance between walking wheels and by adopting narrow wheels with large ground gaps.

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The narrow wheel and high-ground gap ratooning grain header, broad full-tracked double-header ratooning rice harvester, and double-channel feeding ratooning rice harvester were created by Professor Zhang Guozhong of Huazhong Agricultural University *(Zhang et al., 2016; Lu et al., 2017; Fu et al., 2020)*. The ratooning rice harvester was lightened by Professor Li Yaoming of Jiangsu University *(Wang et al., 2021; Huang et al., 2020)* to prevent harm to rolled rice stubble. Path planning navigation and machine vision navigation were used by Shi Huojie and Guo Hanlin from Fujian Agriculture and Forestry University *(Guo et al., 2016)* to minimize the stubble rolled rate of ratoon rice harvesting machines. However, due to constraints imposed by planting patterns, agronomic requirements, working environment, and other factors, there are few application reports in actual production, and the technical equipment for harvesting and rolled rice stubble in the first season of ratoon rice requires additional study.

In order to address the aforementioned issues, this paper developed a double-layer chain gear-finger grain lifter based on the single-layer chain finger grain lifter previously designed for rice ratooning *(Zhang, 2019)*, and the kinematic model and motion trajectory curve were constructed during the working process of lifting finger. To better understand how the grain lifter affects the harvesting of rice stubble, we conducted bench and field experiments in order to identify the optimal combination of working parameters. The results of the experiment will serve as a guide for future research and development of rice stubble-related grain lifter for rolled ratoon rice machine harvesting, as well as for the widespread popularization and application of rice ratooning in suitable areas.

MATERIALS AND METHODS

Overall structure and working principle

The double-chain finger grain lifter used for lifting the ratooning rice stubble rolled by harvesting process is primarily composed of the following components: front lifting chain finger mechanism, rear lifting chain finger mechanism, lifting chain finger transmission mechanism, adjacent chain spacing adjustment, finger buried angle adjustment mechanism and other components as necessary. The lifting unit was formed by the front and rear lifting chain, gear unit, fingers, as illustrated in figure 1. Lifting chain and finger, driven sprocket, active sprocket, rubber block, finger retraction setting assembly, finger unfolding guide, gear finger arc transition ejection mechanism, chain support plate, etc., as illustrated in figure 2, are the major components of the grain lifter.

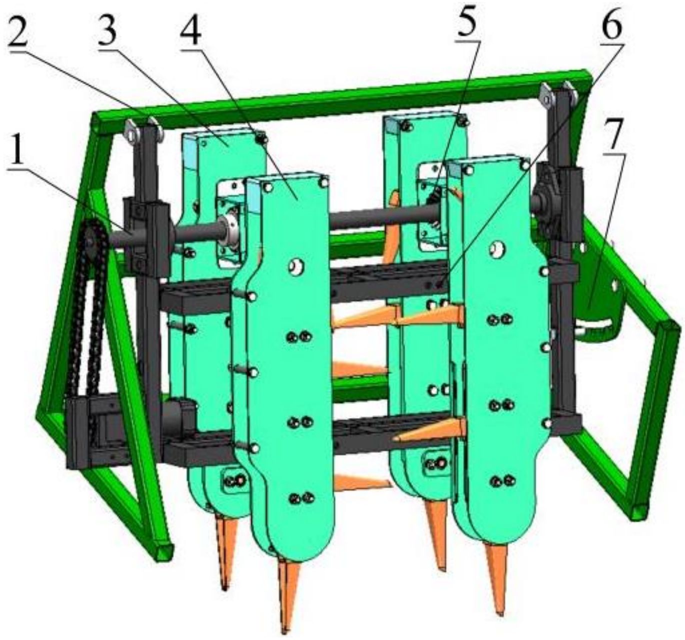


Fig. 1 - **Structure diagram of double-chain finger grain lifter**

1. Power input shaft; 2. Lifting rack; 3. Front lifting chain finger mechanism; 4. Rear lifting chain finger mechanism; 5. Lifting chain finger transmission mechanism; 6. Chain spacing adjustment mechanism; 7. Finger buried angle adjustment mechanism

External power drives the power input shaft to rotate, which drives the axle drive bevel pinion in the lifting chain finger transmission mechanism to rotate, and then drives two groups of passive bevel gears in the lifting chain finger transmission mechanism to rotate during the lifting operation. In this way, the chain in the front and rear lifting chain finger mechanism and the lifting fingers mounted on the chain are driven to rotate, so as the rolled rice stubble lifting operation may be accomplished.

According to different operations, the rotation of the chain in a cycle can be divided into five stages: unfolding process, reeling process, lifting process, retraction process and hollow travel process. As shown in Figure 2, the unfolding and reeling process refers to the process in which the fingers pass around the bottom driven sprocket *2* and start moving up along the chain *3*. In this possess, under the action of transition component *8*, the fingers change from the tangential direction of the chain to the outer normal direction and roll up the lodging stubble. The lifting process is that after the reeling stage, under the action of the unreeling guide rail *7*, the fingers always keep the outward normal direction when moving upward along the chain, so as to ensure that the lodging stubble is lifted until it is separated from the end of the stubble. The fingers continue to move upward along the chain and enter the retraction process until it disengages from *7* guide rail. Then under the action of gravity, the fingers rotate downward from the outer normal direction to the tangent direction. When the fingers continue to go up around the upper drive sprocket *4* of the chain, it maintains the tangent direction under the constraint of the *5,* rubber block. After that, the fingers go around the upper sprocket and move down under the drive of the chain to enter the hollow travel process. During the hollow travel, the fingers still maintain the tangential direction of the chain until it encounters the transition component *8*, and then enters the reeling process. Since then, a lifting cycle is completed.

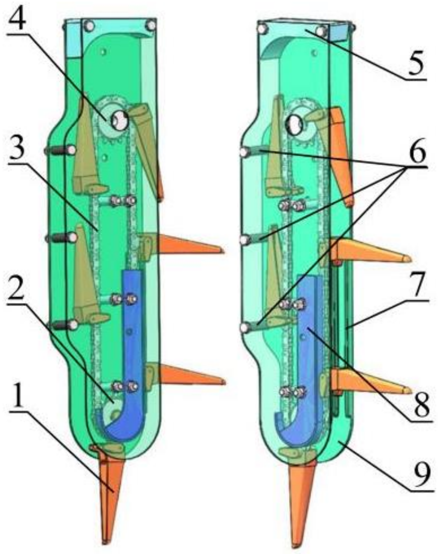


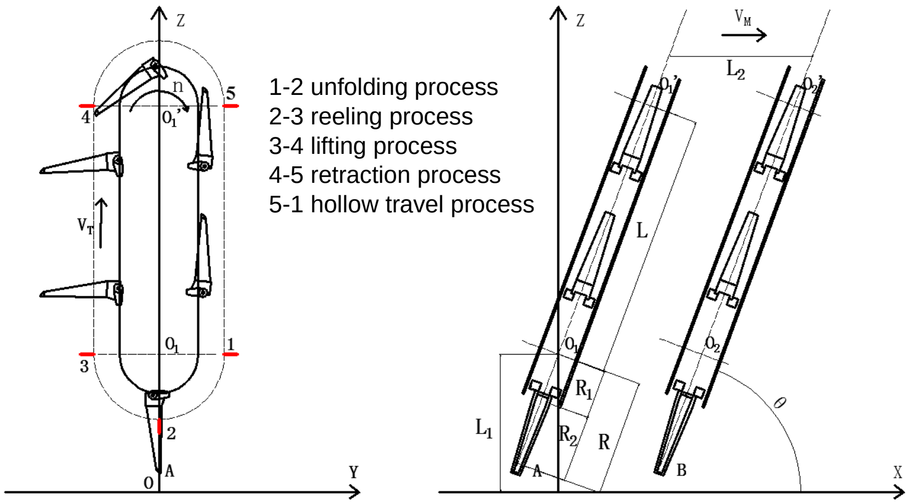
Fig. 2 - Structure diagram of lifting chain finger mechanism

1. Lifting finger; 2. Driven sprocket; 3. Chain; 4. Drive sprocket; 5. Rubber block; 6. Finger retraction setting assembly; 7. Finger unfolding guide; 8. Finger ejection transition component; 9. Chain support plate

KINEMATIC ANALYSIS OF LIFTING FINGERS

Taking the ground projection point of the driven sprocket center as the origin O, taking the forward direction of the machine as the X axis, and the vertical upward direction of the O point as the Z axis, a spatial rectangular coordinate system is established, as shown in the Figure 3. Among them, the inclination angle of chains is θ; the centers of driving sprocket and driven sprocket of rear chains are O_1 and $O_{1'}$, respectively. The center of driving sprocket and driven sprocket of front chains are O_2 and $O_{2'}$, respectively. The distance between the centers of driving sprocket and driven sprocket is L; The distance between the driven sprocket center and the rotation center of finger on the meshing sprocket is R_1; the distance from any point A on the lifting finger to the rotation center of the finger is R_2; the distance from point A to the center of the driven sprocket is R; the distance between the center of the driven sprocket and the ground is L_1; the distance between the front and rear chains in the x-axis direction is L_2. The forward speed is VM, the chain speed is N, and the chain speed is VT.

Furthermore, if the analysis object is any point A on the lifting finger, the one cycle rotation of point A around the chain is recorded as a cycle, and the duration of one cycle rotation is specified as T, a is the number of cycles of finger rotation. A motion trajectory equation of point A is then established by t_1, t_2, t_3, t_4, and t_5 being the total time of the lifting finger unfolding process, reeling process, lifting process, retraction process, and the hollow travel process, as shown in the formula (1)-(5).



(a) (b)

Fig. 3 - Kinematic model of working process

a) Front view of lifting chain; b) Diagram of location relationship for the front and rear chain location

During the unfolding process, the motion trajectory equation of point A is as follows:

$$\left\{\begin{array}{l} X_A = \left[R_2\cos\left[12n\left[t_1\text{-}\lambda_5\right]\right] - R_1\sin\left[6n\left[t_1\text{-}\lambda_5\right]\right]\right]\cos\theta + V_m t_1 \\ Y_A = R_2\sin\left[12n\left[t_1\text{-}\lambda_5\right]\right] + R_1\cos\left[6n\left[t_1\text{-}\lambda_5\right]\right] \\ Z_A = L_1 - \left[R_2\cos\left[12n\left[t_1\text{-}\lambda_5\right]\right] - R_1\sin\left[6n\left[t_1\text{-}\lambda_5\right]\right]\right]\sin\theta \end{array}\right\} \quad t_1 \in \left(\lambda_5, \lambda_6\right) \tag{1}$$

During the reeling process, the motion trajectory equation of point A is as follows:

$$\left\{\begin{array}{l} X_A = -R\cos\left[6n\left(t_2-\lambda_1\right)\right]\cos\theta + V_m t_2 \\ Y_A = -R\sin\left[6n\left(t_2-\lambda_1\right)\right] \\ Z_A = L_1 - R\cos\left[6n\left(t_2-\lambda_1\right)\right]\sin\theta \end{array}\right\} \quad t_2 \in \left[\lambda_1,\ \lambda_2\right] \tag{2}$$

During the lifting process, the motion trajectory equation of point A is as follows:

$$\left\{\begin{array}{l} X_A = V_T\left[t_3-\lambda_2\right]\cos\theta + V_m t_3 \\ Y_A = -R \\ Z_A = V_T\left[t_3-\lambda_2\right]\sin\theta + L_1 \end{array}\right\} \quad t_3 \in \left(\lambda_2, \lambda_3\right] \tag{3}$$

During the retraction process, the motion trajectory equation of point A is as follows:

$$\left\{\begin{array}{l} X_A = \left[R_1\sin\left[6n\left[t_4-\lambda_3\right]\right] + R_2\sin\left[3n\left[t_4-\lambda_3\right]\right] + L\right]\cos\theta + V_m t_4 \\ Y_A = -\left[R_1\cos\left[6n\left[t_4-\lambda_3\right]\right] + R_2\cos\left[3n\left[t_4-\lambda_3\right]\right]\right] \\ Z_A = \left[R_1\sin\left[6n\left[t_4-\lambda_3\right]\right] + R_2\sin\left[3n\left[t_4-\lambda_3\right]\right] + L\right]\sin\theta + L_1 \end{array}\right\} \quad t_4 \in \left(\lambda_3,\ \lambda_4\right) \tag{4}$$

During the hollow travel process, the motion trajectory equation of point A is as follows:

$$\left\{\begin{array}{l} X_A = \left[L + R_2 - V_T\left[t_5-\lambda_4\right]\right]\cos\theta + V_m t_5 \\ Y_A = R_1 \\ Z_A = \left[L + R_2 - V_T\left[t_5-\lambda_4\right]\right]\sin\theta + L_1 \end{array}\right\} \quad t_5 \in \left(\lambda_4,\ \lambda_5\right] \tag{5}$$

In the formula (1)-(5),

$$\lambda_1 = aT,\ \lambda_2 = \frac{\pi R_1}{2V_T} + aT,\ \lambda_3 = \frac{\pi R_1 + 2L}{2V_T} + aT,\ \lambda_4 = \frac{3\pi R_1 + 2L}{2V_T} + aT,\ \lambda_5 = \frac{3\pi R_1 + 4L}{2V_T} + aT,\ \lambda_6 = \frac{2\pi R_1 + 2L}{V_T} + aT\ .$$

In order to obtain the movement trajectory of the lifting finger end in the process of machine movement, the influence characteristics of the structural parameters of the lifting mechanism on the lifting process are analyzed by taking the rotational speed of the chains, the distance between the left and right adjacent chains and the number of the finger in the rear lifting chains as variables. Among them, the structural parameters of the centralizer designed in this study are R_1=0.06 m, R=0.177 m, θ = 70, V_m=0.75 m/s, L=0.405m, L_1=0.17m, L_2=0.233m.

1) The influence of the speed of the chains on the trajectory of finger

Based on formulas (1)-(5), the rotational speeds of chains are 100 r/min, 200 r/min and 300 r/min respectively, and the motion trajectory curves of different rotational speeds for the process of finger unreeling, hugging, lifting, retracting and hollow travel are constructed, as shown in Figure 4.

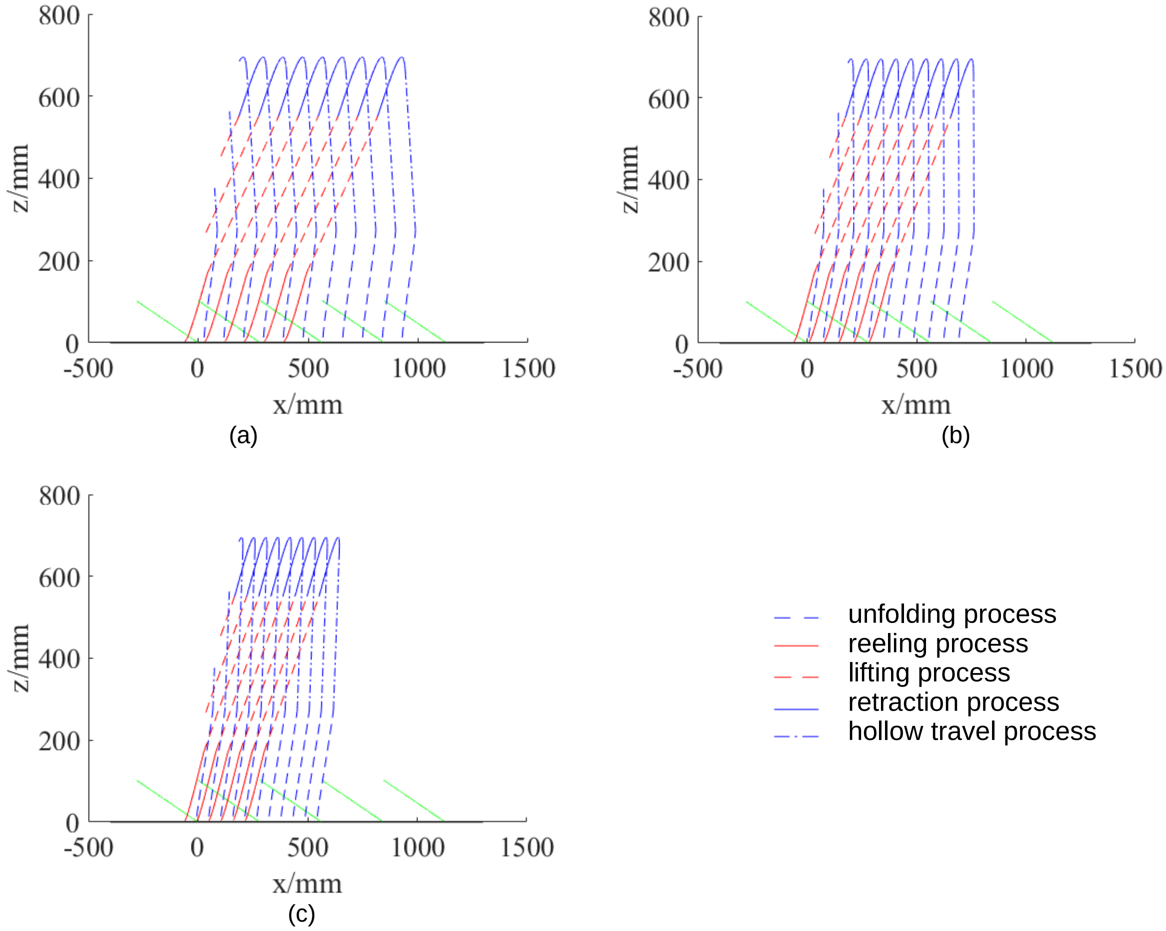


Fig. 4 - Finger motion trajectory of different chain rotational speed

a) Chain rotational speed 100 r/min; b) Chain rotational speed 200 r/min; c) Chain rotational speed 300 r/min

As can be seen from Figure 4, the greater the speed of chains is, the denser the trajectory curves of fingers are. In the case of the same number of fingers, the faster speed of the chain, the more times the fingers focus on the rice stubble, and the higher the success rate of improvement. However, the greater the speed of the chains is, the greater the impact kinetic energy of the fingers on the rice stubble is, which will cause secondary damage to the rice stubble in the process of lifting. Therefore, the determination of chain speed needs to comprehensively consider the centralization rate and secondary damage. In addition, the rotational speeds of the chains and the number of fingers on the chains are the main factors that determine the lifting times of rice stubble. Appropriate combination of the rotational speed of the chains and the number of fingers can coordinate the relationship between the success rate of lifting and the secondary damage rate of lifting.

2) The influence of the distance between adjacent chains on the double-chain lifting breadth

The spacing between chains determines the effective area of lifting process. According to formulas (1)-(5), the motion trajectories of left and right adjacent chains are constructed respectively, and the adjacent spacing is set as 240 mm, 300 mm and 360 mm, respectively. The motion trajectory curves of left and right chains in the process of unfolding, reeling, lifting, retracting and hollow travel are shown in Figure 5.

As can be seen from Figure 5, the distance between adjacent chains is inversely proportional to the overlapping area of left and right finger trajectories and directly proportional to the working area of left and right finger. However, when the distance between adjacent chains exceeds twice the length of finger, missing support will occur, and too close distance will cause too small lifting area. Ideally, the distance between adjacent chains is exactly equal to twice the length of fingers, which can realize the maximum lifting area without leaking support. However, the field ground situation is complex, and the different lifting resistance of adjacent fingers will cause asynchronism, that is, missing support will still occur. Therefore, the maximum adjacent distance between left and right chains without missing support still needs to be obtained through experiments.

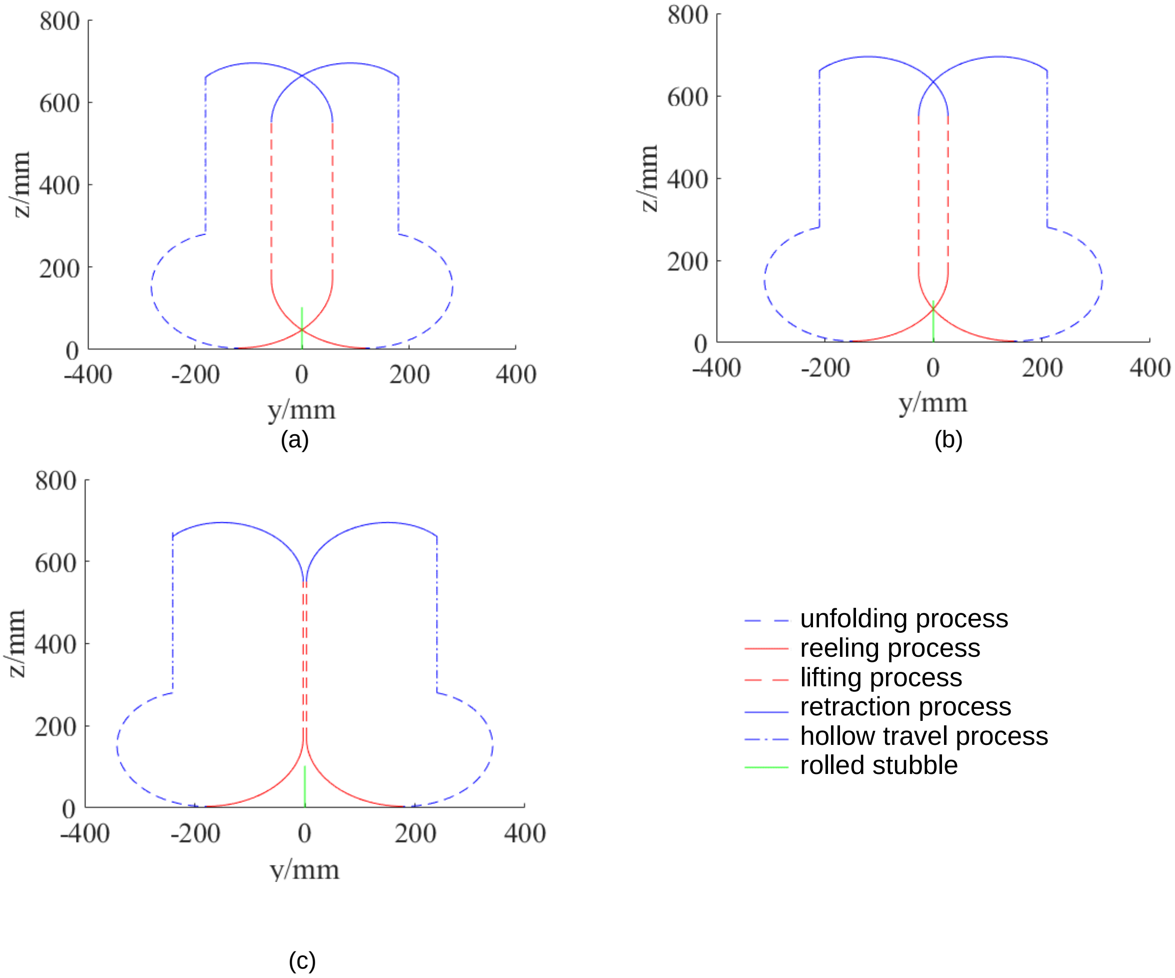


Fig. 5 - Finger motion trajectories with different distances between adjacent chains
a) Space 240 mm; b) Space 300 mm; c) Space 360 mm

Bench test

In the field, the rice stubble was randomly selected according to the average number of rice tillers, the stubble height was 350 mm, and the soil column of 200 mm long ×200 mm wide × 250 mm deep was dug by the field soil column method. The ratoon rice variety was Kenliangyou 801. A double-chain finger lifting test bench is built, which is mainly composed of double-chain finger grain lifter, speed regulating motor, installation frame, H80-70 guide rail, rolled rice stubble and test soil tank, etc. Fifteen bags of rolled rice stubble soil column samples are prepared in the test soil tank, as shown in Figure 6.

Based on the previous studies, the forward speed of the centralizer is 0.75 m/s, the front chains finger is 6, and the chains speed is 263 r/min, 345 r/min and 431 r/min respectively *(Zhang, 2019)*. Taking the speed of chains, the distance between adjacent chains and the number of fingers in the rear lifting chains as test factors, and the success rate of lifting and the secondary damage rate as evaluation indexes, the all-factor bench test of lifting performance was carried out. Among them, the distance between adjacent chains is 240 mm, 300 mm and 360 mm, and the number of fingers in the rear chains is 0, 3 and 6, respectively.

Fig. 6 - **Performance test rack of double-layer chain finger grain lifter**

1. Layer chain finger grain lifter; 2. Adjustable-speed motor; 3. Installation rack;
2. 4. H80-70-type guide rail; 5. Rolled rice stubble 6. Test soil trough

Field test

In order to verify the actual operation effect of the optimal combination of working parameters in bench test, a field test was carried out in Yangwan Village, Duchang County, Jiujiang City, Jiangxi Province in August 2020, and the traction power was the transplanter head. The experimental field area is 1334 m^2, the variety is Kenliangyou 801, the planting density is 140 mm × 300 mm, and the average stubble height is 350 mm. The operation effect is shown in Figure 7. After mechanical lifting, 10 stumps were randomly selected to roll lifting rice stubble, and the success rate of lifting was counted, with 5 repetitions. Because the straightening machine has transplanter head traction, it is inevitable that rice stubble will be rolled again during the traveling process, and the causes of secondary damage in the straightening process are difficult to define clearly, so the secondary damage rate is not counted in the field test in this paper.

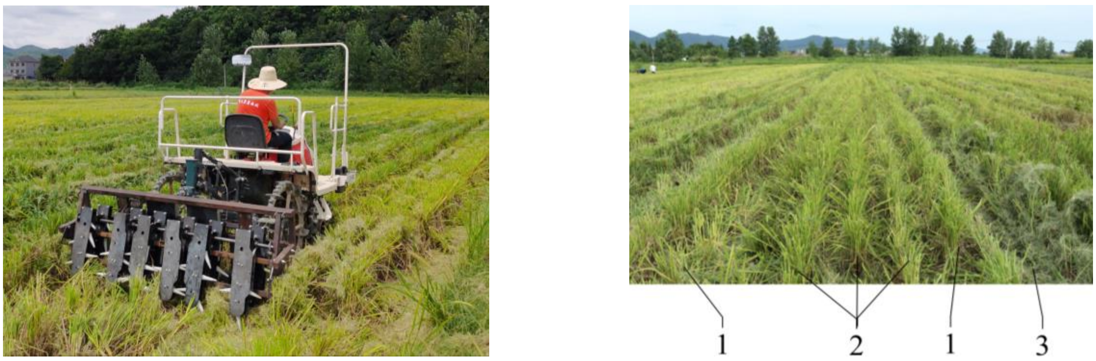


Fig. 7 - **Field verification test**

a) Harvesting and rolled rice stubble lifting prototype of ratoon rice;
b) Mechanical lifting effects drawing of field rolled rice stubble;
1. Raising rice stubble after milling; 2. Rice stubble chain without being rolled; 3. No rice stubble after milling;

Tests evaluation index

If the angle between the rolled rice stubble and the ground after lifting is ≥ 45°, the rolled rice stubble is considered to be successfully righted, and if the rolled rice stubble is broken during the lifting process, it is considered secondary damage to the rolled rice stubble, as illustrated in figure 8.

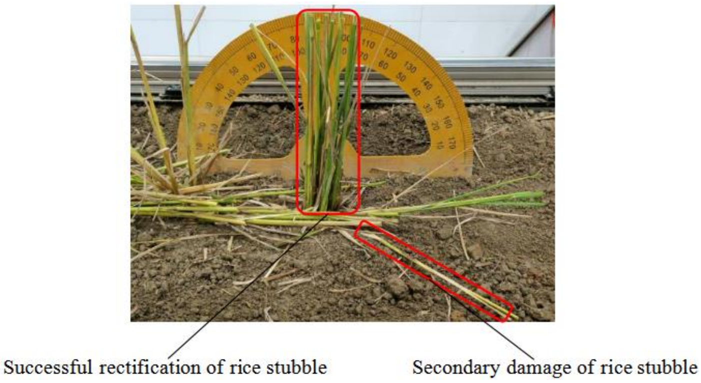


Fig. 8 - Lifting effect of rolled rice stubble

Then, the following formulas are used to calculate the lifting success rate F and the secondary damage rate S:

$$F = \frac{M_C}{M_Z} \times 100\% \tag{7}$$

$$F = \frac{N_D}{M_Z} \times 100\% \tag{8}$$

Wherein:

F -- lifting success rate, %

S — secondary damage rate of lifting, %

M_C — Number of rolled rice stubble after lifting,

N_D — The number of rolled rice stubble broken after lifting,

M_Z — Total number of rolled rice stubble

RESULTS

BENCH TEST

(1) Effect of different factors on lifting success rate of rolled rice stubble.

As can be seen from Table 1, when the distance between adjacent chains and the number of fingers in the rear chains is consistent, the lifting success rate is proportional to the rotational speed of the chains. When the rotational speed of the chains and the number of fingers of the rear chains are the same, the success rate of lifting first increases and then decreases with the increase of the distance between adjacent chains, and the success rate of lifting is the highest when the distance between adjacent chains is 300 mm, which is consistent with the previous theoretical analysis. When the distance between adjacent chains is the same, the relationship between the success rate of lifting and the number of fingers in the rear chains is affected by the speed of the chains, and the success rate of lifting is positively correlated with the number of fingers in the rear chains when the speed of the chains is 263 r/min and 345 r/min; at 431 r/min, the success rate of lifting no longer increased with the increase of the number of fingers in the subsequent chains, but showed a downward trend. It was considered that the single-layer chains could fully lift the rolled rice stubble at a higher chains speed, and the increase of the number of fingers in the later lifting chains caused a secondary negative effect on the lifted rice stubble. The results showed that when the rotational speed was 431 r/min, the distance between left and right adjacent chains was 300 mm, the number of fingers in the rear chains was 0, and the highest success rate of lifting rice stubble was 95.05%.

Table 1

Success rate/% of lifting for rolled rice stubble

chain speed/r·min^{-1}	distance between adjacent chains/mm	number of rear lifting chain fingers/piece		
		0	3	6
263	240	62.44±6.19aA	63.76±2.91aA	68.26±2.80aA
	300	65.72±7.79aA	69.67±3.10aA	77.68±4.47aA
	360	50.59±6.47aA*	63.30±5.74aA	73.70±4.77aA*
345	240	83.80±4.52bA	84.99±4.56bAB	85.01±3.40bAB
	300	85.74±4.12bA	90.05±2.37 bB	89.77±3.11bB
	360	73.63±5.88bA	74.30±4.60aA	75.22±5.19aA
431	240	94.72±1.33bA	88.33±2.77bA	90.19±2.60bA
	300	95.05±1.64bA	91.14±2.04bA	90.95±1.29bA
	360	87.95±3.43bA	87.90±2.60bA	87.52±2.23bA

Note: When p=0.05, the lowercase letters a and b in the table indicate that different chain rotational speed has a significant impact on lifting success rate; The uppercase letters A and B in the table indicate that different chain spacing has a significant effect on the success rate of lifting when p=0.05; "" in the table indicates that the success rate of lifting is significantly influenced by the number of fingers that are used.*

(2) Effects of different factors on secondary damage rate of rolled rice stubble lifting.

It can be seen from Table 2 that when the distance between adjacent chains and the number of fingers in the rear chains are the same, the secondary damage rate of lifting increases with the increase of chains speed. When the rotational speed of the chains and the number of fingers of the rear chains are the same, the secondary damage rate of lifting decreases first and then rises with the increase of the distance between adjacent chains. When the distance between adjacent chains is consistent, the secondary damage rate of lifting increases greatly with the increase of chains speed; the relationship with the number of fingers in the rear chain is affected by the speed of the chain. The secondary damage rate increases with the number of fingers in the rear chain when the speed of the chain is 263 r/min and 345 r/min, but the opposite trend appears at 431 r/min, namely the number of fingers in the rear chain decreases with the increase of the number of fingers in the rear chain. The results showed that the lowest secondary damage rate was 1.20% when the rotational speed was 263 r/min, the distance between left and right adjacent chains was 300 mm, and the number of fingers in the rear chains was 0.

Table 2

Secondary damage rate of rolled roll stubble lifting

chain speed/r·min^{-1}	distance between adjacent chains/mm	number of rear lifting chain fingers/piece		
		0	3	6
263	240	1.43±0.81aA	1.44±0.78aA	2.06±0.99aA
	300	1.20±0.65aA	1.37±0.93aA	1.46±0.82aA
	360	1.37±0.74aA	1.54±0.86aA	2.16±0.97aA
345	240	1.81±1.07aA	2.13±1.19aA	3.05±1.24aA
	300	1.58±0.89aA	1.72±0.79aA	1.94±1.34aA
	360	1.62±1.10aA	1.93±1.06aA	3.68±1.09aA
431	240	4.32±1.63aA	4.23±1.71aA	3.49±1.38aA
	300	3.83±1.22aA	3.15±1.11aA	2.93±1.34aA
	360	4.79±1.25bA	5.57±1.51bA	4.24±1.71aA

Note: The lowercase letters a and b in the table indicate that varying chain rotational speed has a significant effect on the secondary damage rate when p=0.05; the uppercase letters A and B in the table indicate that varying chain spacing has a significant effect on the secondary damage rate when p=0.05.

(3) Inter-subject effect inspection of lifting success rate and secondary damage rate

As shown in tables 3 and 4, the distance between the adjacent chains and the number of fingers of the rear lifting chain all affect the success rate and secondary damage rate.

Table 3

Inter-subject effect inspection of lifting success rate

Source of variance	Type III Sum of Squares	*df*	Mean Square	*F*	*P*	Partial Eta squared	Eta squared
Corrected Model	.322^a	6	0.054	25.742	0.000	0.885	
Intercept	17.142	1	17.142	8217.932	0.000	0.998	
Rotational speed of the chains	0.276	2	0.138	66.226	0.000	0.869	0.759
Spacing of adjacent chains	0.037	2	0.019	8.956	0.002	0.472	0.103
Number of tooth fingers	0.009	2	0.004	2.045	0.156	0.170	0.023
Within groups Error	0.042	20	0.002				
Total	17.506	27					
Corrected Total	0.364	26					

a. R^2 = 0.885 (After adjustment R^2= 0.851)

In conclusion, the secondary damage rate of rolled rice stubble lifting increases with the increase of lifting success rate as a whole. According to the results of inter-agent effect test, it can be concluded that the biggest factor affecting the success rate of lifting and the secondary damage rate is the speed of chains, which directly affects the contact lifting kinetic energy and the contact lifting frequency of rolled rice stubble, and the number of fingers in the rear chains also affects the contact lifting frequency of rolled rice stubble. Because the secondary damage mainly comes from two aspects: the kinetic energy produced by the contact between the rotation of the lifting chain finger and the lifting of the rolled rice stubble, and the contact lifting frequency of the rolled rice stubble, considering the success rate of lifting and the secondary damage rate comprehensively, the optimal working parameter combination of the grain lifter is as follows: the speed of the chains is 345 r/min, the distance between adjacent chains is 300 mm, and the number of fingers of the rear lifting sprocket is 3.

Table 4

Inter-subject effect inspection of lifting secondary damage rate

Source of variance	Type III Sum of Squares	*df*	Mean Square	*F*	*P*	Partial Eta squared	Eta squared
Corrected Model	.003a	6	0.001	17.651	0.000	0.841	
Intercept	0.018	1	0.018	556.271	0.000	0.965	
Rotational speed of the chains	0.003	2	0.002	46.967	0.000	0.824	0.746
Spacing of adjacent chains	0.000	2	0.000	5.164	0.016	0.341	0.082
Number of tooth fingers	5.371E-05	2	2.685E-05	0.822	0.454	0.076	0.013
Within groups Error	0.001	20	3.267E-05				
Total	0.022	27					
Corrected Total	0.004	26					

a. R^2= 0.841 (After adjustment R^2= 0.793)

Field test

It can be seen from Table 5 that the average lifting success rate of the double-chain finger grain lifter developed in this study in the field operation is 55%. It is quite different from the bench test results. On the one hand, the operation trajectories of mechanical planting and harvesting machines are irregular, resulting in an inconsistent lodging direction of the rolled stubble. This makes it difficult for the grain elevator to align with the lodging stubble that part of the lodging stubble outside the lifter and cannot be lifted. On the other hand, the grain lifter designed in this study does not consider the ground copying mechanism. Due to the rough ground, the fingers cannot touch into the stubbles or get buried in the soil, which can easily lead to the disengagement of the chain and sprocket. During this process, the grain lifter fails to work effectively. To this end, this study will introduce the unmanned driving technology for rice planting in the future to ensure the straight end of the rice field distribution and harvesting rolled path, so as to realize the high-precision improvement of the rice stubble grain lifter. In addition, a copying device and an elastic lifting finger are designed to reduce the tooth jumping and jamming of the lifting finger.

Table 5

Success rate of field lifting

targets of test	test number					average value
	1	2	3	4	5	
lifting success rate	40%	60%	65%	60%	50%	55.00%

CONCLUSIONS

1) A double-chain finger grain lifter for lifting the rolled ratoon rice stubble in mechanical harvesting is designed; the kinematics model and its trajectory curve of the process of unfolding, reeling, lifting, retracting and hollow travel of the finger are constructed by establishing the kinematics analysis of the lifting chain. The main factors affecting the lifting performance are analyzed and determined, such as the rotational speed of the chain, the distance between adjacent chains and the number of fingers on the rear lifting chain.

2) Bench test was carried out with the success rate of lifting and the secondary damage of lifting as indexes. The results show that the speed of the chains, the distance between adjacent chains and the number of fingers in the rear chains all significantly affect the centralization performance of the device. When the speed of the chains is 345 r/min, the distance between adjacent chains is 300 mm and the number of fingers in the rear lifting sprocket is 3, the success rate of lifting is 90.05%, and the secondary damage rate of lifting is 1.72%.

3) The field test validates the effectiveness of lifting operations; the average success rate of lifting operations in the field is 55%, which shows that the double-chain finger grain lifter designed in this study has a good potential for lifting the ratoon rice stubble rolled by mechanical harvesting.

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